RESERVOIR SEDIMENTOLOGY
(505613)
By
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RESERVOIR SEDIMENTOLOGY 505613

วิทยาการตะกอนหินกักเก็บ

วิชาบังคับก่อน...505306 วิทยาการตะกอนหรือโดยความเห็นชอบของสาขาวิชา

การไหลของของไหล กลไกการพัดพาตะกอน รูปแบบชั้นหินและโครงสร้างของหินตะกอน การพัดพาตะกอนด้วยแรงโน้มถ่วงของโลก รูปแบบจำลองสภาวะแวดล้อมของการตกทับถมของตะกอนและลักษณะปรากฏของหินคลาสติก ส่วนประกอบ การจำแนกและรูปแบบจำลองลักษณะปรากฏของหินคาร์บอเนต กระบวนการต่างๆ หลังการตกทับถมของตะกอนที่มีผลต่อชั้นหินกักเก็บปิโตรเลียม

หัวข้อ

■การพัดพาและการไหลของตะกอนเนื่องจากแรงโน้มถ่วงของโลกและการกระทำของคลื่น (Mass movement & wave)

■กลไกการพัดพาตะกอน (River system)

■การสะสมตัวของตะกอนเป็นระบบซีเควนซ์ (Sequence stratigraphy)

■รูปแบบจำลองสภาวะแวดล้อมของการทับถมตะกอนและลักษณะปรากฏของหินคลาสติก (รวมถึงรูปแบบของชั้นหินและโครงสร้างของหินตะกอน) (Clastic reservoir)

■ส่วนประกอบ การจำแนก และรูปแบบจำลองลักษณะปรากฏของหินคาร์บอเนต (Carbonate reservoir)

■กระบวนการกดทับ การแปรสภาพ การเชื่อมประสานและการละลายของหินคลาสติกและคาร์บอเนต และผลที่มีต่อความพรุนและความสามารถในการซึมผ่านได้ของชั้นหินกักเก็บไฮโดรคาร์บอน (Diagenesis process)

Mass movement

สาขาวิชาเทคโนโลยีธรณี

ผศ. ธารา เล็กอุทัย 1 ม.ค. 2550

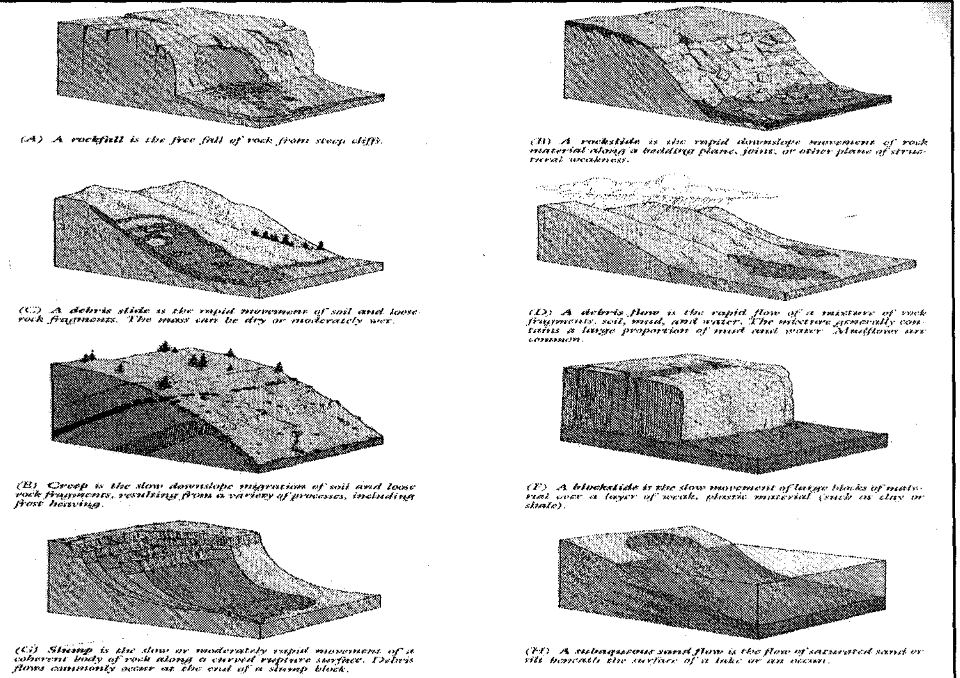


FIGURE 10.3
Mass movement takes various forms, all of which produce slope retreat and enlarge valleys. Examples of various types of mass movement are illustrated in the diagrams.

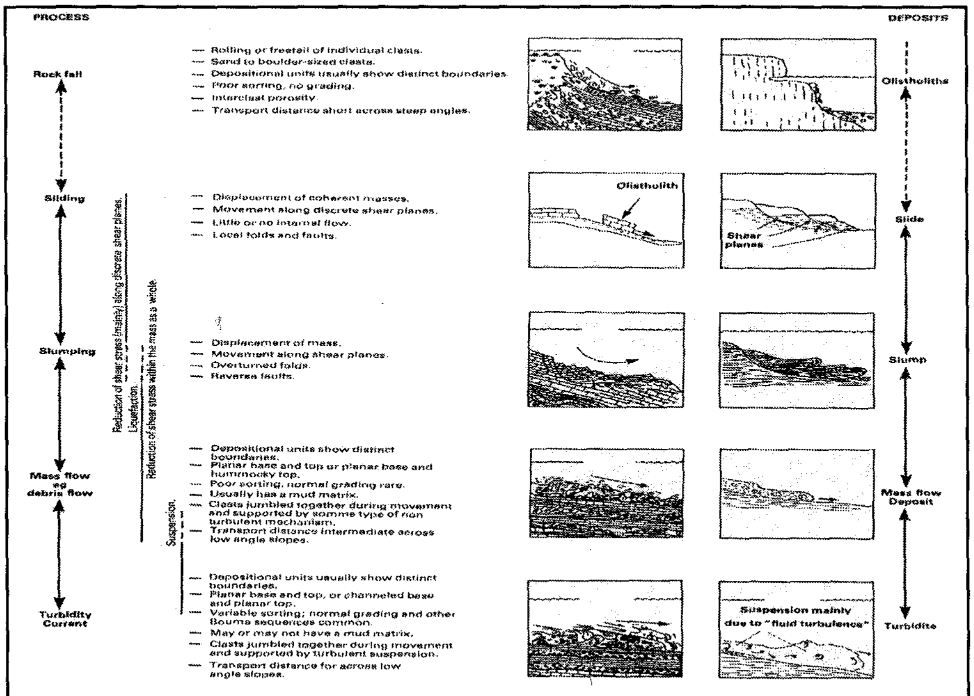


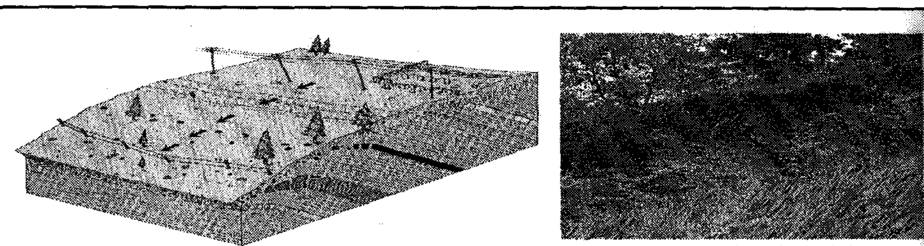
Fig. 5.9-12. Major types of gravity transport processes (adapted from Dott, 1963).

Mass Wasting

Slow-flow (not perceptible)

Creep:

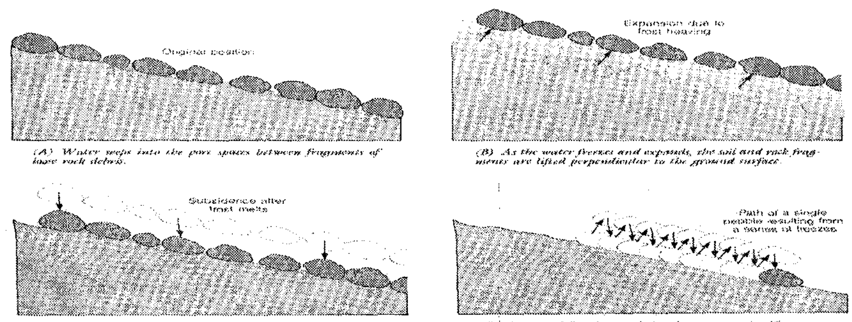
- Creep is an extremely slow movement, almost imperceptible down slope of soil creep, rock creep (glacier), debris creep (talus).



(A) Creep is expressed in various ways, such as the downslope displacement of fence lines, roads, telephone poles, headstones in cemeteries, and rock debris from original outcrop debris.

(B) Surface expressions of creep. One of the most vivid expressions of creep is seen in exposures along the side of a hill slope where the upper edges of stratified rock bend downslope.

FIGURE 10.4
Creep.



(A) Water seeps into the pore spaces between fragments of loose rock debris.

(B) As the water freezes and expands, the soil and rock fragments are lifted perpendicular to the ground surface.

(C) As the ice melts, gravity pulls the particles down vertically, displacing them slightly downhill.

(D) Repeated freezing and thawing cause a significant net displacement downslope.

FIGURE 10.5
Creep can result from repeated frost heaving. With each freeze, there is a net downslope displacement of all loose material.

Solifluction:

- Solifluction is a regolith creep, common in polar regions, where groundwater in the pore spaces of soil & rock is permanently frozen (permafrost layer).
- During spring and early summer, the ground surface begins to thaw down hill because the melt water cannot percolate pass the impermeable permafrost layer.
- It is not confined in a channel leaving ground patterns (stone rings, stone nets, stone stripes, earth hummocks, block-fields)

FIGURE 10.6
Solifluction is a major type of mass movement in polar regions and in some high mountains. In view of a hill in Alaska, the water-saturated regolith moves slowly downslope like a viscous liq-

Rapid-flow (perceptible)

Fall:

- Rock falls: include the free fall of a single fragment ranging from a small grain to huge block.
- Debris falls: overtime, great quantities of small to moderate grain size fragments shower down from the face of a cliff and accumulate at the base as talus (clasts rolling, move short distant)

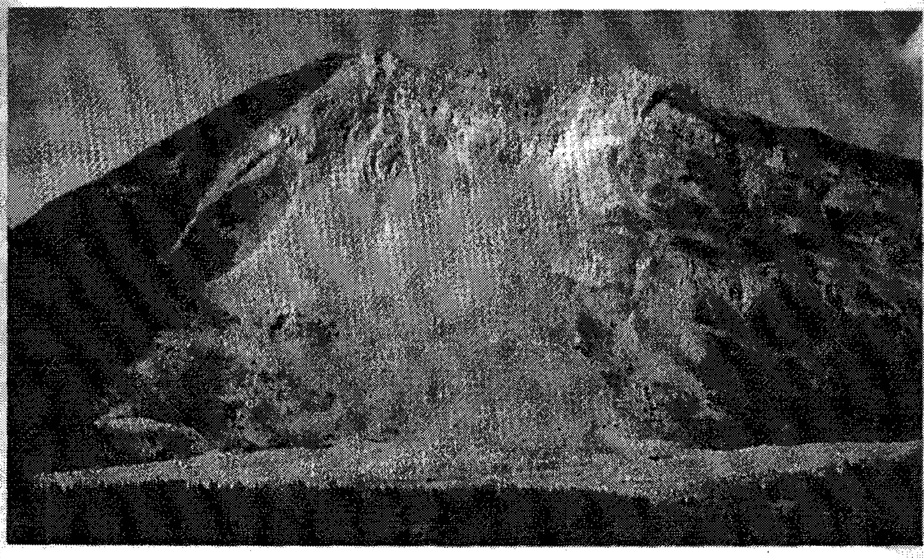


FIGURE 10.10
The Frank rockfall, Alberta, Canada, involved a huge mass of rock that broke away from the mountain face completely burying the mining town of Frank, Alberta. Among the factors that contributed to this slope failure were the steepness of the mountain front, the dip of the bedding planes parallel to the mountain face, and underlying weak shale and coal beds. Mining activity may have triggered the movement.

Landslide:

- True landslide block move as a unit (coherent mass) or series of units (without internal flow & without backward rotation) along a well defined slip page fracture plane (discrete shear plane).
- The block leaves behind a groove or scar.
- Debris avalanche is debris slide in narrow track, like snow avalanche near arctic area
- (Slump: the unit mass movement have internal flow/ overturned folds & reversed faults?)

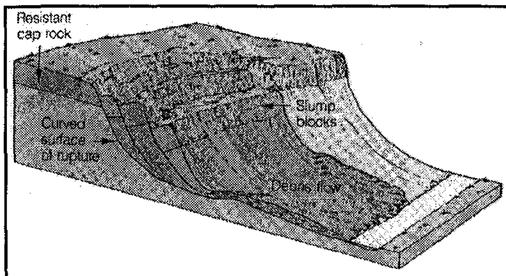
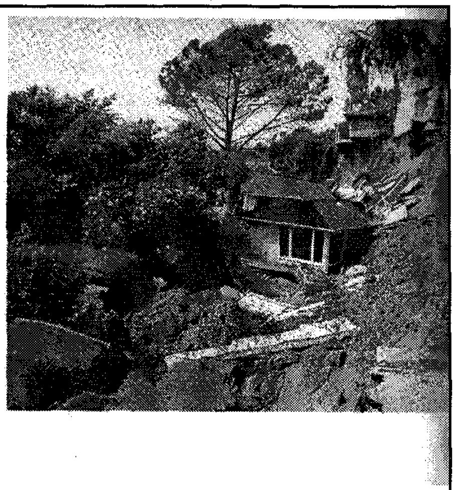


FIGURE 10.9
Landslides occur along rather well-defined slippage surfaces. Large blocks will slump and rotate downslope and many will grade into debris flows at their lower margins. The photograph shows the upper part of a landslide in California where homes were displaced along the curved rupture surface of the slump block.



Sub-aqueous mass movements:

- They are effect large areas of the seafloor.
- They are active near deltas and convergent continental margins, where sediment accumulates rapidly and slopes are steep.
- They are include sliding, slumping, flow and turbidity current.

Flow:

- Flows are generally occur during intense rainfall and begin on steep hill slopes as soil slumps that soon liquefy and flow at speed as great as 50 km/hr.
- Debris flow: Mixture of rock fragment, mud and water that flow as viscous fluids.
- Earth flow: Water saturated earth material, Not confined in a channel, Humid area

  Mud flow: Water saturated rock debris, Confined in a channel, Arid area

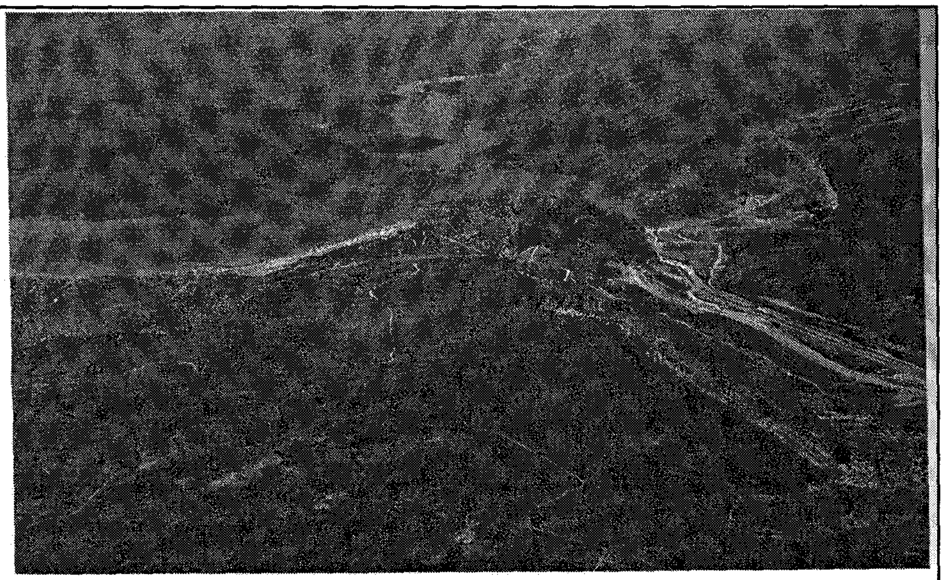


FIGURE 10.7
A debris flow in Spanish Fork Canyon, Utah, was mobilized in April 1983, as a result of high rainfall combined with rapid melting of a thick snowpack. The mass of debris blocked the canyon and formed a lake upstream that completely flooded the town of Thistle. Four million m^3 of debris flowed downslope and cut off railway and highway access to a large area of the western United States. Concerns that the lake would overflow, destroy the dam, and flood the cities and towns downstream prompted engineers to quickly construct a diversion tunnel to control the lake level. The "natural dam" still remains. Damages were estimated as $250 million, making the Thistle debris flow the most costly in U.S. history. More than 90 other debris flows occurred along the steep front of the Wasatch Mountains, some crashing through towns, burying homes. *(U.S. Department of Agriculture, ASCS Western Aerial Photo Lab., Salt Lake City, Utah.)*

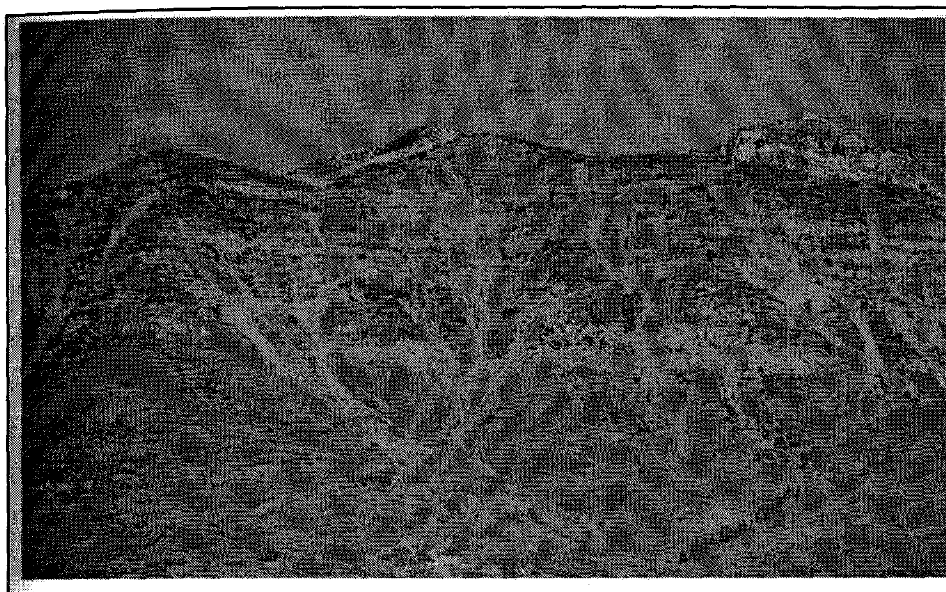


FIGURE 10.8
Mudflows typically originate on steep slopes where there is an abundance of unconsolidated shale, volcanic ash, or thick regolith. They commonly mobilize during periods of high precipitation and spread out in the valley, forming a large fan, or lobe. These mudflows in the Wasatch Mountains, Utah, resulted from a period of heavy rain in 1983. More than 90 mudflows occurred along the Wasatch front during a period of two months.

Subsidence:

- Subsidence is downward movement of earth material lying at/near the surface.
- The primary force producing subsidence is gravity but before gravity can act other processes must operated to create space such as dissolution of rock by ground water, burning coal in the subsurface, isolated block of glacial ice loading or lava tubes.

<u>Waves</u>

Origin

- Wind generated waves provide most of the energy for erosion, transportation and deposition of sediment.

Morphology

Water-wave can be described in the terms of wave-length, wave-crest, wave-trough and wave-period.

SHORELINE SYSTEMS ■ 407

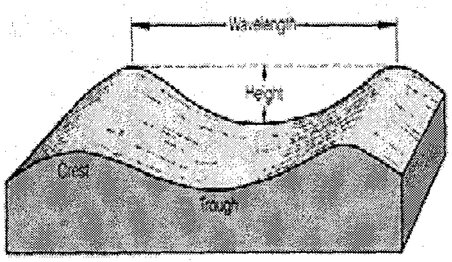
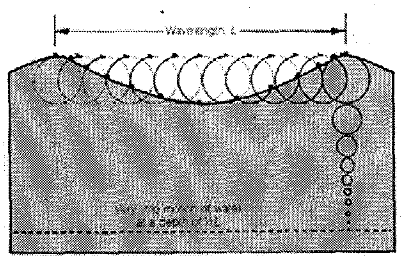


Figure 16.1
The morphology of a wave can be described in terms of its length (the distance from crest to crest), height (the vertical distance between crest and trough), and period (the time between the passage of two successive crests).

Motion

Water-wave move in a circular orbit with a diameter equal to the wave height. The diameter decreasing with depth and dies out at a depth equal to about half of the wavelength (wave-base).



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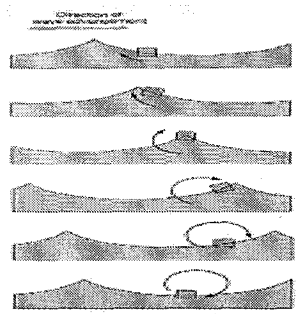
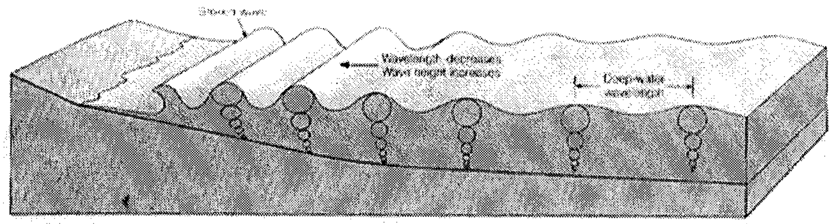
rbital motion of water in a wave decreases with depth and dies out at a depth to about half the wavelength.



Breaker

- As waves approaches shallow water, the wave-length decreases but wave-crest increases due to frictional drag as wave base encounters the sea floor.
- Finally, the wave-crest extends beyond the support of column orbiting water and breaks. All of the water in the column moves forward, releasing its energy as a wall of turbulent surf know as a breaker.
- After a breaker collapses the swash flow up dissipates against the beach slope and flow down as backwash.

Breaker (Surf)



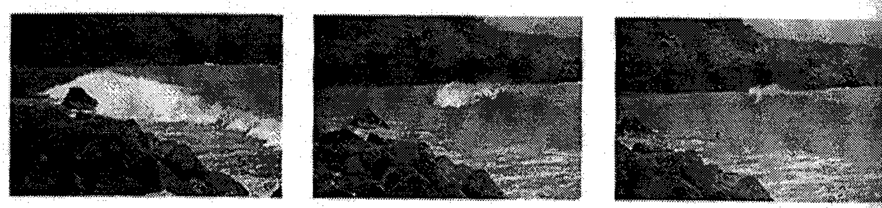
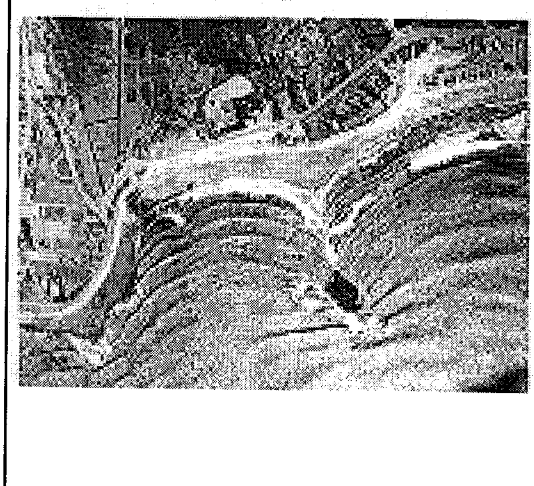
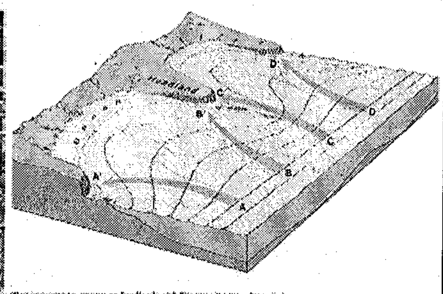


Figure 16.4
A wave approaching the shore undergoes several significant changes as the water in orbital motion encounters the sea floor. (1) The wavelength decreases due to frictional drag and the waves become crowded together as they move closer to shore. (2) The wave height increases as the column of water, moving in an orbit, stacks up on the shallow sea floor. (3) The wave becomes asymmetrical, because of increasing height and frictional drag on the sea floor, and ultimately breaks. The water then ceases to move in an orbit and rushes forward to the shore. Note the change in wave morphology in the time lapse photos (right to left).

Wave refraction

- Wave refraction concentrates energy on headlands and disperses it across bays

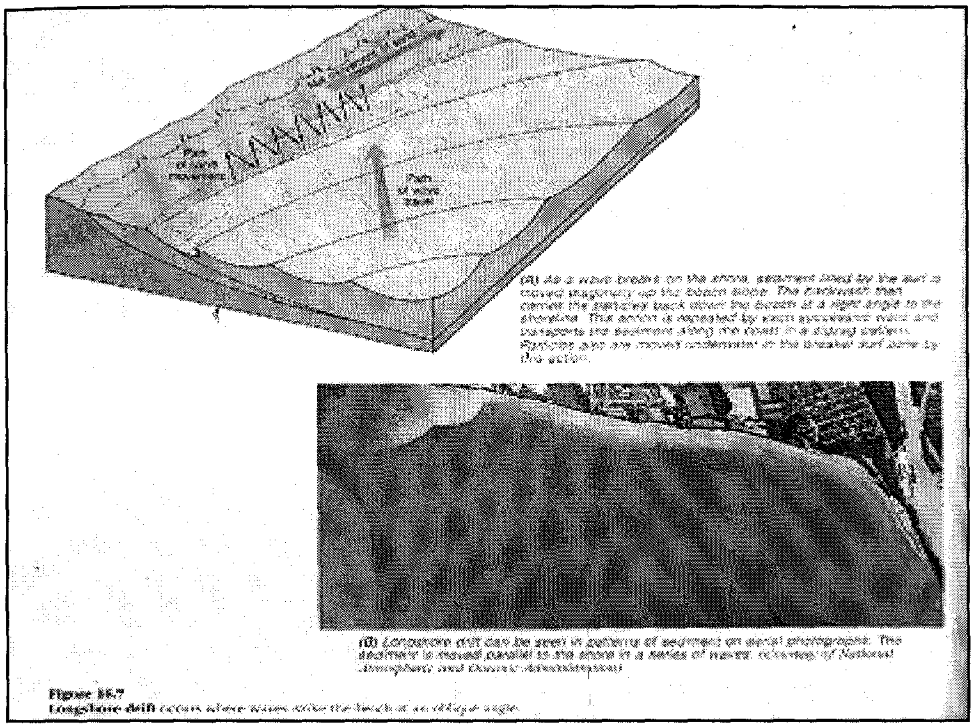




Long-shore drift

- As wave advance obliquely to the shore, sediment lifted by the swash is moved up in the direction of wave's advance. The backwash then carries the sediment down the beach at a right angle to the shoreline.
- This action is repeated by each successive wave and transports the sediment along the coast in a zigzag pattern with net transport parallel to the shore. This process is known as beach drift.

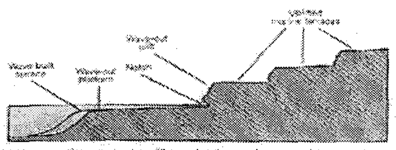
- A similar process known as long-shore current, develops in the breaker zone.
- Thus, long shore movement occurs in two zones. One is along upper limit of wave action (beach drift) the other is in the breaker zone (long-shore current).
- Both beach drift and long-shore current combined action work together, which is know as long-shore drift.



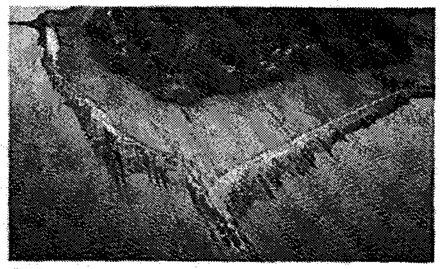
Erosion along shoreline

Principal features

- Erosion along shoreline results from the abrasive action of sand and gravel moved by the waves and currents with a lesser extent of solution and hydraulic action.
- The undercutting action of waves and currents produces notch, sea cliff and wave cut platform.
- Minor erosion associated with the development of sea cliffs include sea-caves, sea-arches and sea-stacks.

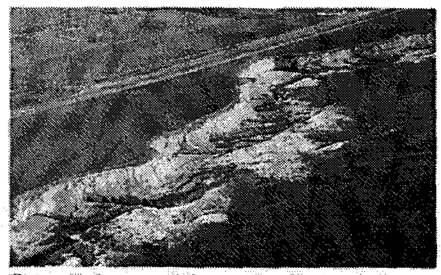


(A) Wave action operates like a horizontal saw cutting at the base of the cliff. The cliff is undermined and collapses. The debris is soon removed by wave action, and undercutting continues. As erosion continues, the cliff recedes farther, and a gently sloping wave-cut platform is left. Some sediment eroded from the shore can be deposited in deeper water to form a complementary wave-built terrace.



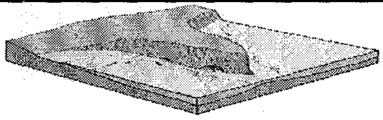
(B) A wave-cut platform on the Washington coast. (Courtesy D. Eserlnuck)

(C) Wave erosion along a coast of Mexico has produced this notch and overhanging cliff. Collapse appears imminent.

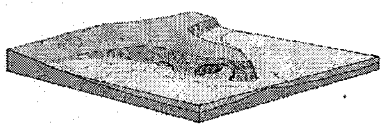


(D) An uplifted wave-cut platform and sea cliffs along the Pacific Coast. (Courtesy D. Eserlnuck)

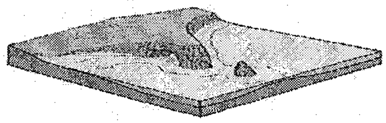
Figure 16.9
A wave-cut platform is the fundamental landform produced by wave erosion.



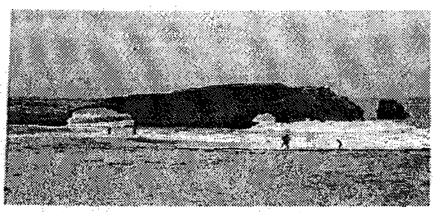
(A) Wave energy is concentrated on a headland as a result of wave refraction. Zones of weakness, such as joints, faults, and nonresistant beds, erode faster, so that sea caves develop in those areas.



(B) Sea caves enlarge to form a sea arch.



(C) Eventually, the arch collapses, leaving a sea stack. A new arch can develop from the remaining headland.



(D) Sea arches and stacks along the coast of southern California, 1969.

(E) Same area as shown in (D), 1987.

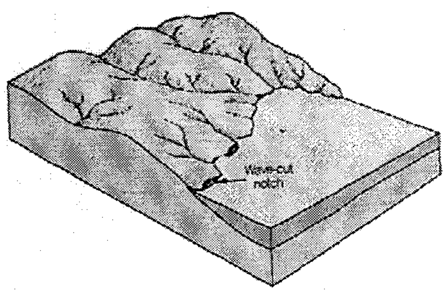
Figure 16.10
The evolution of sea caves, sea arches, and sea stacks is associated with differential erosion of a headland. Sea arches and sea stacks along the coast of southern California are shown in Figure D as they appeared in 1969. The same area was photographed in 1987 (right). Erosion eliminated the small sea stack, eroded the cliff behind it, and caused the collapse of the large sea arch.

415

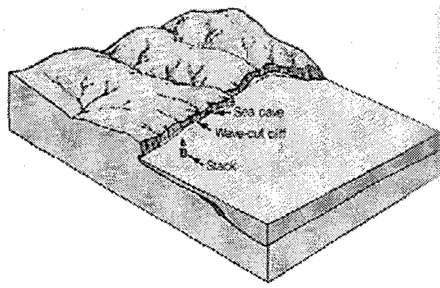
Evolution of a shoreline

- Initial stage: (cliff)
  - Sea level rise (Melting of glaciers)
  - Tectonic (Uplift or subsidence of land)
  - Expansion and contraction of the sea
- Intermediated stage: (platform)
  - Sea caves, Sea arches, Sea stacks
- Late stage: (beaches)

416 ■ CHAPTER 16



(A) Initial stage. Wave action begins to develop a notch at sea level, which evolves to form a wave-cut cliff.



(B) Intermediate stage. Continued wave erosion causes the cliff to recede, and a wave-cut platform develops. Sea stacks, sea arches, and sea caves result from differential erosion along zones of weakness.

(C) Late stage. The wave-cut platform grows so large that wave energy is dissipated across it. Erosion along the shore is greatly reduced. Beaches develop, and the sea cliff retreats through mass movement.

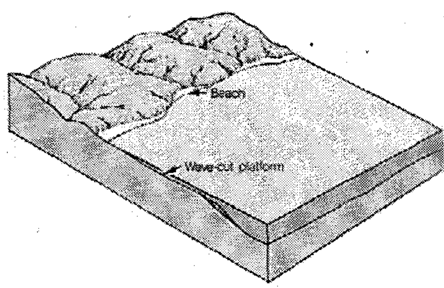


Figure 16.11
The evolution of a shoreline involves a series of stages in which the configuration of the coast is modified by both erosion and deposition until, finally, only a minimum of energy is expended on it. The most stable shoreline form has a smooth, straight coast and a wide platform.

Deposition along shoreline

- Sediment transported along shoreline may came form river, headland/cliff erosion and shell debris.
- It is deposited in areas of low wave energy and produces beaches, spits, tombolos and barrier islands.

- Beach It is a shore built of unconsolidated sediment.
- Spits A straight shoreline beach can grow far out across the bays or estuaries. It may extend completely across the bay forming a bay-mouth bar.
- Tombolos Beach deposit can also grow outward and connected the shore with an offshore island.
- Barrier island A long sprit grows parallel to the shoreline. They are separated from the main land by a lagoon and most barrier islands are cut by tidal inlets.

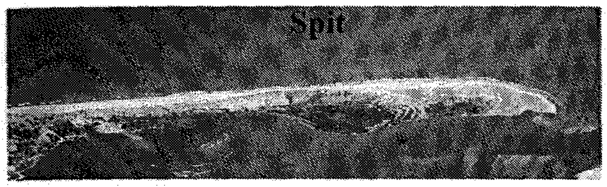
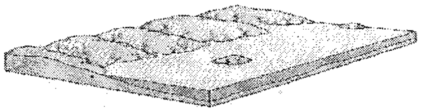


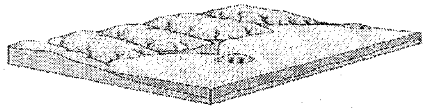
Figure 16.14
Curved spits develop as longshore drift moves sediment around the point of a barrier beach. Note the movement of sediment in a series of sand waves around the end of the beach and into the lagoon. The waves strike the shore obliquely causing longshore sediment transport. An older period of growth can be seen in the central part of the spit.

Tombolos

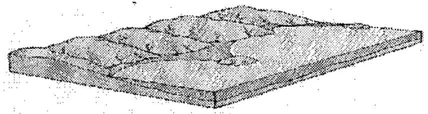
Beach deposits can also grow outward and connect the shore with an offshore island to form a *tombolo*. This feature commonly is produced by the island's effect on wave refraction and longshore drift (Figure 16.15). An island near shore can cause wave refraction to such an extent that little or no wave energy strikes the shore behind it. Longshore drift, which moves sediment along the coast, is not generated in this wave shadow zone. Sediment carried by longshore currents is therefore deposited behind the island. The sediment deposit builds up and eventually forms a tombolo, a bar or beach connecting the shore to the island. Longshore currents then move uninterrupted along the shore and around the tombolo.



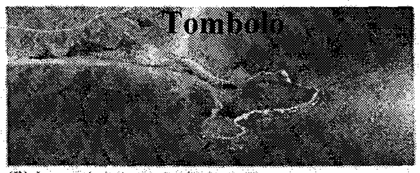
(A) An offshore island acts as a breakwater to incoming waves and creates a wave shadow along the coast behind it.



(B) Sediment moved by longshore drift is trapped in the shadow zone.



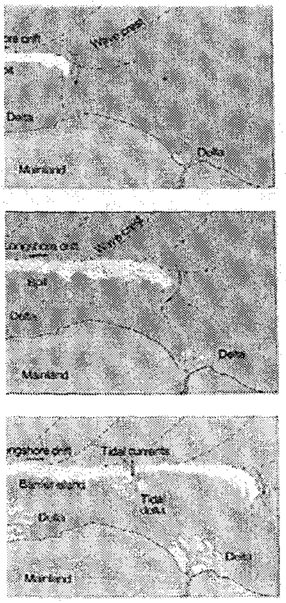
(C) The zone of sediment deposition eventually grows until it connects with the island. Longshore drift will then move sediment along the shore and around the tombolo.



(D) An aerial photograph of a tombolo.

Figure 16.15
A tombolo is a bar or beach that connects an island to the mainland. It forms because the island creates a wave shadow zone along the coast, in which longshore drift cannot occur.

Barrier island



(A) Sediment moving along the shore is deposited as a spit in the deeper water near a bay.

(B) The spit grows parallel to the shore by longshore drift.

(C) Tidal inlets cut the spit, which is then long enough to be considered a barrier island.

e 16.17
rier island may form by migration of a spit.

Reef

- Most reefs form a unique of shoreline feature and occur in warm tropical latitude 30N-30S, under water condition Clear, Warm, Shallow (< 76 m).

SHORELINE SYSTEMS ■ 427

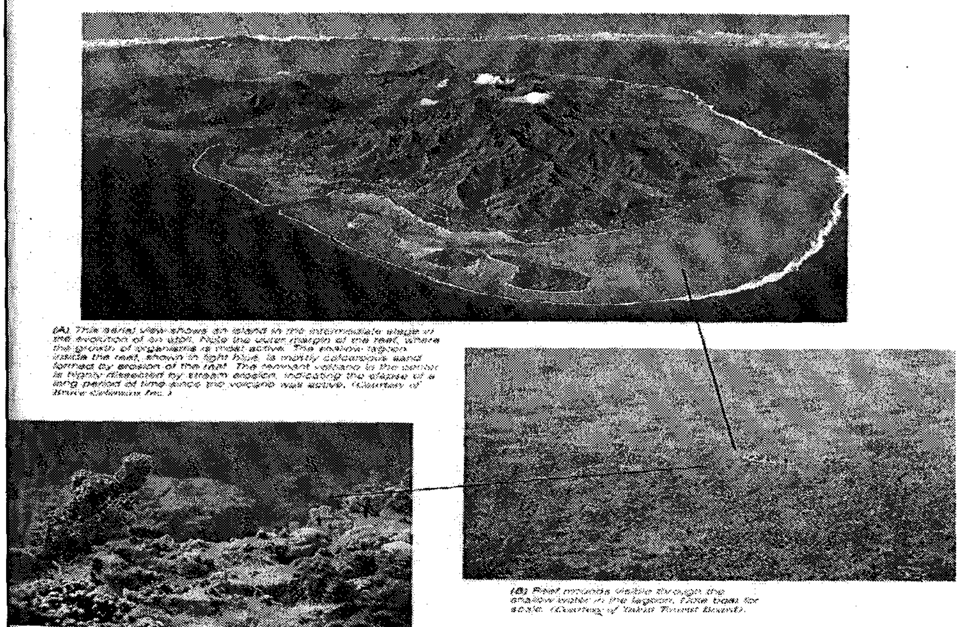
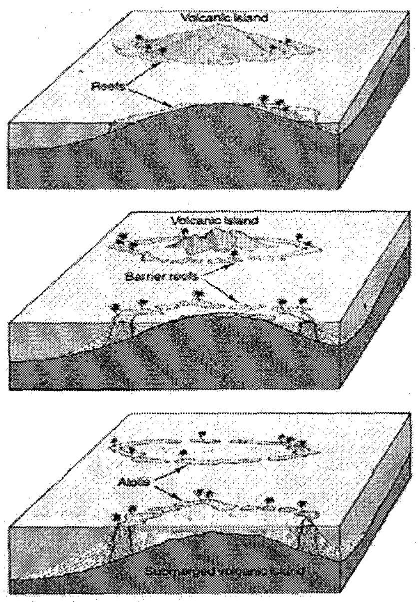


Figure 16.23
A barrier reef in the Society Islands, French Polynesia

Reef types

- Fringe reef: It is attached to mainland such as volcanic island
- Barrier reef: It is separated from mainland by lagoon
- Atoll: It is circular reef enclosing a shallow lagoon
- Platform reef: It is isolated oval patches on the continental shelf

Evolution of an atoll



(A) A fringe reef begins to grow along the coast of a newly formed volcanic island.

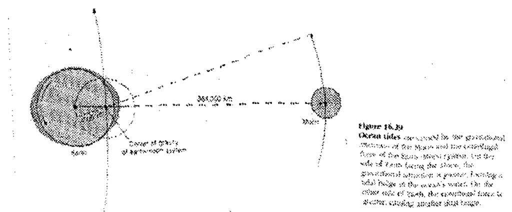
(B) As the island subsides, the reef grows upward and develops a barrier that separates the lagoon from open water.

(C) Further subsidence completely submerges the island, but if subsidence is not too rapid, the reef continues to grow upward to form an atoll.

Figure 16.25 •
The evolution of an atoll from a fringing reef was first recognized by Charles Darwin. The theory assumes that continued slow subsidence of the ocean floor allows the reef to continue growing upward.

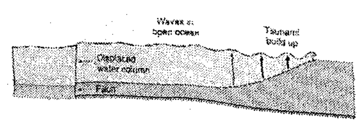
Tidal

- Tidal are produced by the gravitational attraction of the moon and the centrifugal force of the earth-moon system.
- They effect shoreline in two major ways (1) by initiating a rise and fall of the water level (2) by generating tidal current.
- Most shorelines in the world, the sea advances and retreats twice in a day.



Tsunamis

- Sea floor movement by earthquakes, volcanic eruptions or submarine landslides frequently produces tsunami, which has a long wave-length & travel across ocean at high speed.
- As the tsunami approaches shore, its wave-length decreases and wave-crest increases which can be dangerous agent for destruction.
- Tsunami differs from wind-wave in that energy is transferred to the water from a sea-floor disruption.



RIVER SYSTEM

- Stream valleys created by stream erosion are abundant and significant landform on the continents.
- A typical river can be divided into 3 segments
  - A collecting system
  - A transporting system
  - A dispersing system

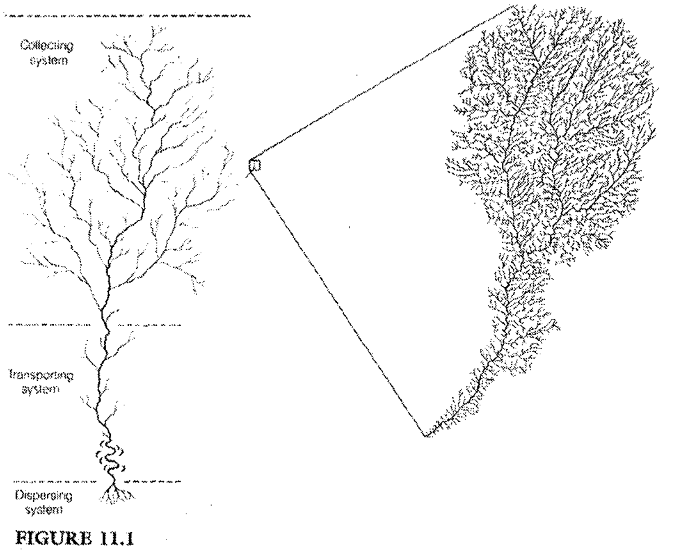


FIGURE 11.1
The major parts of a river system are characterized by different geologic processes. The tributaries in the headwaters constitute a subsystem that collects water and sediment and funnels them into a main trunk stream. Erosion is dominant in this headwater area. The main trunk stream is a transporting subsystem. Both erosion and deposition can occur in this area. The lower end of the river is a dispersing subsystem, where most sediment is deposited in a delta or an alluvial fan, and water is dispersed into the ocean. Deposition is the dominant process in this part of the river.

■Collecting system consisting network of tributaries (dendritic/tree like) in the headwater region collects of water and sediment to the main stream.

■Transporting system is the main trunk stream, which functions as a channel-way through which water and sediment move from the collecting area toward the ocean.

■Dispersing system consists of network of distributaries at the mouth of a river, where water and sediment are dispersed into an ocean, a lake or a dry basin such as delta, alluvial fan etc.

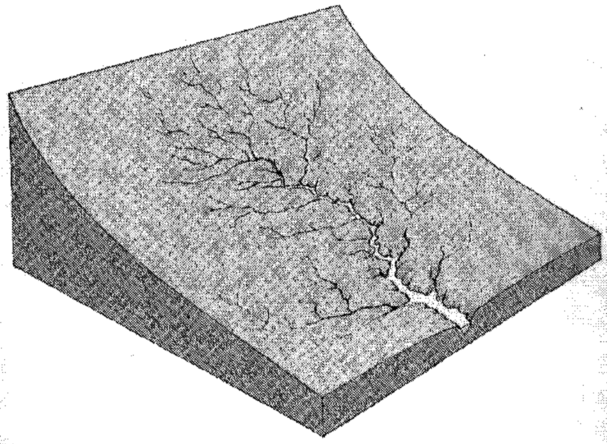


FIGURE 11.2
The characteristics of a river change systematically downstream. The gradient decreases downstream, and the channel becomes larger. Other downstream changes include an increase in the volume of water and an increase in the size of the valley through which the stream flows.

- Factors influencing the flow of water
  - Discharge (Climate control)
  - Gradient/Slope (Tectonic control)
  - Velocity
  - Sediment load
  - Base level
- Discharge is the amount of water passing a given point during a specific interval of time.
- The water comes from both surface runoff water and seepage of ground water.
- It varies from season to season with fluctuations of longer climatic cycle.

- Gradient/Slope is steepest in the head valley (head channel) and decreases down-slope.
- The stream profile is concave upward curve that becomes very flat at the lower end of the stream.
- Velocity is not uniform throughout the stream channel.
- It is usually greatest near the center of the channel and above the deepest part, away from the frictional drag of the channel wall and floor.
- As the channel curves, the zone of maximum velocity shifts to the outside of the bend while the zone of minimum velocity forms on the inside of the curve.

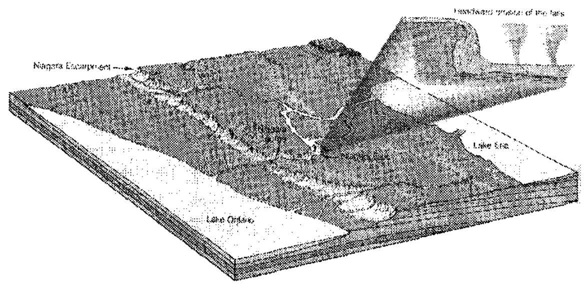


FIGURE 11.8
Retreat of Niagara Falls upstream occurs as hydraulic action undercuts the weak shale below the limestone. The Niagara River originated as the last glacier receded from the area and water flowed from Lake Erie to Lake Ontario over the Niagara cliffs. Erosion causes the waterfalls to migrate upstream at an average rate of 1.3 m per year.

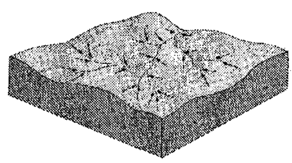


FIGURE 11.9
Headward erosion is the basic mechanism by which a drainage system is extended upslope. Water flows as a sheet down the regional slope (away from the foreground of the figure). As it converges toward the head of a tributary valley, its velocity is greatly increased, and so its ability to erode also increases. The tributary valley is thus eroded headward, up the regional slope.

- Sediment load is the material transported by the river.
- Fine particles are moved down stream in suspension-load while large particles collect on the channel floor, are moved in bed-load/traction-load (sliding, rolling and saltation).
- Bed-load movement is one of the major tools of stream erosion as they abrade the bottom and side of stream channel.
- In addition some soluble material are moved in dissolved load.

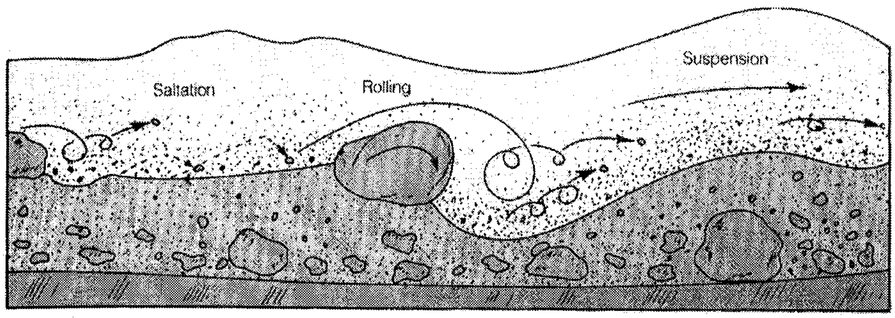


FIGURE 11.3
Movement of the bedload in a stream is accomplished in a variety of ways. Particles that are too large to remain in suspension are moved by sliding, rolling, and saltation. Increases in discharge, because of heavy rainfall or spring snowmelt, can flush out all of the loose sand and gravel, so that the bedrock is eroded by abrasion.

- Bed level is the lowest level to which the stream can erode.
- The final base level for all practical purposes, is sea level, but local base levels may occur such as tributary cannot erode lower than the level of the main stream or lake.
- Equilibrium: The increased slope across the stream profile greatly increases the stream's velocity, so that rapid erosion occurs and the waterfall/rapid migrates upstream.

▪The additional erosion material, therefore deposits part of it load at that point, thus building up the channel gradient until a new stream profile of equilibrium (neither erosion nor sedimentation) is established.

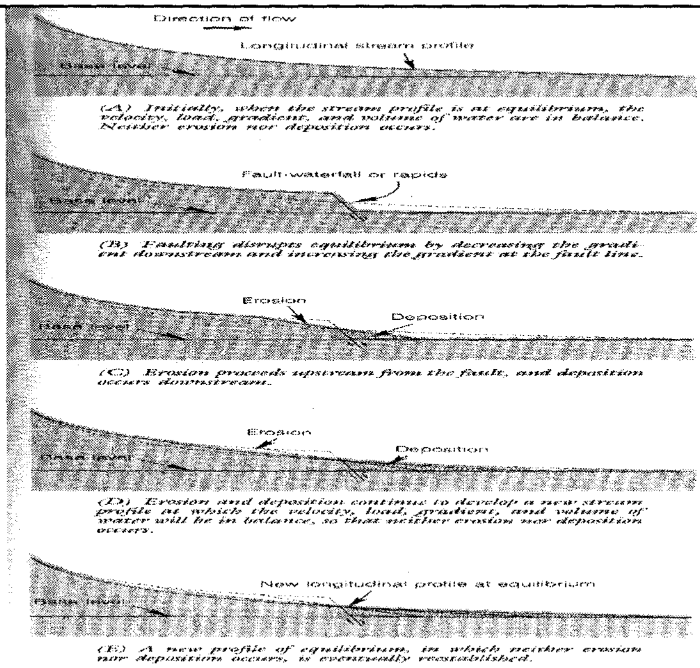
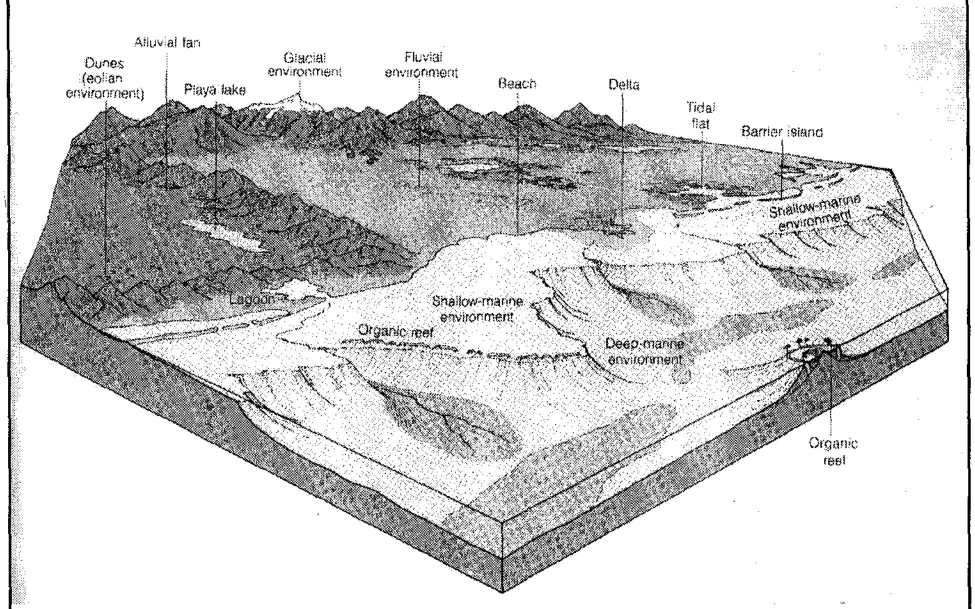


FIGURE 11.4
Adjustments of a stream to reestablish equilibrium are illustrated by profile changes after disruption by faulting.

CLASTIC RESERVOIR

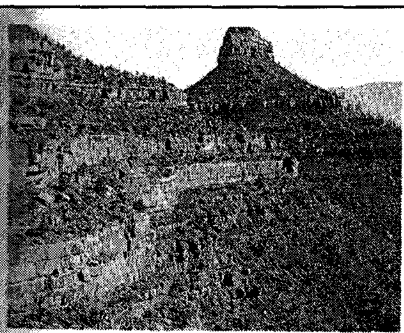
Non-marine reservoir

- Alluvial fan: braided streams (temporary / ephemeral). Sand is high energy deposited.
- Fluvial: braided & meandering streams (permanent / perennial). Sand is progressively finer and more water worked deposited.
- Desert: meandering stream (temporary / ephemeral), aeolian, playa lake. Sand is non-aqueous deposited.
- Lacustrine: great variety facies. Sand is many type deposited.

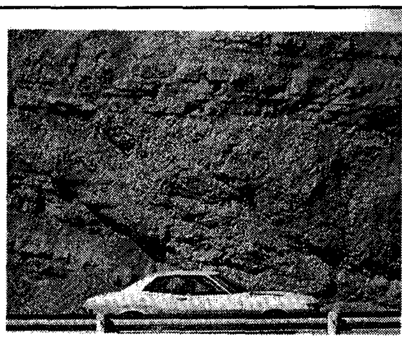


Non-marine indicator

- Tectonic setting: Non-marines are often overlie or between major unconformities. (also in rift, sag, strike-slip basin etc.)
- Fossils: Vertebrates, gastropod, insect, rootlet and exposed surface structures
- Associated Facies: Non-marine facies are often lateral & vertical variation as seismic shows discontinuous reflections. Upland are often reddish color due to oxidizing above water table while lowland are often drab color due to reducing below water table. (except lacustrine?)

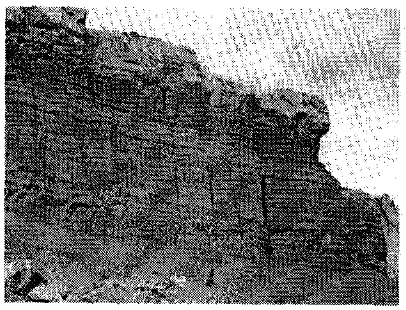


(G) Deltaic deposits in the Grand Canyon, Arizona.



(I) Alluvial fan deposits, Rocky Mountains.

(H) Beach deposits, Central Utah.



(J) Tidal flat deposits, Central Utah.

SEDIMENTARY STRUCTURE

- Selley (1970), structures "unlike lithology and fossils are undoubtedly generated in place and can never have been brought in from outside".
- The structures concern with the organization of deposition including the internal, external and deformation of bed.
  - Base on time
  - Pre-deposition (erosion surface)
  - Syn-deposition (during deposition)
  - Post-deposition (diagenetic often chemical)

- Base on process
- Physical (ripple mark, tool mark, convolute etc)
- Chemical (dissolution, concretion etc)
- Biological (burrow, track, trail, foot-print etc)
- Base on location
- External structure (bed shape, bed boundary)
- Internal structure (internal organization of bed)

Relationship of structures and well logging

Base on location (External structure)

- ***1. Bed shape***
- *Bed thickness*:
- Bed (cm) thickness and grain size is related and decreases in the direction of flow. V-Thin (1) Thin (10) Medium (30) Thick (100) V-Thick
- Laminations (mm) are either the indication of very fast deposition or minor fluctuation condition at sea floor. (1) Thin (3) Medium (10) Thick (30)

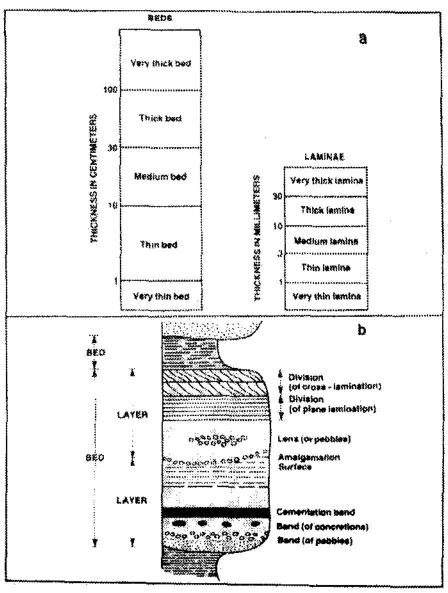


Fig. 2-4. (a) Terminology for thickness of beds and laminae (modified after Ingram, 1954, and Campbell, 1967; in Reineck & Singh, 1975), (b) Terms for description of beds with internal structures (from Blatt et al., 1980).

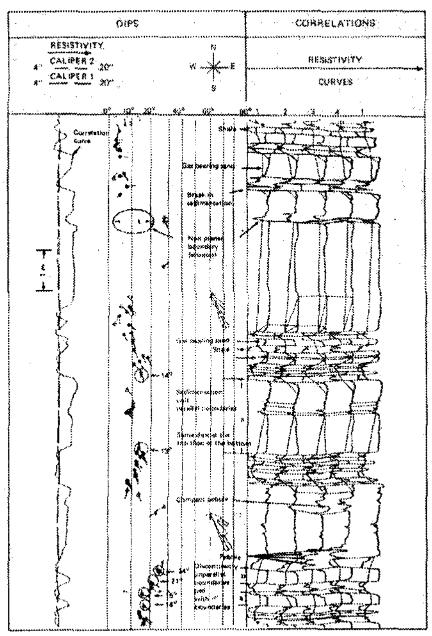


Fig. 2-7. Variation of bed thickness as illustrated by a GEODIP display.*

* Mark of Schlumberger

- *Bedding planes*:
- Campbell (1967) defined bedding planes as:
  - Non-deposition (no thickness)
  - Rapid change in condition (var. in energy)
  - Erósion surface (limited lateral extension)
- He also defined the bedding planes as even/uniform or wavy or curve. (Fig. 2-10)

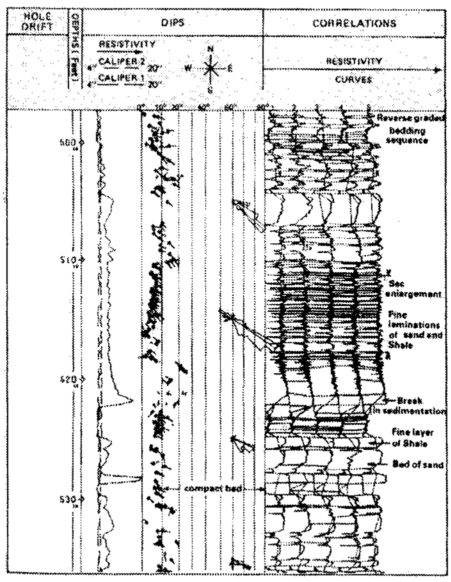


Fig. 2-8. Very fine beds detected by HDT tool, showing wavy bedding.

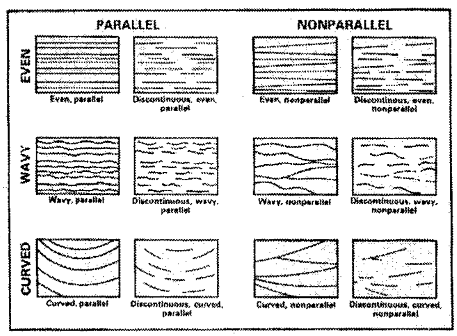


Fig. 2-10. Diagram showing different shapes that can be acquired by beds and laminae, and the corresponding descriptive terms (from Campbell, 1967).

Lateral extension of beds:

- The more bed thickness, numerous bed with parallel bedding planes thus the more lateral extension of the bed.

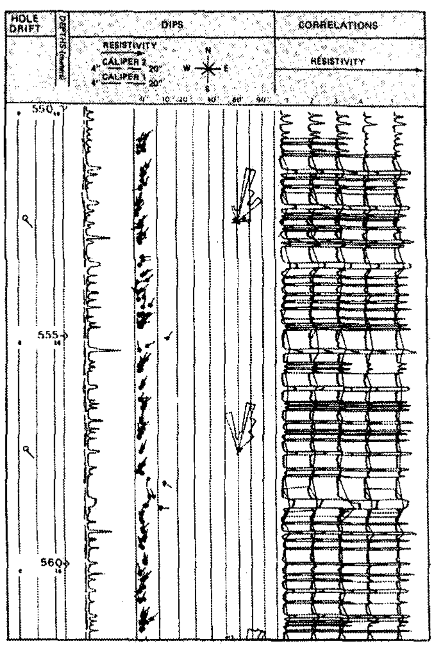


Fig. 2-16. Example of numerous beds with good consistency of dips suggesting lateral extension.

2. *Bed boundaries*

- The transition from one layer to another can either be abrupt/gradual boundary.
- Abrupt boundaries are clearly defined and agree with bedding planes.
  - Conformable boundary: break without change the sequence (parallel bedding plane)
  - Unconformable boundary: break with change the sequence (erosion bedding plane)
- Gradual boundaries are not clearly defined and agree with a sequence which is either grain size or mineral or both.

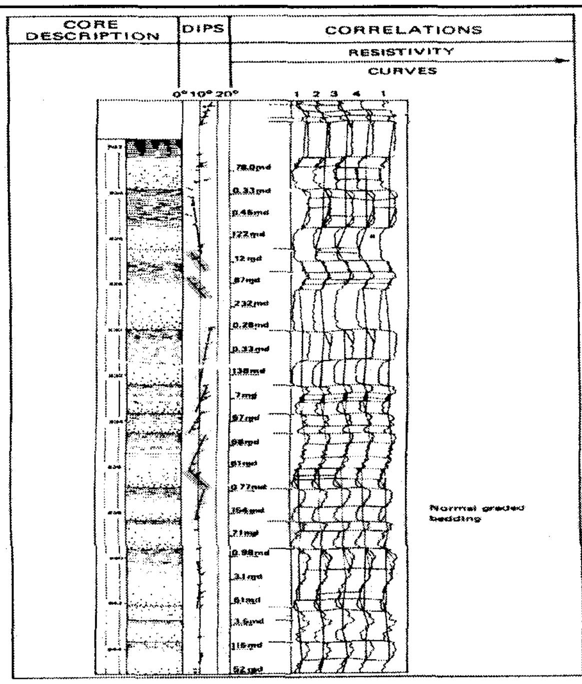


Fig. 2-17. Example of gradational transition corresponding to sequences.

- *Top of bedding plane*
- Climate (mud crack, rain pit)
- Current (erosion mark, ripple mark)
- Organic marking (track, trail, burrow, rootlet, foot impression etc.)
- *Within bedding plane*
- Parting, lineation
- Organic marking (track, trail, burrow, rootlet, foot impression etc.)
- *Bottom of bedding plane*
- Climate (load cast)
- Current (scour mark, tool mark)
- Organic marking (track, trail, burrow, rootlet, foot impression etc.)

Base on location (Internal structure)

- *Massive bed:*
- Resistivity appears to be no variation.
- A bed can be homogeneous (i.e. without any resistivity variation due to textural change or sedimentary features).
- This corresponds to a constant condition of sedimentation without stratification either absence of ripples or bioturbation.

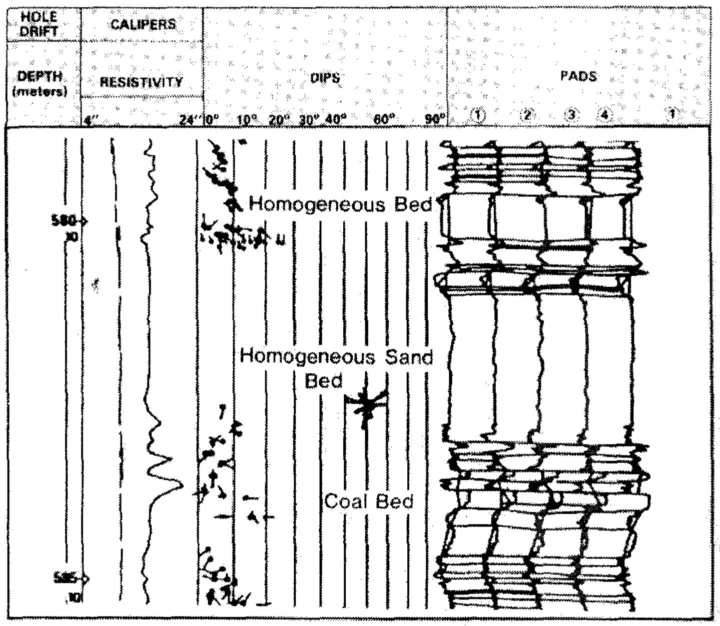


Fig. 2-19. Example of homogeneous beds.

- *Laminated bed:*
- Resistivity appears to be noisy
- A bed can be finely layered and therefore with stratifications either parallel, oblique/ cross bedded
- Since lamination is too thin to be detected by each electrode, the amplitude of deflection is weak, so the event is rarely correlates and the resistivity appears to be noisy.

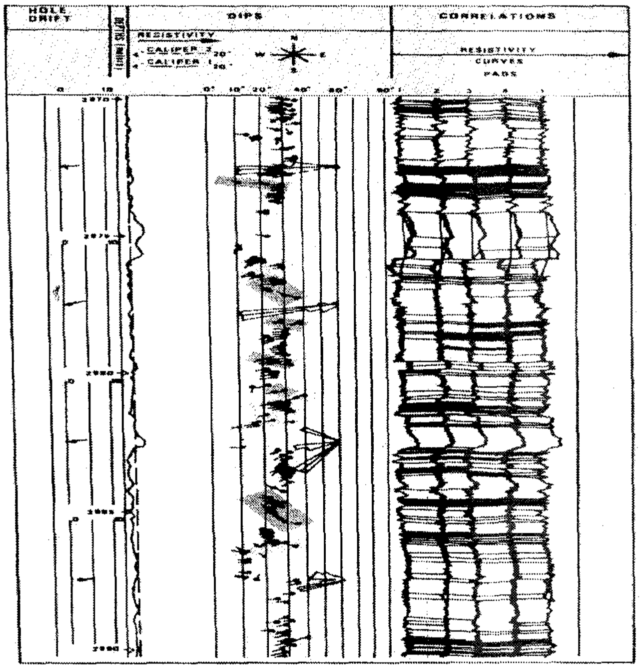


Fig. 2-21a. Example of GEODIP results in an aeolian sand.

- *Graded bed:*
- Abrupt contact in difference grain size will shows abrupt change in resistivity.
- There are two types of grain size profile fining up or coarsening up.
- Fining up is generally underlined by an abrupt contact at the base and the coarse sands on the base are less resistive than the silt or shale at the top.

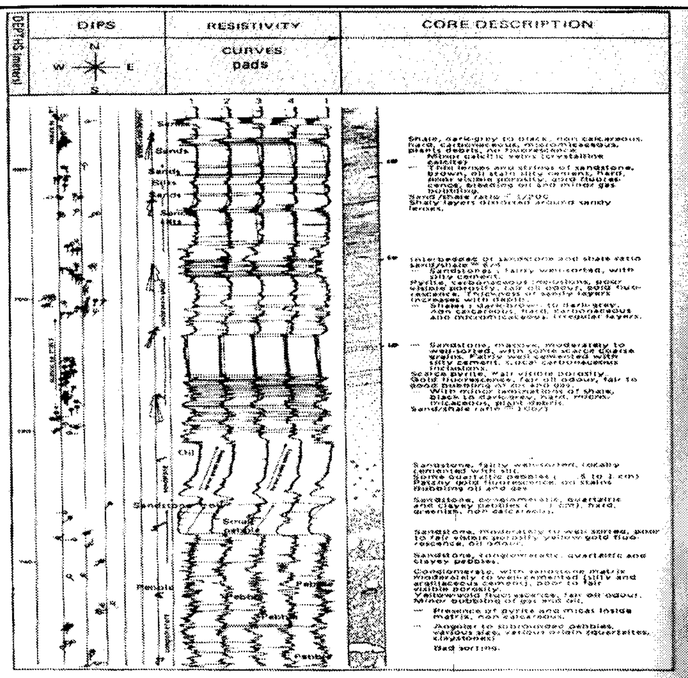


Fig. 2-26. Example of a general fining upward sequence starting with a grain-supported conglomerate.

- *Imbricated bed:*
- Close pebbles will show close peaks of resistivity where isolated pebbles will show isolated peak of resistivity.
- Each pebble may be larger than the electrodes so shape peak of resistivity varies with the proportions of the pebble and total absence of correlation between them.
- When the pebbles touch each other (grain support) the peaks are very close, where the pebbles are isolated (mud support) the peaks are isolated.

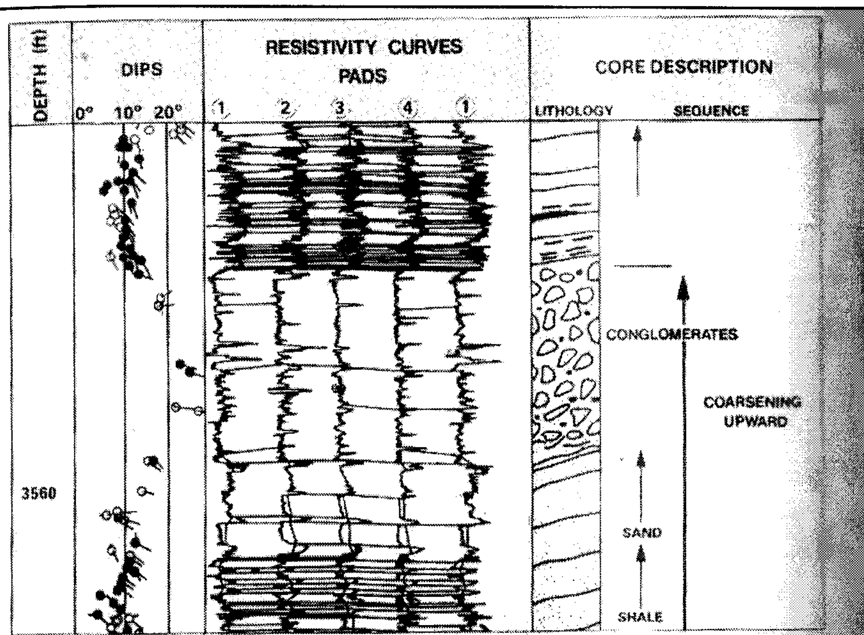


Fig. 2-27. Example of a mud-supported conglomerate.

- *Deformation of bed*
- Primary structures at the time of deposition caused by current velocity and gravity flow (load cast, convolute bed, slumping etc.).

Environment and sand structure

Environment	*Characteristic*	*Orientation*
Braid…confine	Dip large spread	One & large scatter
(Bar)	Trough	Slope & // current
Meandering…confine	Dip large spread	One & severe scatter
(Point bar)	Trough	Slope & ⊥ current
Eolian…open	Dip consistent	One & little scatter
(Dune)	Tabular (L angle at base)	No Slope & ⊥ current

Delta…confine	Dip moderate spread	One & moderate scatter
(Distr. channel)	Tabular (H angle at base)	$\perp$ coastline
Delta…open	Dip moderate spread	One & moderate scatter
(Distr. mouth bar)	Tabular (L angle at base)	// long-shore current
Beach & Bar…open	Dip -	One or 180*
(Distr. mouth bar)	Tabular (L angle at base)	Slope & // coastline
Estuarine…confine	Dip -	180* & scatter
Tidal channel	Tabular (H angle at base)	$\perp$ coastline
Shelf…open	Dip -	Poly or Random
	Tabular (L angle at base)	-
Turbidite…open	Dip -	One
	Tabular or absent	Slope & // current

- <u>Note</u> Orientation = One or 180* direction
- Confine area: high angle; Open area: low angle
- Low angle…10*…Moderated angle…20*…High angle

SEQUENCE STRATIGRAPHY

By
Assistant professor
Thara Lekuthai
1 January 2007

SEQUENCE STRATIGRAPHY

- Objective: To predict occurrence & distribution of petroleum system in sedimentary basin.
- Method: Difference Area, Difference Geology, and Difference Seismic (Acquisition, Process/ Display, Interpretation)
- There are four major variables that control the variations in strata patterns & lithofacies distributions within sedimentary rocks

•Tectonic (uplift/ subsidence = control space for sedimentation): Basin volume (sea floor spreading, basin fill)

•Eustasy (up/ down = control strata pattern & lithofacies distribution): Water volume (glacial, continental water, water expansion)

•Sedimentary supply (control water depth): Tectonic (LST = progradation; TST = retro-gradation; HST = aggradation)

•Climate (control type of sediments): Eustasy (Wet -> clastic; Dry -> evaporation/ carbonate)

▪Relative sea level change = Eustasy – Tectonic

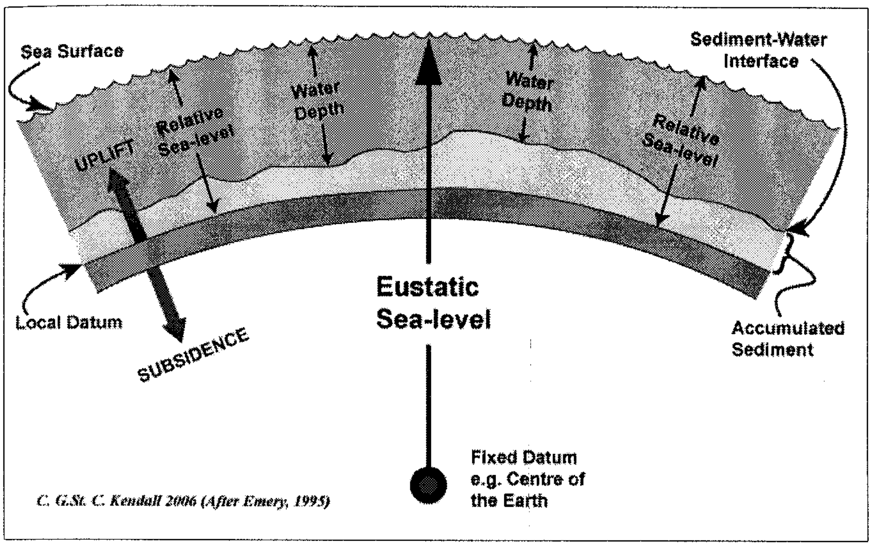
▪Relative sea level change is defined as an apparent rise/ fall of sea level with respect to the land surface (local datum).

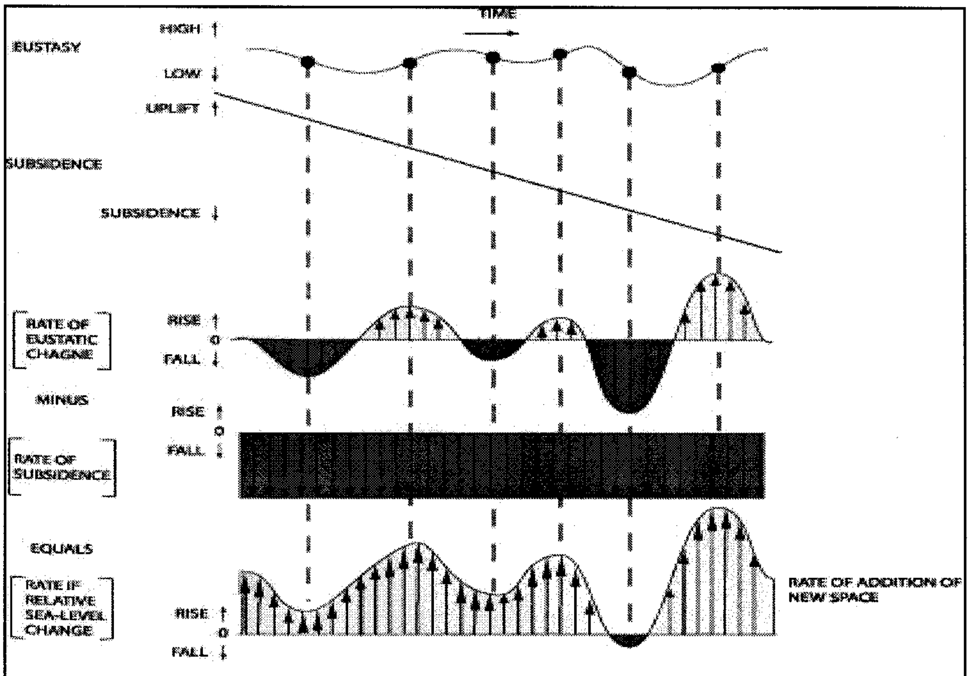
▪Sedimentary supply > Relative sea level rise = Marine regression

▪Sedimentary supply < Relative sea level rise = Marine transgression

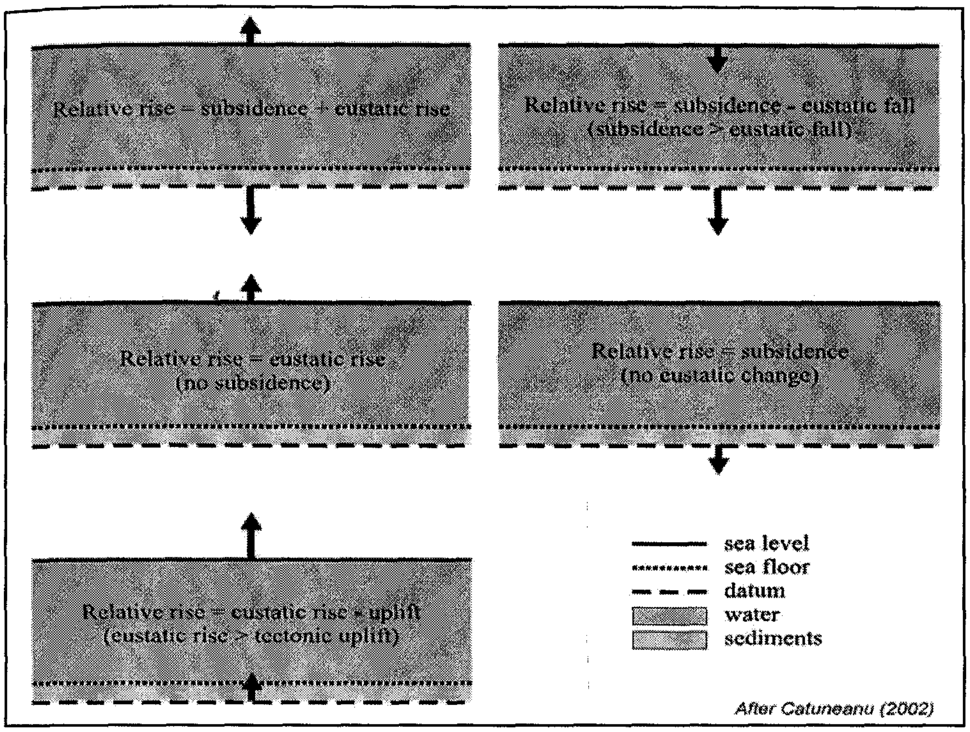
▪Sedimentary supply = Relative sea level rise = Marine stationary

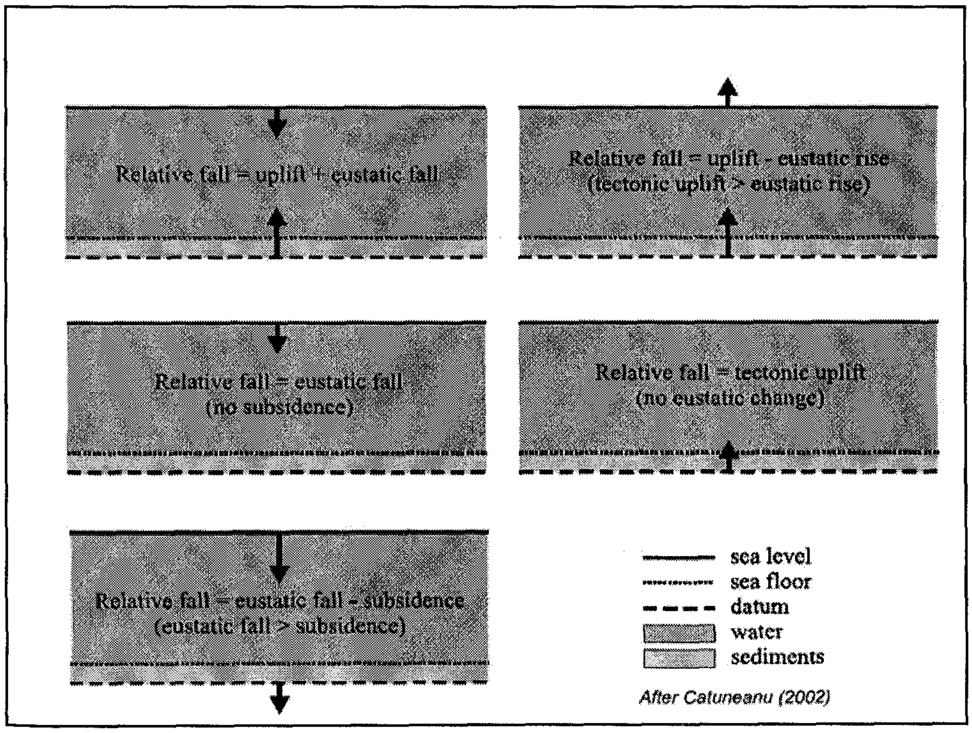
Global sea level, which refers only to the position of the sea surface with reference to a fixed datum





Relative Sea-level *(from Posamentier & Jervey & Vail, 1988)*


Relative rise = subsidence + eustatic rise
Relative rise = subsidence - eustatic fall
(subsidence > eustatic fall)
Relative rise = eustatic rise
(no subsidence)
Relative rise = subsidence
(no eustatic change)
Relative rise = eustatic rise - uplift
(eustatic rise > tectonic uplift)
sea level
sea floor
datum
water
sediments
After Catuneanu (2002)


Relative fall = uplift + eustatic fall
Relative fall = uplift - eustatic rise
(tectonic uplift > eustatic rise)
Relative fall = eustatic fall
(no subsidence)
Relative fall = tectonic uplift
(no eustatic change)
Relative fall = eustatic fall - subsidence
(eustatic fall > subsidence)
sea level
sea floor
datum
water
sediments
After Catuneanu (2002)

▪Eustasy and tectonic produces a relative sea level change and space for sedimentation.

▪Short term eustasy superimposed on longer term tectonic.

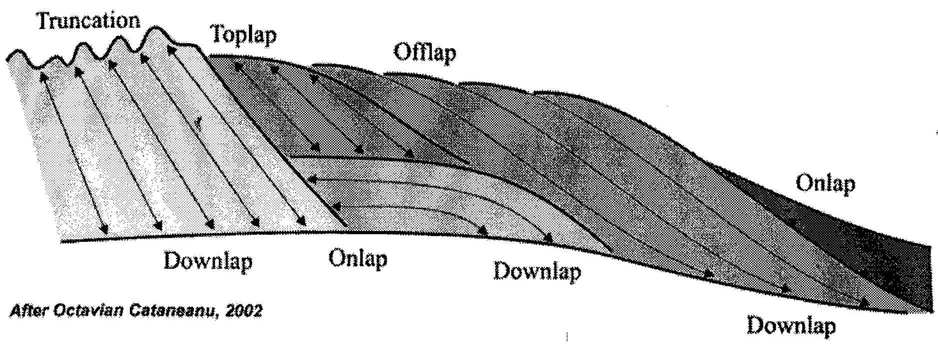
▪A unique relation between the rate of relative sea level change and deposition processes.

▪Relative sea level change curve is subdivided into a number of time intervals.

▪Systems tracts represent the rocks deposited within these time intervals.

▪A sequence is interpreted to be deposited during a cycle of the relative sea level change curve starting and ending in the vicinity of the inflection points on the falling limbs of the sea level curve.

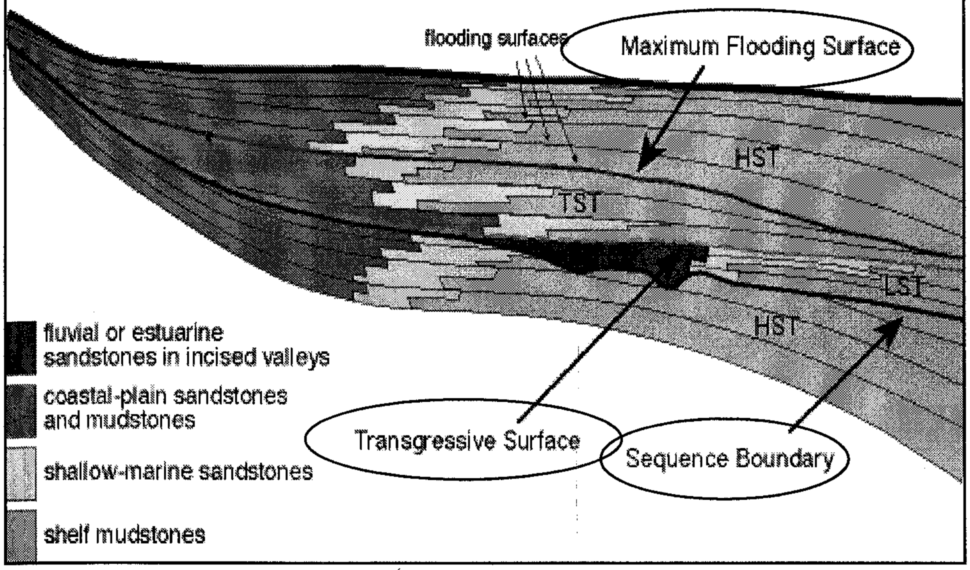
▪Sequence boundary (SB): The upper SB is characterized by top lap & erosional truncation while the lower SB is characterized by on lap & down lap.

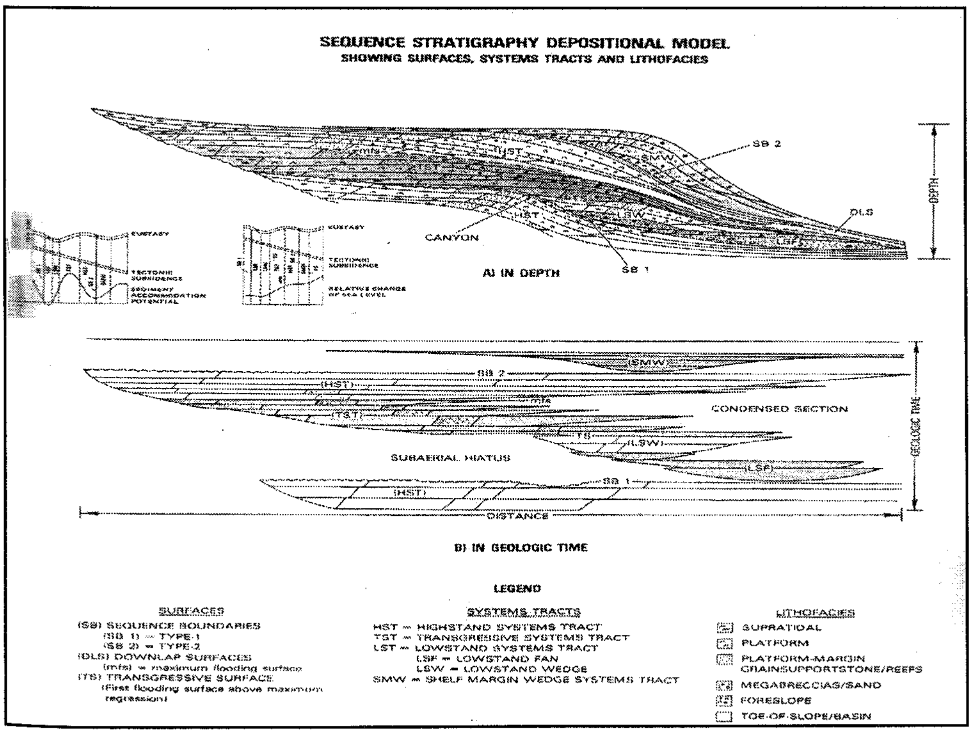


Systems tracts

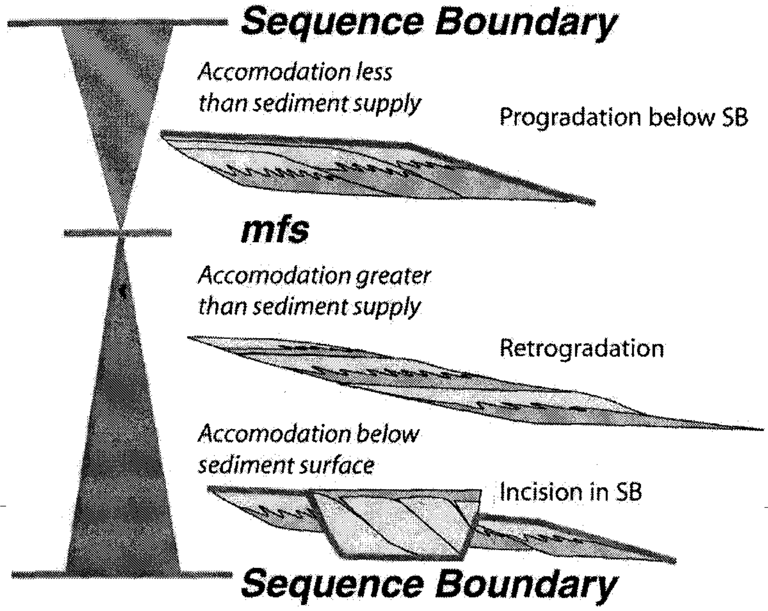
- There are four systems tracts:
  - Low-stand systems tracts (LST)
  - Transgressive systems tracts (TST)
  - High-stand systems tracts (HST)
  - Shelf margin wedge systems tracts (SMW)

SEQUENCE BOUNDARY

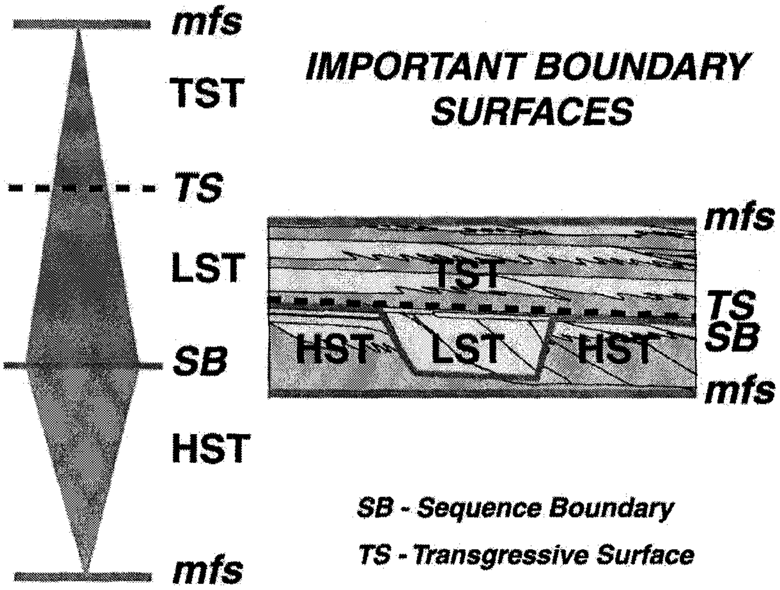


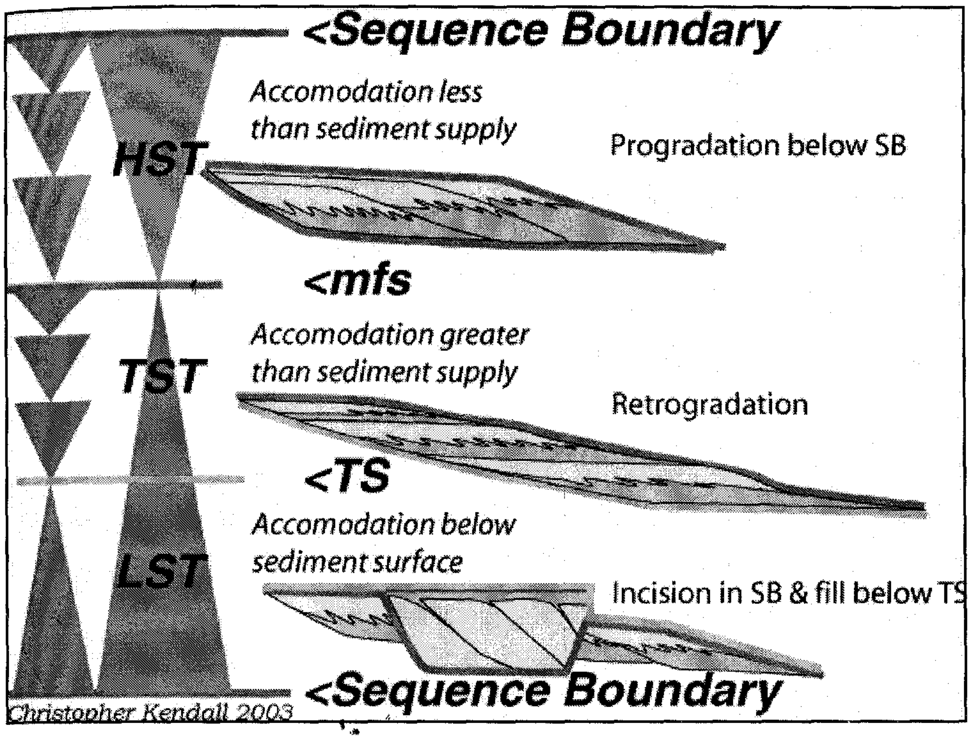


Clastic Sequence Stratigraphic Hierarchies



Clastic Sequence Stratigraphic Hierarchies





Low-stand systems tracts (LST)

- SB1: There are deposited basin-ward on the previous shelf edge & overlie SB1 (eustatic fall > subsidence = larger exposed)
- LST: Posamentier and Allen (1999) defined LST as <u>Lower LST</u> (LSF) = basin-floor fan, slope fan, and <u>Upper LST</u> (LSW) = often filling incised valleys that cut down into the HST.

•Basin-floor fan: Siliciclastic bypasses the shelf and slope through the valleys and canyons to feed the basin-floor fan. Hunt & Tucker (1992) show down-lap of basin-floor fan and express as the end of a base level fall.

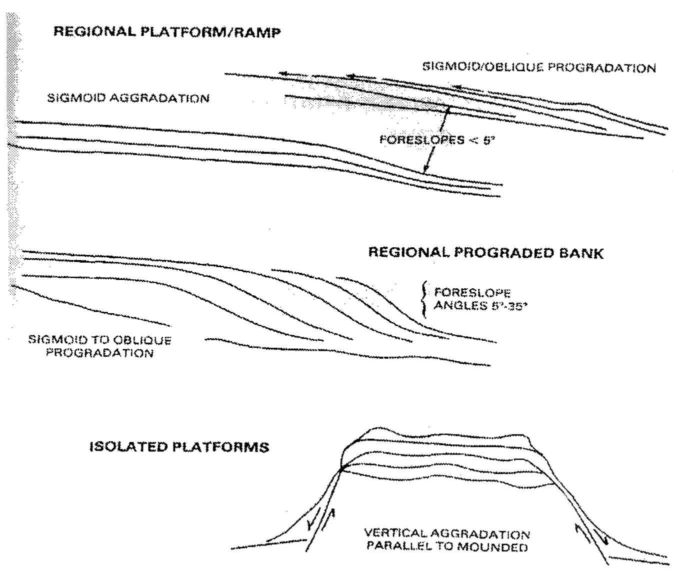
•Slope fan: They overlie the basin-floor fan and are down-lapped by the overlying LSW.

•Low-stand wedge: They are on-lap the shelf edge slope and down-lap on the slope fans.

▪Climate is cold, dry, intense physical weathering providing high sedimentary supply in deep sea.

▪Less organic productivity & less faunal diversity in shallow sea.

Three case of strata patterns:
Shelf edge case, Ramp case, and Growth fault case



▪Shelf edge case: (LSF, LSW)

- •Low-stand basin floor fans are compose of deep marine mounds made up of massive sands/carbonate debris deposited as lobes/channels.
- •Low-stand slope fans are made up of mass flows and turbidite channel/over-bank deposits
- •Low-stand wedges are shallowing upward low-stand deltas/terraces that prograde basin-ward and pinch out land-ward.
- •Incised valley fills are made up of sediments that fill previously cut valleys.

▪Ramp case:

- •Lower low-stand wedges are interval that pinches out basin-ward and is the most basin restricted unit.
- •Upper low-stand wedges are on lap the lower wedge and pinches out in the vicinity of the shoreline break above the lower wedge.
- •Low-stand incised valley fills

▪Growth fault case:

- •Low-stand sediments are thick section of inerbedded sands and marine shales deposited on the downside of the growth fault
- •Low-stand incised valley fills

Transgressive systems tracts (TST)

▪Upper TST: There are on-lap at the base and thicken up-ward.

▪Lower TST: Due to sediment starvation, there are thinning up-ward.

▪Transgressive surface (TS): The lower boundary of first flooding surface above the LSW and often characterized by consolidated muds of firm-grounds/ carbonate cementation of hard-grounds.

▪Organic shale usually occur close to the base of transgressive sequence.

▪In high sediment supply, TS will mark aggradation and on-lap that thicken land-ward.

▪In low sediment supply, TS will merge land-ward with the maximum flooding surface (mfs).

High-stand systems tracts (HST)

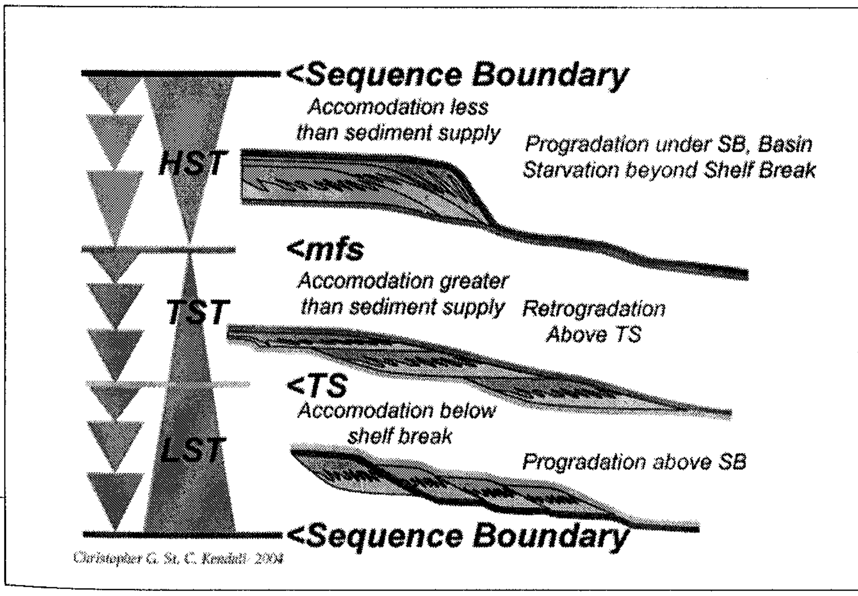
- There are made up of three parts:
  - Early high-stand is characterized by up-ward & out-ward building sigmoid progradation. (Catch up/ slow rate of accumulation)
  - Late high-stand progradation is characterized by out-ward building oblique progradation. (Keep up/ rapid rate of accumulation)
  - Late high-stand sub-aerial is characterized by sediments deposited above the sea level. (Rapid progradation may causes top-lap unconformity)

- Climatic condition is warm, wet, intense chemical weathering providing low sedimentary supply in deep sea.
- High organic productivity & high faunal diversity in shallow sea.
- Upper HST is on-laps on the SB and Lower HST is down-laps on the mfs (maximum flooding surface).

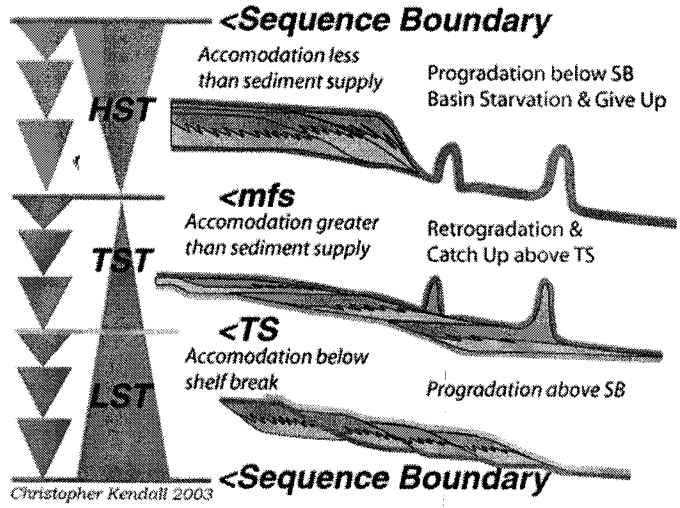
Shelf margin wedge systems tracts (SMW)

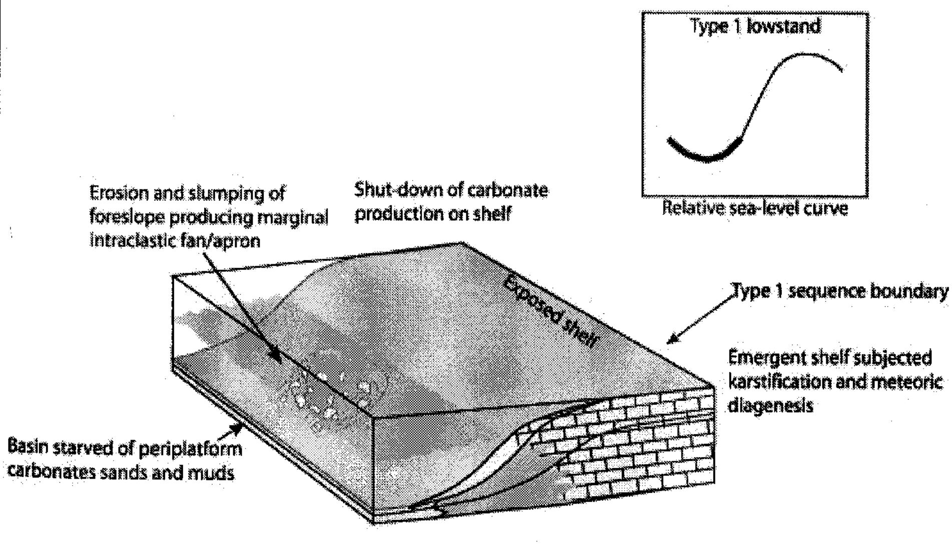
- It is characterized by progradation & aggrading wedge.
- Its lower boundary is a conformable sequence boundary, and its upper boundary is TS.
- It is overlies Type II sequence boundary (SB2): eustatic fall < subsidence = smaller exposed

Lst Sequence Stratigraphic Hierarchies



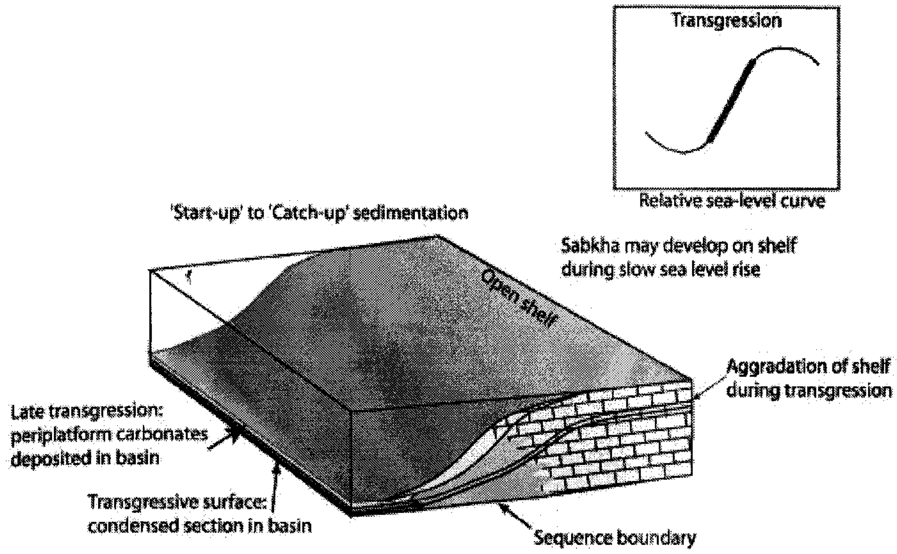
Lst Sequence Stratigraphic Hierarchies





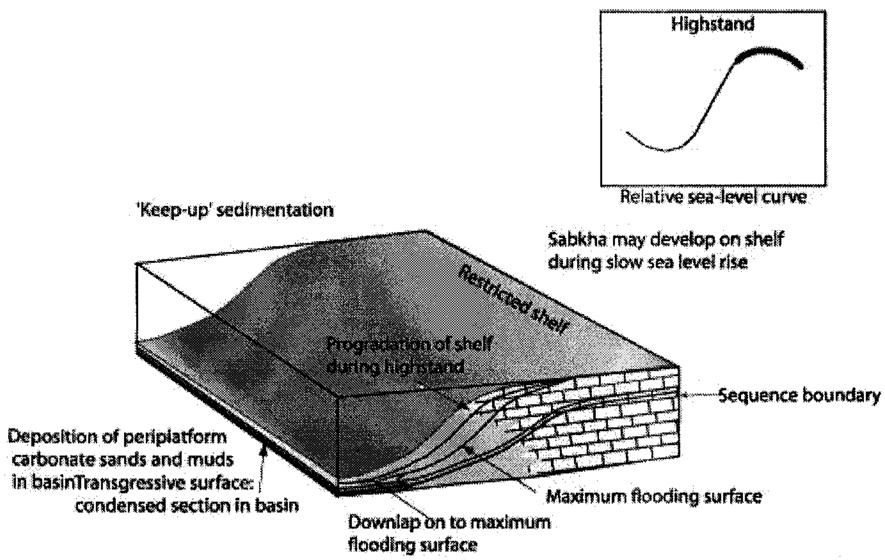
Type 1 Lowstand (carbonates)

(after: Doyle et al., 1998, Unlocking the carbonate depositional model)



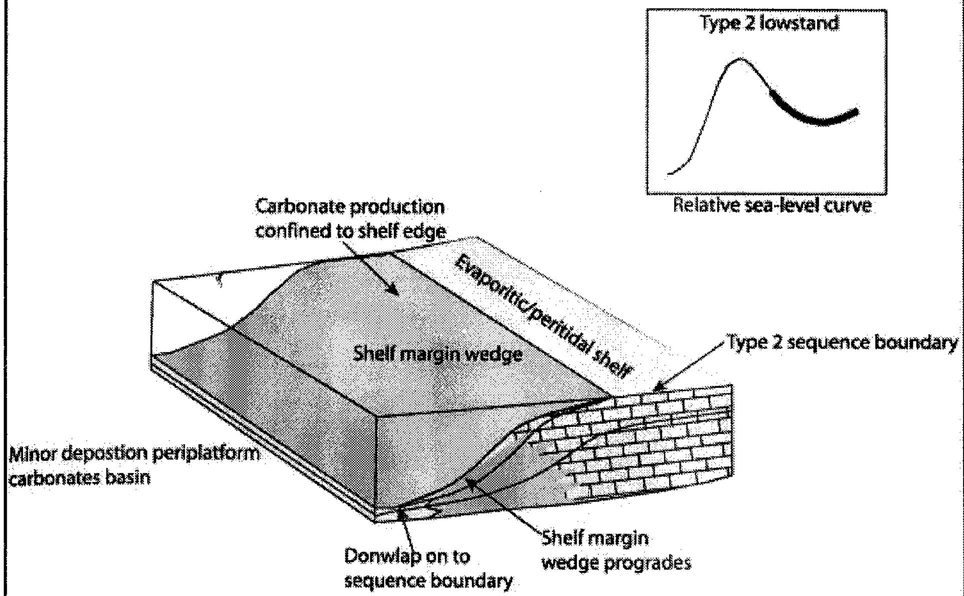
Transgressive Systems Tract (carbonates)

(after: Doyle et al., 1998, Unlocking the carbonate depositional model)



Highstand Systems Tract (carbonates)

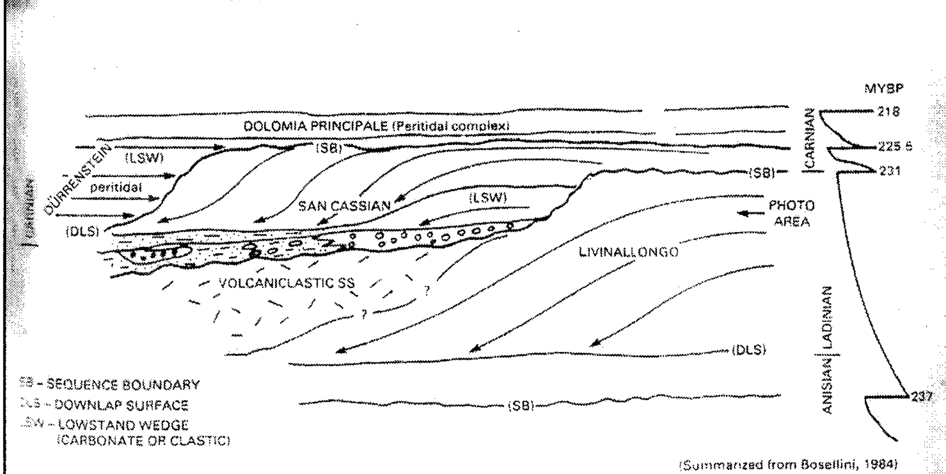
(after: Doyle et al., 1998, Unlocking the carbonate depositional model)



Type 2 Lowstand (carbonates)

(after: Doyle et al., 1998, Unlocking the carbonate depositional model)

TRIASSIC OF THE DOLOMITE MOUNTAINS ITALY



SEISMIC STRATIGRAPHY INTERPRETATION PROCEDURE

- **Seismic sequence analysis**
  - It defines the genetic reflection packages referred to as seismic sequences and seismic systems tracts by identifying discontinuities.
  - On-lap, down-lap termination pattern occur above the discontinuities.
  - Top-lap occur termination pattern below the discontinuities.

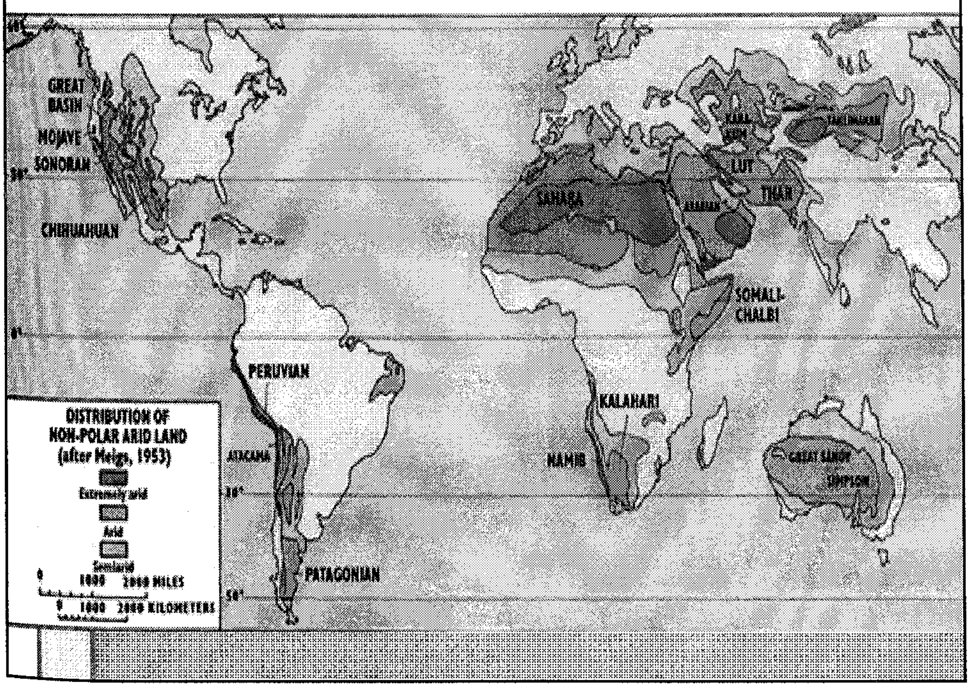
- **Well log sequence analysis**
  - Interpretation lithofacies on wire-line logs using cores and cuttings to calibrated the log.
  - Following this, we estimate sequences and systems tracts from the interpretation lithofacies.
  - We cross check the estimate sequences and systems tracts with biostratigraphy time correlation and global cycle correlation.
- **Systhetic, well to seismic ties**
  - Tie the well-log depth to seismic time by synthetic seismogram.

- **Seismic facies analysis**
  - Its purpose is to determine all variation of seismic parameters within seismic sequences and systems tracts in order to determine lithofacies and fluid type changes.
  - The seismic parameters are amplitude, frequency, continuity and interval velocity.
- **Depositional environment and lithofacies**
  - Its purpose is to determine seismic facies parameters with the regional geology.
- **Seismic modeling**
  - Its purpose is to determine statigraphy and fluid composition, geologic cross section, and reflection pattern.
- **Final interpretation**

AEOLIAN ENVIROMENT

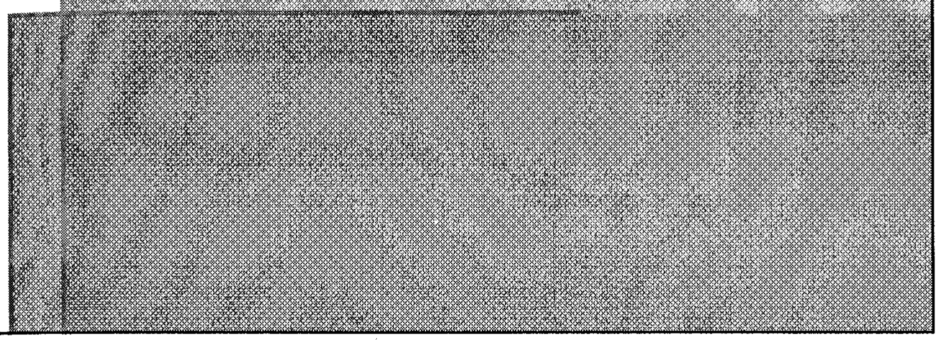
Definition

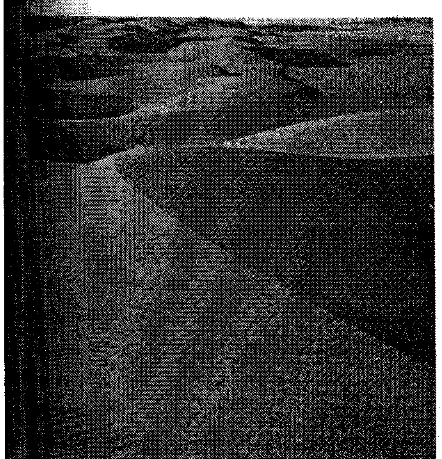
- A continental environment characterized by deposits resulting from wind action, often mixed with fluvial or sabkha facies.
- Three sub-environments (Ahlbrandt et. al. 1982)
- Dune: giant sand sea/ ergs
- Inter-dune: sabkhas/ playa lake/ ephemeral river
- Sand sheet: stony wastelands/ deflated surface



▪Equilibrium: Aeolian is in a state of deposition equilibrium between sedimentation and erosion.

▪When wind blows: Dust (silt & clay) is carried higher up into the atmosphere and settled in playa lake while Sand is transported by saltation process and settled asymmetric ripples/ dunes whose overall geometry is much like that transported by water.





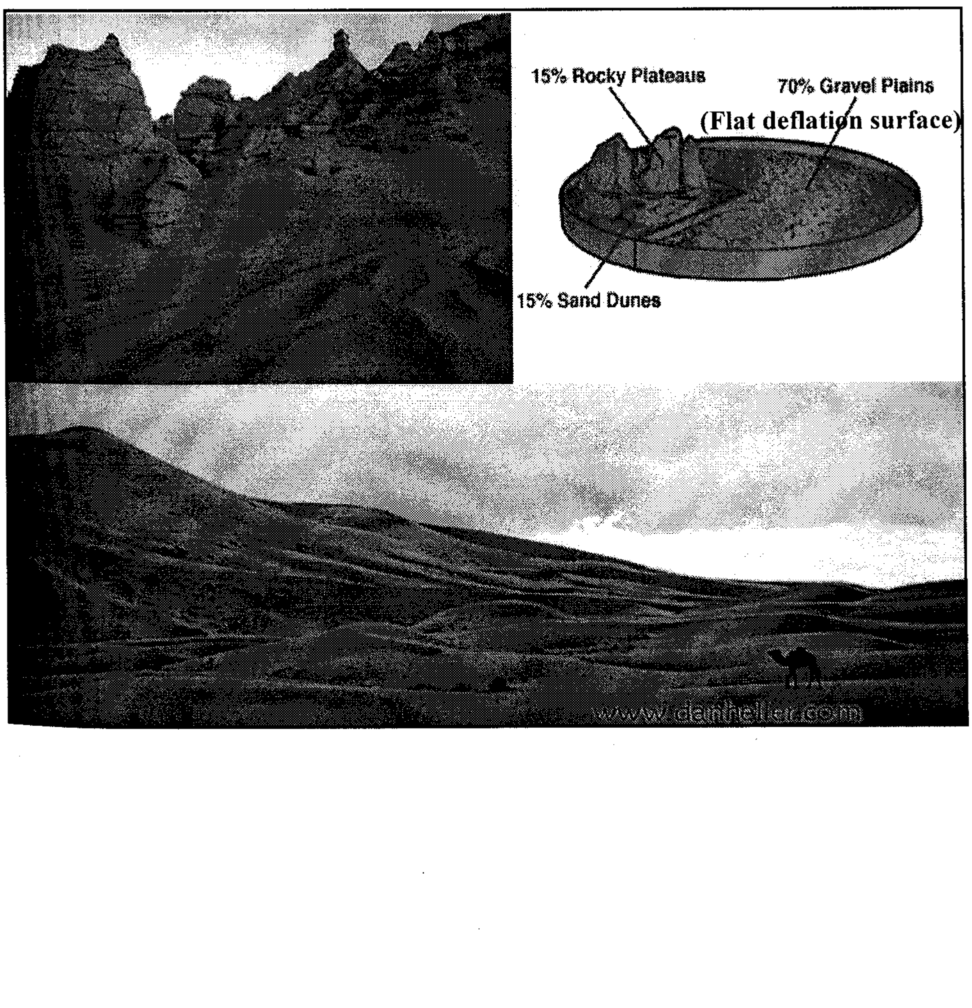
(A) Modern sand dunes in the Sahara Desert, Africa. *(E. McKee)*

(B) Ancient dune deposits in Zion National Park, Utah.

Figure 5.12 The eolian (wind) environment. Wind is a very effective sorting agent. Silt and dust are lifted high in the air and may be transported thousands of kilometers before being deposited. Sand is winnowed out and transported close to the surface and eventually accumulates in dunes. Gravel cannot be moved effectively by wind. A major process in an eolian sedimentary environment is the migration of sand dunes. Sand is blown up and over the dunes and accumulates on the steep dune faces. Large-scale cross-strata that dip in a downwind direction are thus formed. Ancient dune deposits are characterized by large-scale cross-strata consisting of well-sorted, well-rounded sand grains. The most significant ancient wind deposits are sandstones that accumulated in large dune fields comparable to the present Sahara and Arabian deserts and the great deserts of Australia. These sandstones are vast deposits of clean sand that preserve, to an unusual degree, the large-scale cross-bedding developed by migrating dunes.

Lithology

- Dune:
- Clean & excellent sorting quartz sandstone
- Inter-dune:
- Clay, silt, evaporite (playa lake)
- Sand, gravel (flat deflation surface)
- Layers of heavy mineral: may present
- Pure carbonate sand: much more rare
- Traces of oxidized: (iron/ spores/ heavy minerals) between sand grain can be significantly diagnostic.



Composition

- Sand Typical sand dunes are made up of proto-quartzite to quartzite sands (quartz grain > 85%) and considered to be mature sediment.
- Clays, modules of gypsum or anhydrite are minor components, occurring in inter-dune (wadi, sabkha), inland sabkha and playa lake.
- Cement may be calcite or dolomite due to often rise of water table (phreatic level).

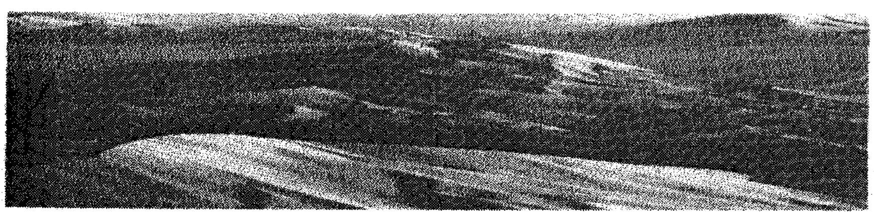


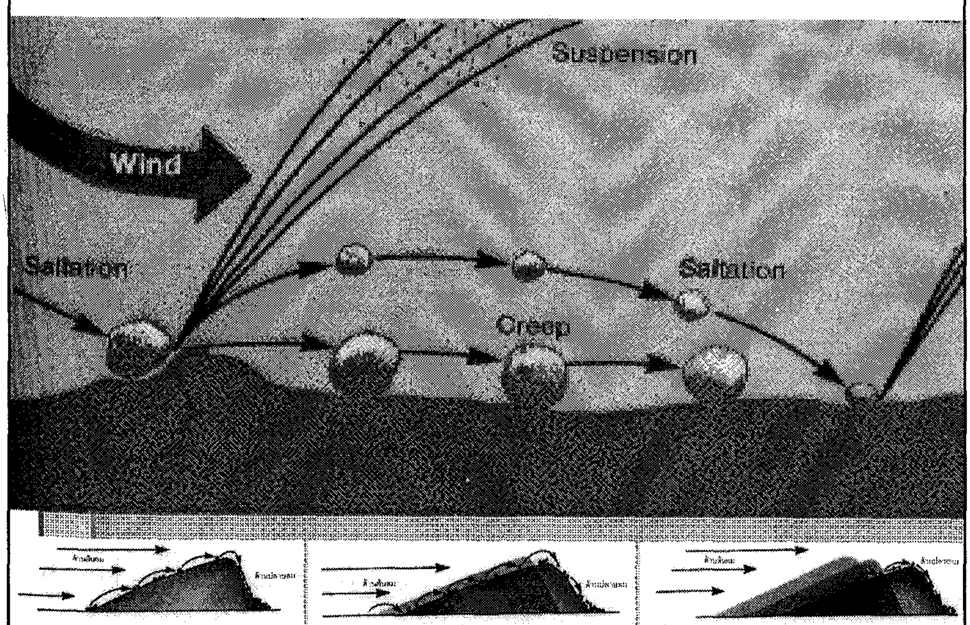
Fig. 5.3-1. Aerial photograph of a sand dune in the Saudi Arabian desert (from ARAMCO).

Fig. 5.3-2. Vertical cross-section in aeolian deposits in northwest Europe, southcentral part of Rotliegendes basin (from Glennie, 1970).

- Texture
- Size fine to medium sand (0.2-0.5 mm)
- Shape well round (result of repeated reworking)
- Sorted excellent (wind is an excellent sifting)

Ahlbrandt (1979)	*Size*	*Sorted*
Dune (Inland)	Med	Good-Excellent
Dune (Coastal)	Fine	Excellent
Inter-dune	-	Poor-Mod

- Absence of clays and micas due to aeolian winnowing gives a high grain/matrix ratio.
- Flat deflation surfaces (serris) may have characteristic lag deposits.



Structure

- Surface exposure features (inter-dune):
- Rain drops, mud crack, rootlets, tracks and trails
- Giant cross-bedding (dune):
- Both trough & tabular are often thicker (5-30 m.), steeper (20* to 35*) and more concave upward, than in aqueous sands.
- They are commonly low angle toe-set & concave upward to be high angle top-set.
- Separated boundaries: The cross-sets frequently truncate the upper laminae, producing the thinning-upward pattern of sets.
- Contorted bedding and rare ripple laminae

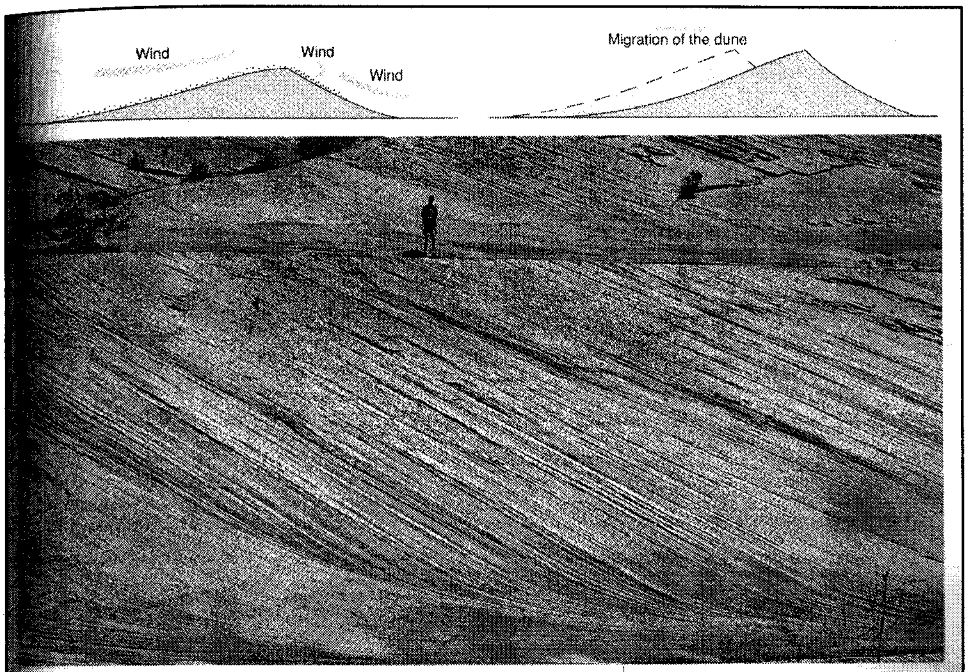
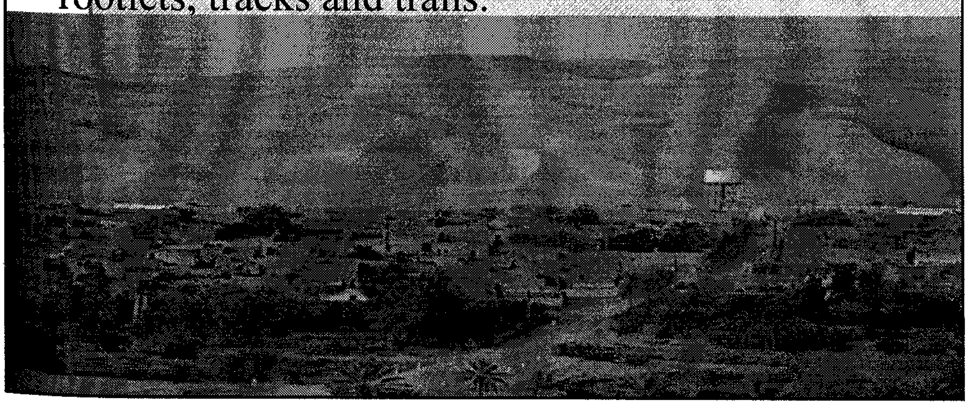


Figure 5.5 Cross-bedding is formed by the migration of sand waves (ripple marks or dunes). Particles of sediment, carried by currents, travel up and over the sand wave and are deposited on the steep downcurrent face to form inclined layers.

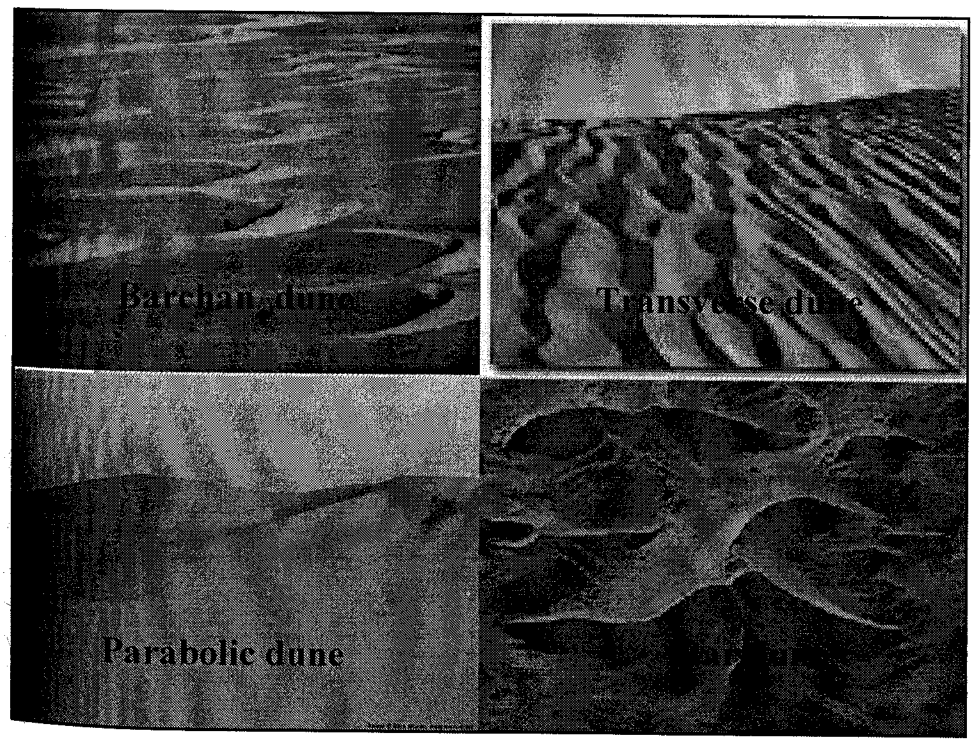
Paleontology

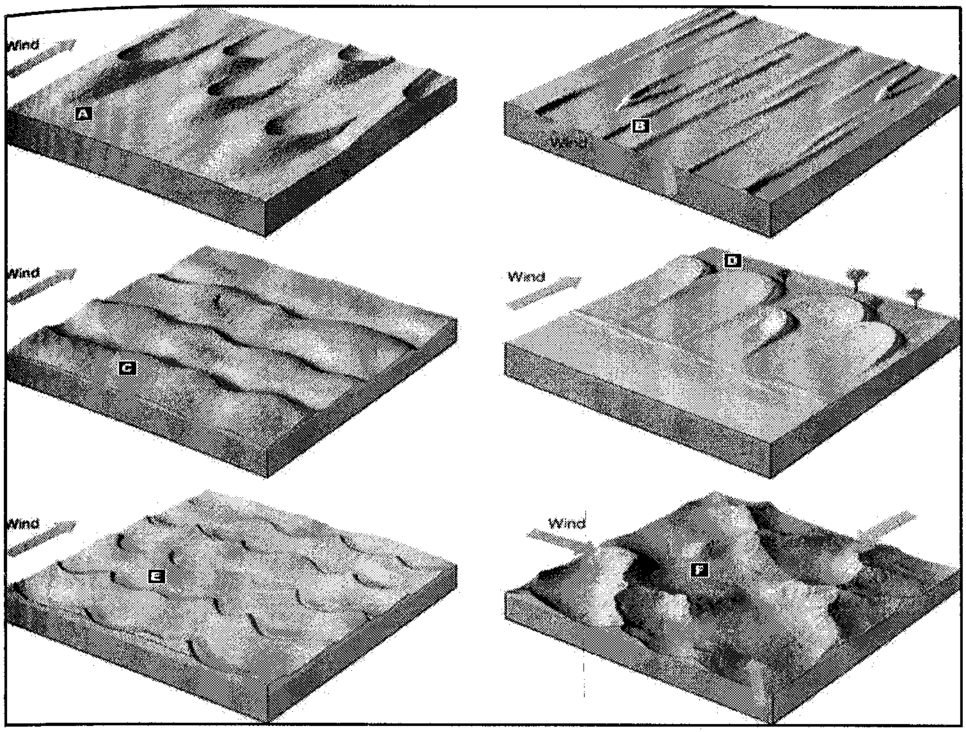
- Barren fossil: Rare vertebrate remains, non-marine mollusks, crustaceans and arthropods
- Red color: Oxidized spores, pollen
- Wet inter-dune areas: Rain drops, mud crack, rootlets, tracks and trails.



Geometry

- Sheet-like: The original dune morphology of a sand sea is generally reworked and planed out by transgressing waters. Basically, the final shape is a blanket.
- Dune types: Seif, Barchan, Parabolic, Transverse and Beach ridge (dip pattern and shape of azimuth frequency plot can characterize each dune types)





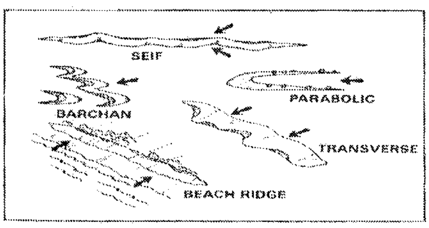


Fig. 5.3-5. Major dune types, showing orientation with respect to dominant wind direction (arrows) (from Spearing, 1971).

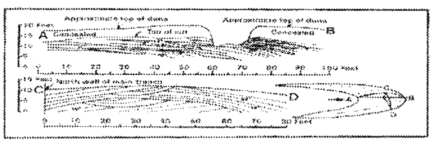


Fig. 5.3-6. Internal stratification of parabolic dune, White Sands, New Mexico (McKee, 1966).

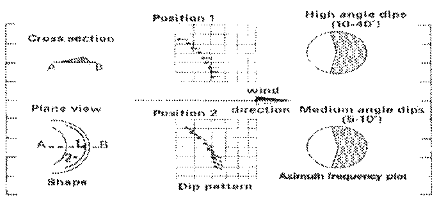


Fig. 5.3-7. Shape, dip pattern and azimuth frequence plot of a parabolic dune.

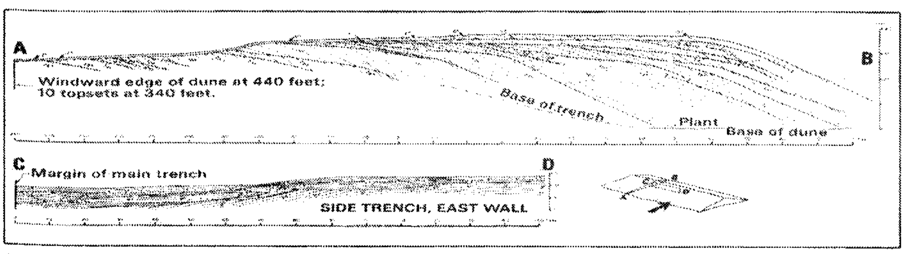


Fig. 5.3-8. Internal stratification of transverse dune, White Sands, New Mexico (McKee, 1966).

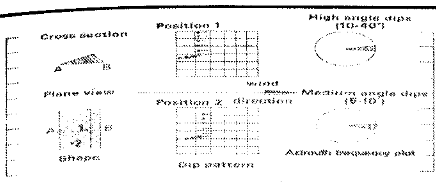


Fig. 5.3-9. Shape, dip pattern and azimuth frequence plot of a transverse dune.

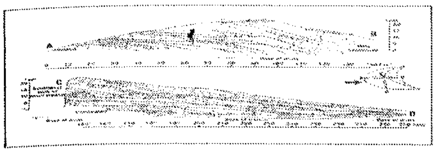


Fig. 5.3-10. Internal stratification of barchan dune, White Sands, New Mexico (McKee, 1966).

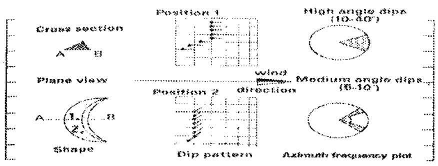


Fig. 5.3-11. Shape, dip pattern and azimuth frequence plot of a barchan dune.

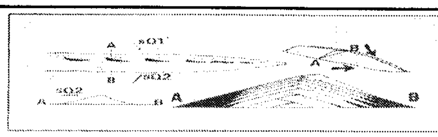


Fig. 5.3-12. Internal stratification of seif dune, North Africa (Bagnold, 1941)

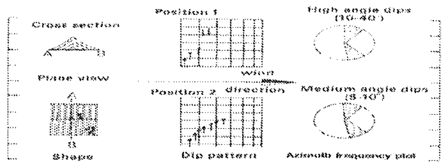


Fig. 5.3-13. Shape, dip pattern and azimuth frequence plot of a seif dune.

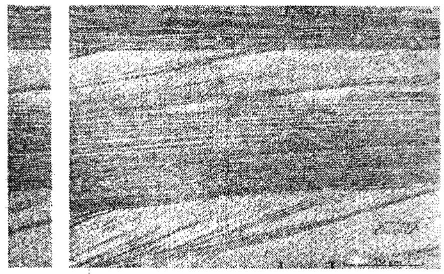
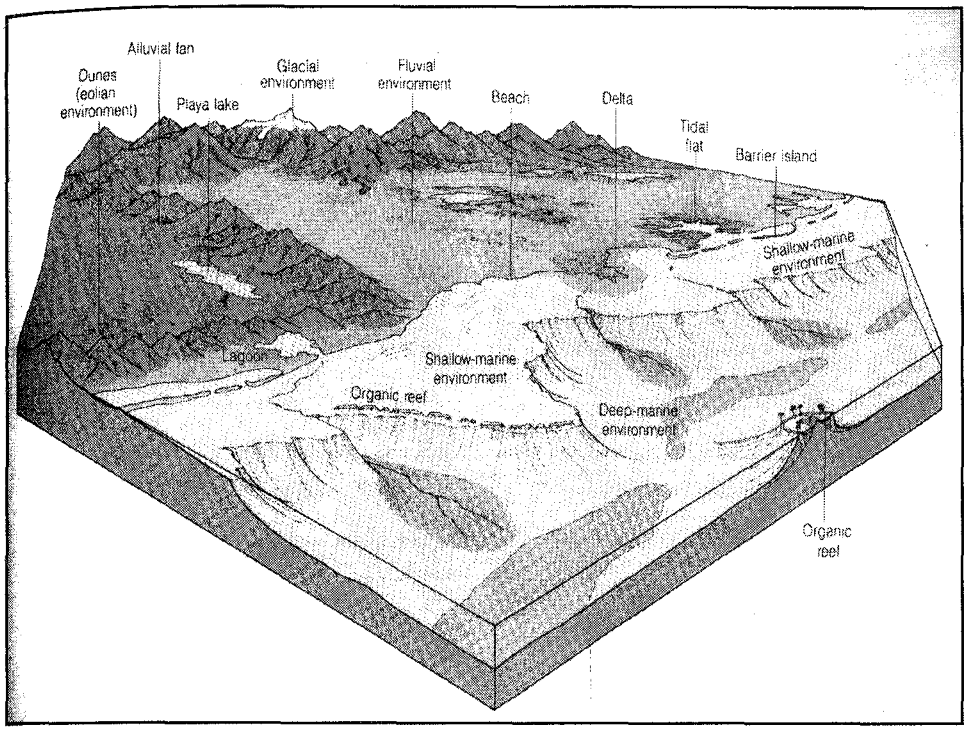


Fig. 5.3-14. Lacquer peel and "core" from a seif dune. Dubai, Trucial Coast (from Glennie, 1970)

Associated facies

- Dune areas: do not involved the deposition introduced by water so adjacent environments are thickly evaporite whether coastal dune (wadi-sabkha) or inland dune (playa lake).
- Dune (Inland): alluvial fans, braided streams, playa lake, inter-dune sabkha
- Dune (Coastal): barrier island, lagoon, wadi-sabkha
- Unconformity: They are frequently occur immediately above a major unconformity or associated with several minor unconformities.



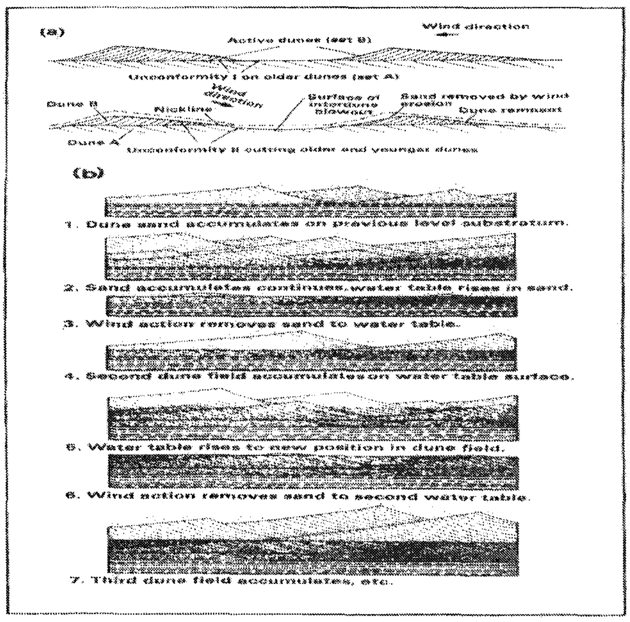


Fig. 5.3-4. (a) Development of scoop-like erosion surfaces and nicklines within aeolian dune sands by the development of a interdune blowout (from Walker & Harms, 1972). (b) Schemes showing horizontal truncation surfaces and the role of phreatic level (from Stokes, 1968).

- Sequences: dune is a fining and thinning upward units but may be interrupted by wadi fluvial system.
  - Dunes: along rivers (inland dune) and along coastline (coastal dune).
  - Inter-dune (sabkha) is characterized by inter-bed with dolomite or anhydrite shale.
  - Wadi (flash flood) is characterized by coarser, poorly sorted sediments richer in clay material and consequently a little more radioactive.

Core

- Almost clean, well sorted quartz sandstone
- Often rework from older deposits
- Thick sets of monotonous cross-bedding
- Traces of oxidized impurities between sand grains

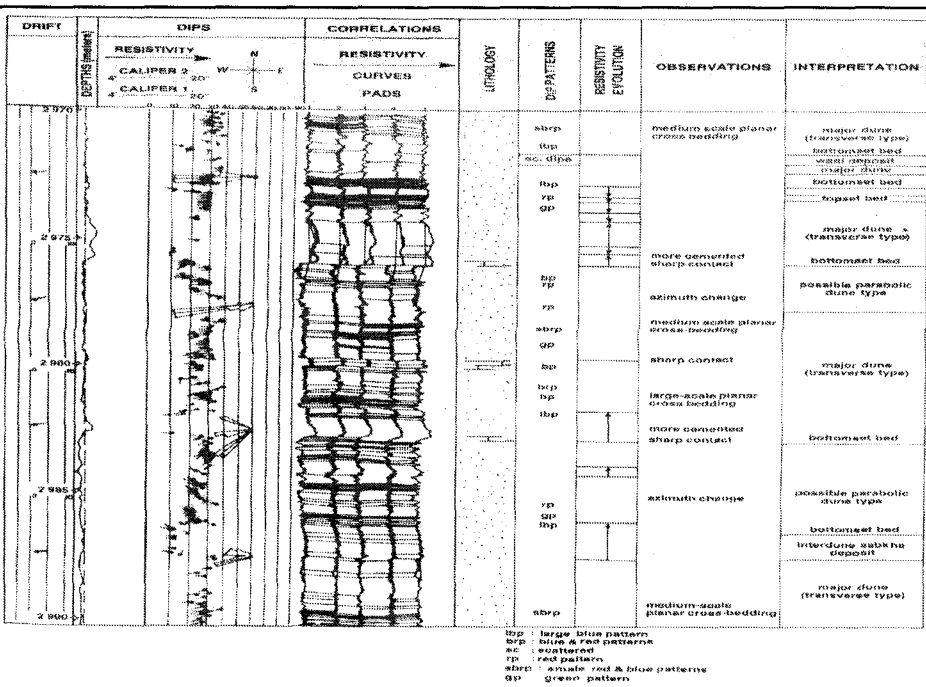


Fig. 5.3-20. Example of GEODIP results and its interpretation indicating an aeolian environment.

Wire-line logs

- GR: Saw toothed blocky shape, it is caused by mica at the base with low dip angle of new dune that abruptly truncate the fore-sets.
- Pb vs. ∅n points of dunes fall close to sandstone line indicating quartz as the main component.
- High radioactive clay, dolomite, gypsum, anhydrite are common in inter-dune (wadi, sabkha) or bottom set.

- Dipmeter:
- Each dune begins at the base with low angle dips (toe-set beds), which then increase upwards (blue dip) until reaching a maximum of about 25*-35* (fore-set beds).
- This maximum is easy to see in dipmeter and indicates both the large size and constant (green dip) direction of the cross bedding (down wind direction).
- Green Dip (inter-dune clays), Blue Dip (low angle toe-set increase up to 25*-35* fore-set), Random Dip (wadi)

▪GR: Saw toothed blocky shape, it is caused by mica at the base with low dip angle of new dune that abruptly truncate the fore-sets.

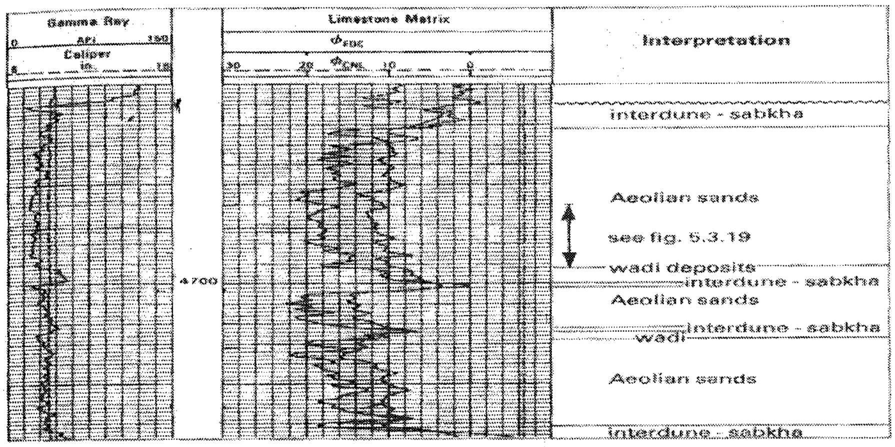


Fig. 5.3-16. FDC-CNL-GR logs show typical responses in dune sands.

▪Pb vs. ∅n points of dunes fall close to sandstone line indicating quartz as the main component.

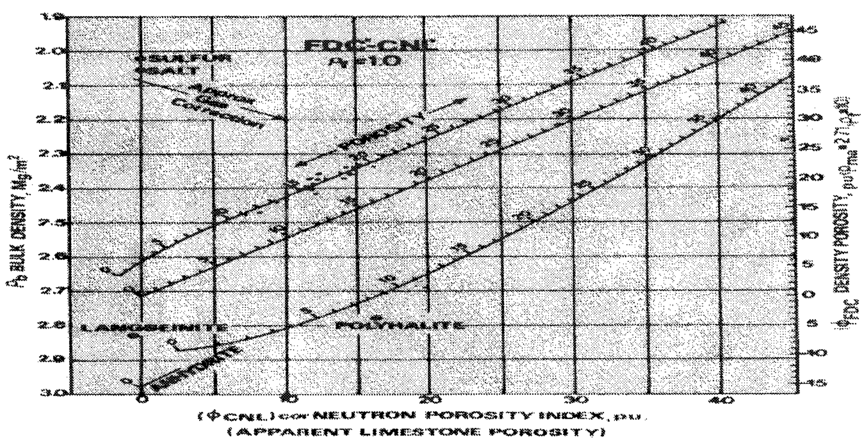


Fig. 5.3-17. Density-neutron porosity cross-plot showing the lithology (quartz sandstone) of the aeolian sands represented by Fig. 5.3-16.

▪High radioactive clay, dolomite, gypsum, anhydrite are common in inter-dune (wadi, sabkha) or bottom set.

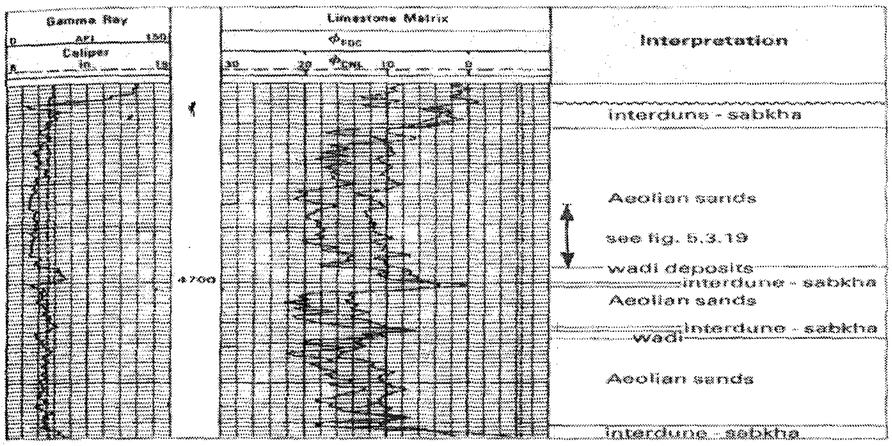


Fig. 5.3-16. FDC-CNL-GR logs show typical responses in dune sands.

▪Dipmeter: Green Dip (inter-dune clays), Blue Dip (low angle toe-set increase up to 25*-35* fore-set), Random Dip (wadi)

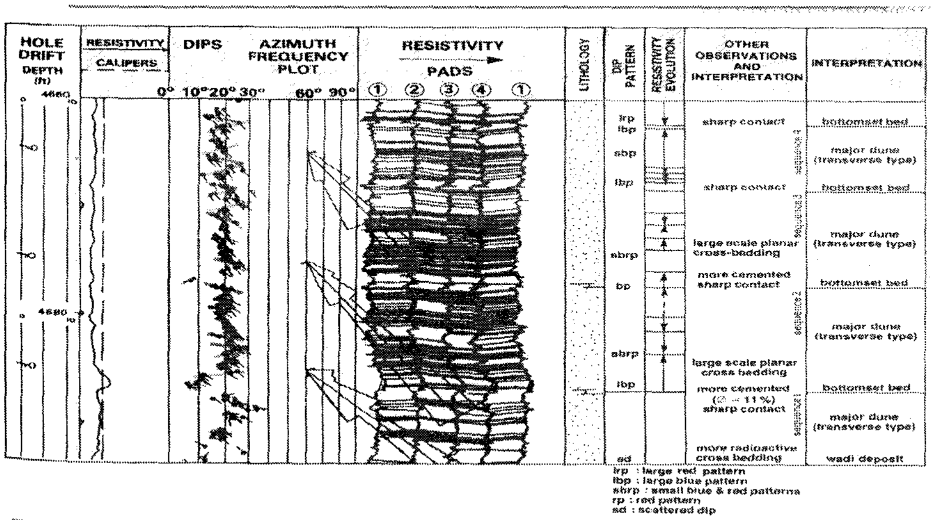


Fig. 5.3-19. GEODIP results over 35 feet of the aeolian sands shown on Fig. 5.3-16, and its interpretation.

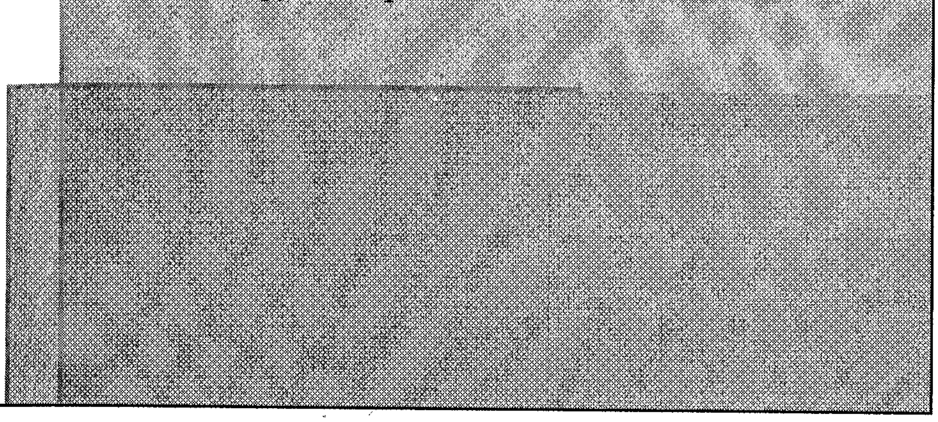
Petroleum aspect

- Heterogeneous reservoir:
- Dune are heterogeneous complex reservoirs with vertical and lateral variation in fluid conductivity.
- One reason for this is the differential texture that exists along individual cross-beds, which influences differential fluid flow.
- Specifically, grain orientation normally takes place along each cross-bed, with micas and more lenticular sand grains aligned in toe-set plane.

- Toe-set plane introduce significant permeability heterogeneity. Moreover, cementation is also influenced these heterogeneity and, result in differential porosity/ permeability preservation.
- As the result, fluids may be best able to migrated along, rather than across cross-bed layers.
- Trap:
- structural, stratigraphic and combination

Seismic

- Sheet-like: In general, subsurface dunes are sheet-like geometry, associate with unconformities and lack of good internal reflectors.
- Deposition limit: Seismic are most useful in delineating the depositional limits, rather than the actual lithology of a potential dune reservoir.



ALLUVIAL FAN ENVIRONMENT

Definition

- Outlet of upland valley:
- A continental environment characterized by coarse sediments, shaped like an open fan/cone, deposited by an emerging mountain stream at the outlet of a narrow upland valley upon an alluvial plain. (fig.1-2)
- Where the outlet has taken place along margins of marine, called fan delta.
- Where the outlet is in arid/semi arid regions, formed by debris, commonly as a result of extensive sheet flood, called Bajada (Spanish, drop)

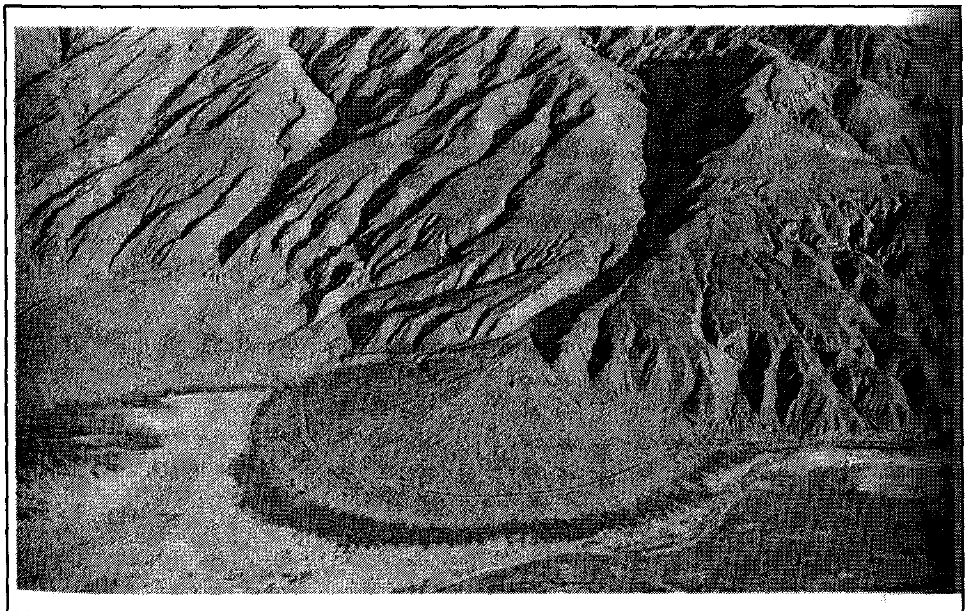


Figure 12.32 Alluvial fans form in arid regions where a stream enters a dry basin and deposits its load of sediment. This fan is in Death Valley, California.

- Syntectonic:
- They are often referred as syntectonic deposits, being generated by rapid uplifting.
- Rapid erosion supplies coarse detritus and deposits of debris flow, sheet-floods, stream channels and sieve deposits.
- Fanglomerate is the rock term for the most diagnostic of coarsest grains in proximal fan.
- They are juxtaposed with older, highly deformed basement.
- Old alluvial fans: are preserved in Late Paleozoic – Early Mesozoic and Late Mesozoic – Mid Tertiary age. These represent times of significant tectonic activity throughout the world.

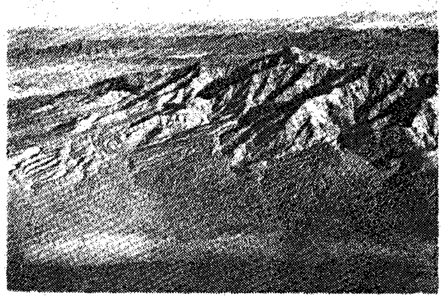


Fig. 5.2-1. Alluvial fans in the Mohave desert, California. Each cone-shaped fan has been deposited where the slope changes abruptly at the base of the mountains (photo by J.R.Balsley, U.S. Geological Survey; in Press & Siever, 1978).

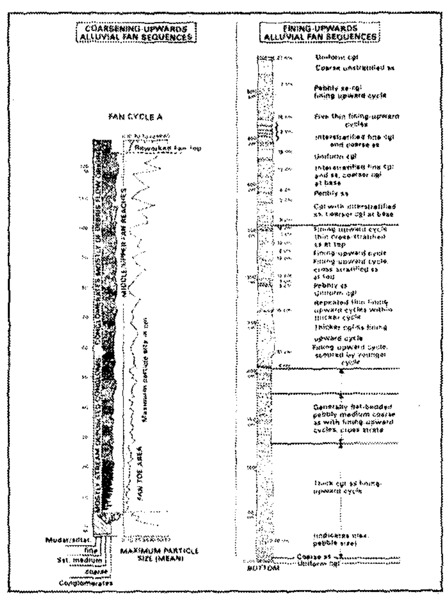


Fig. 5.2-2. Examples of coarsening upward (Devonian alluvial fan cycle in the Hornelen Basin, Norway from Steel et al., 1977), and fining upward (Devonian, western Norway, from Nilsen, 1969), showing cyclic deposition.

Lithology

- Fanglomerate (some very large fragments)
- Channel sand, conglomerate
- Thin shale layers (mud flows may occasionally spread clay over parts of the fan)
- Rapid vertical and lateral changes
- Common red beds

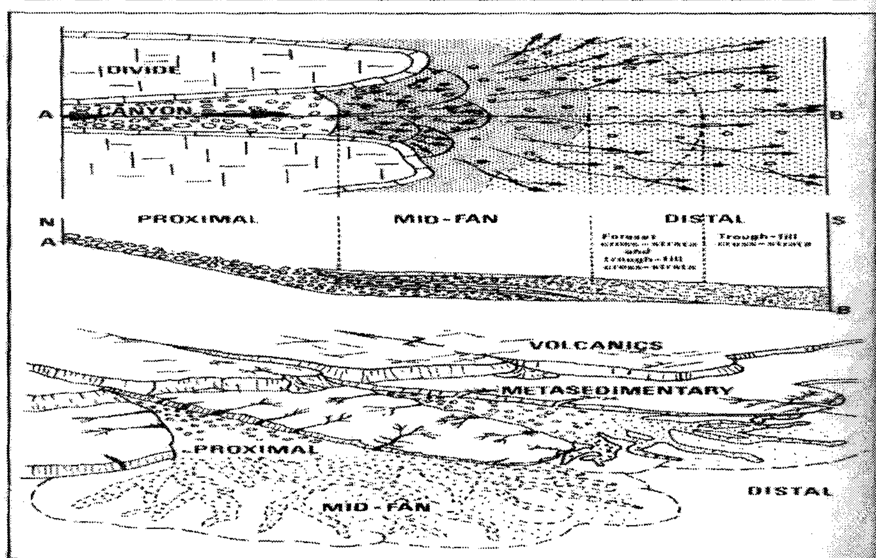
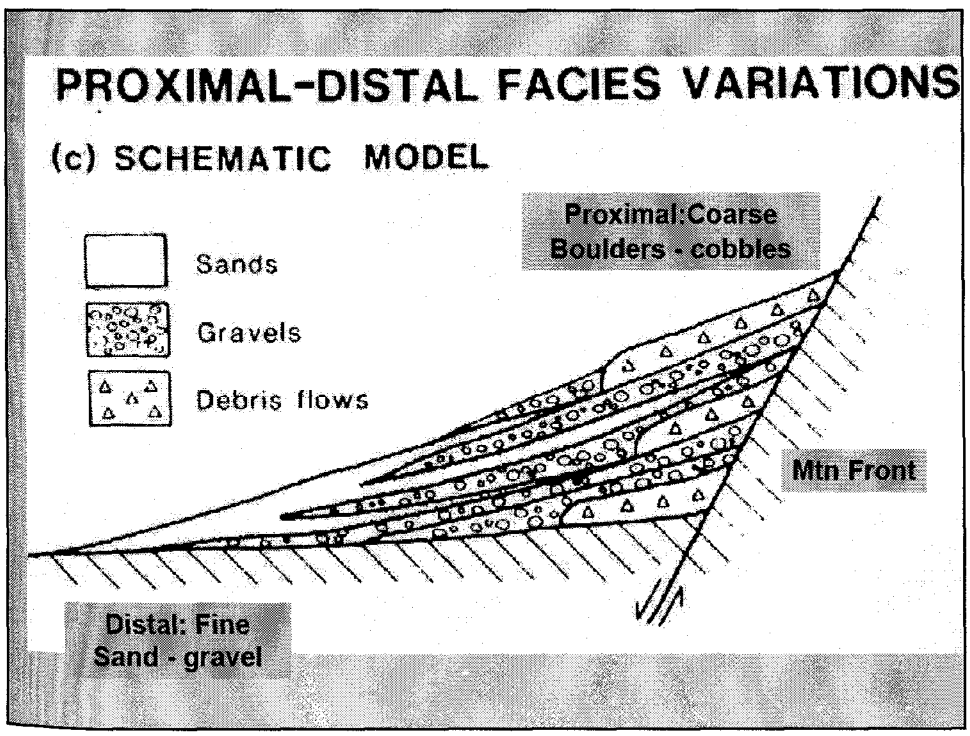
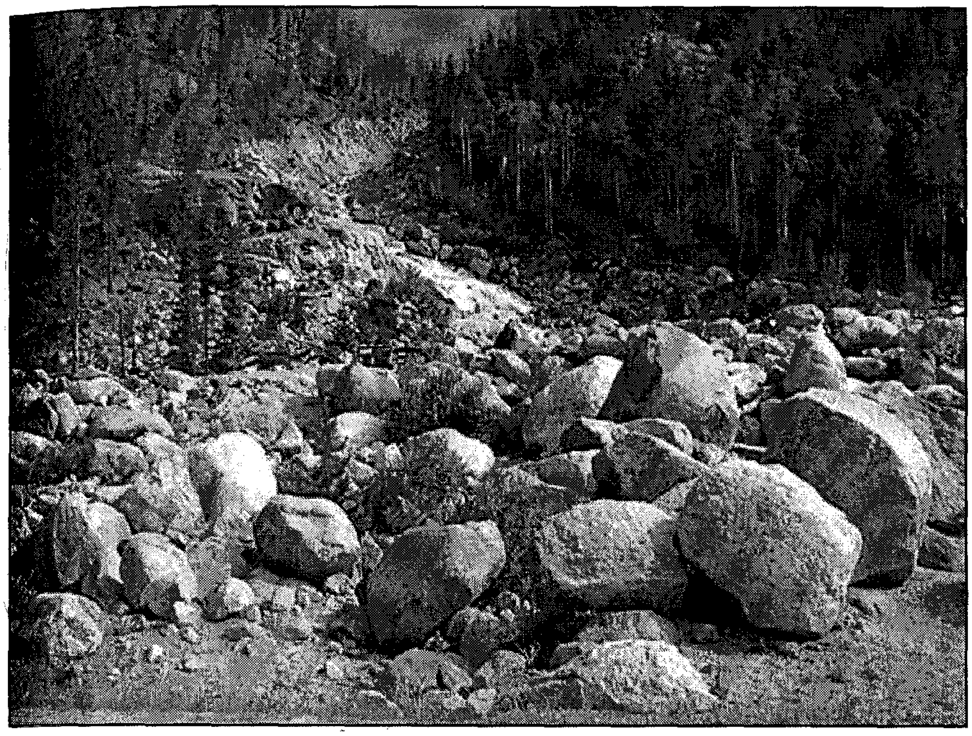


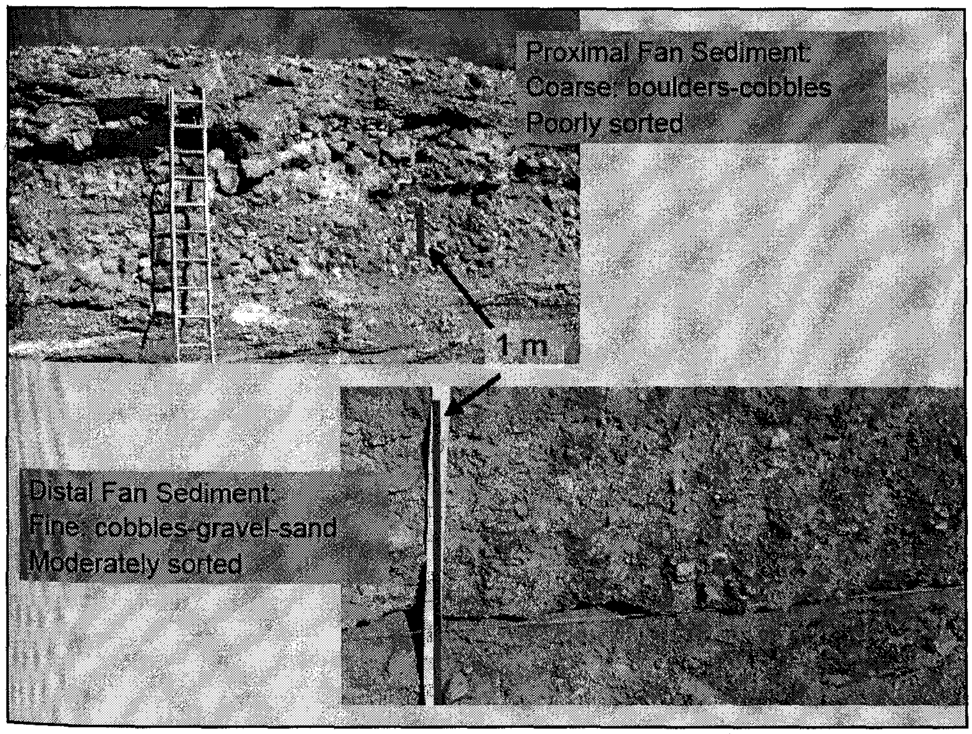
Fig. 5.2-4. Block-diagram, plan view and cross-section of Van Horn fan, West Texas. Widths of arrows, in plan view, indicate relative competency of stream flow. Profile and section show downfan decrease of slope and particle size and the types of stratification: proximal fan = massive conglomerate; mid-fan = interbedded conglomerate and cross-stratified sandstone; distal fan = cross-stratified sandstone (from McGowen & Groat, 1971).

Lithology

- Alluvial fan sediment is a combination of
  - Landslide of debris & mud flow (rock fragments & mud?)
  - Braided stream channel flow (conglomerate)
  - Sheet flooding (sand, silt)
- Proximal fan, is very steep gradient and high discharge produces unsorted sediments.
- Mid fan, where braided channel flow begins, more gravel beds alternate with cross-bedded sands.
- Distal fan, the proportion of sand increases, and the shallow cut and fill of braided channel deposits predominated.






Proximal Fan Sediment:
Coarse: boulders-cobbles
Poorly sorted
1 m
Distal Fan Sediment:
Fine: cobbles-gravel-sand
Moderately sorted

Composition

- Rock fragment/ Conglomerate?: Alluvial fan deposits are essentially composed of rock fragment.
- Immature Sand: It is immature sediment range from arkoses to graywackes.
- Film Clay: Clay occurs as films around sand grains or as partial filling in the inter-granular void.
- Matrix Sand/ Clay: Sand or clay are filled the inter-granular void of conglomerate.

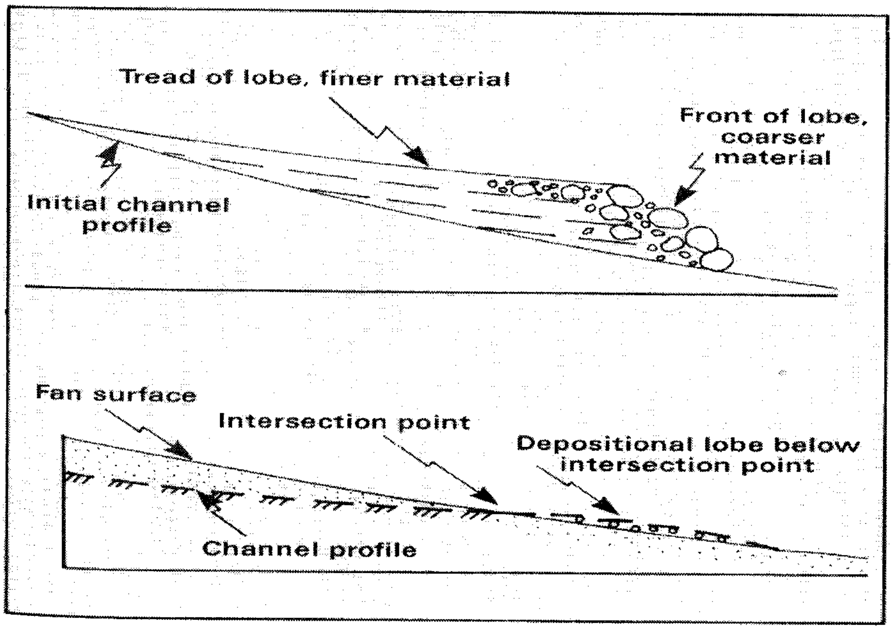


Fig. 5.2-5. Schematic sketch of a sieve lobe (from Hooke, 1967).

Texture

- Size: gravel are majority, sand/silt are minority
- Size decreases from proximal to distal fan (fig.4). Except sieve deposits near the intersection point, where water is unable of further transport, coarse material can accumulate and act as sieves holding back finer material. (fig.5)
- Shape: range from angular to very well round.
- Sorted: in proximal fan,
- *Matrix-supported conglomerates* (ephemeral/dry) with higher clay content are characteristic of debris flow. (fig.7)
- *Grain supported conglomerates* (perennial/wet) are characteristic of stream channel flow. (fig.6)

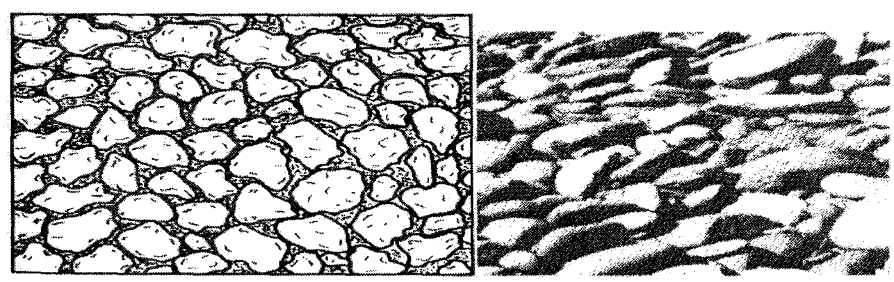


Fig. 5.2-6. Example of grain-supported conglomerate.

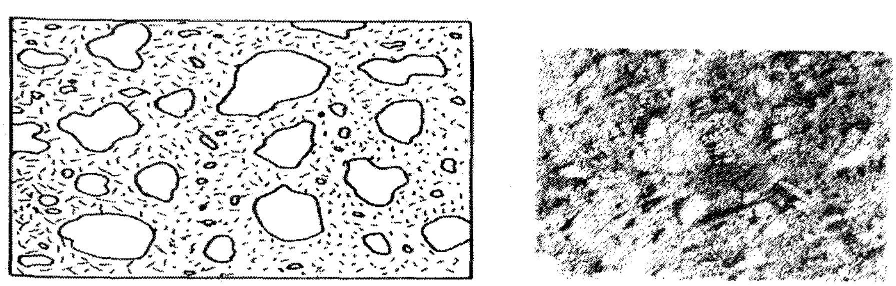


Fig. 5.2-7. Example of matrix-supported conglomerate.

Structure

- Un-bedded fanglomerate & Imbricate/ Oriented pebbles
- Various scale of cross bedding in channel & Current lineation

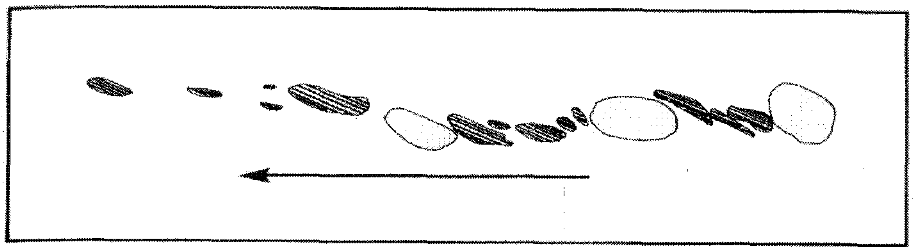
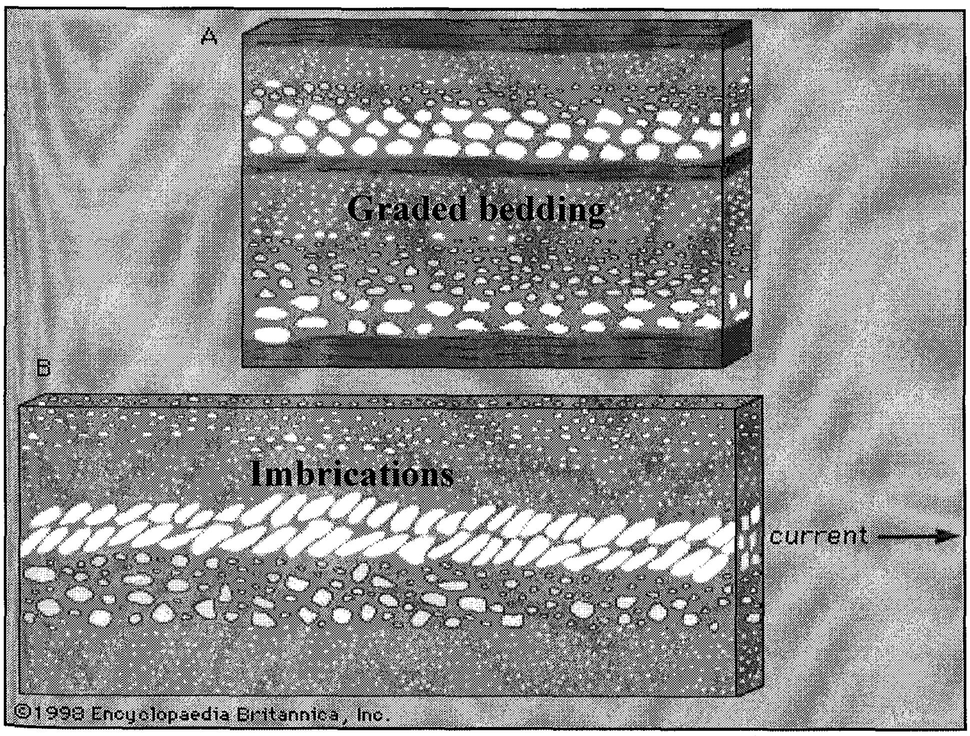


Fig. 5.2-11. Sketch showing the imbricate arrangements in a single pebble band. Archean conglomerate, Little Vermilion Lake, Ontario, Canada. The arrow gives the direction of the flow (from Pettijohn, 1930).



Structure

- Structure will be concentrated in channel, where current action is most dominant.
- Various scale of cross-bedding and imbricate pebbles, are the most commonly found.
- Trough cross-bedded conglomerate (grain-supported) are the major structure while tabular cross-bedded conglomerate, trough & tabular cross-bedded sand are the minor structure. (fig.8)

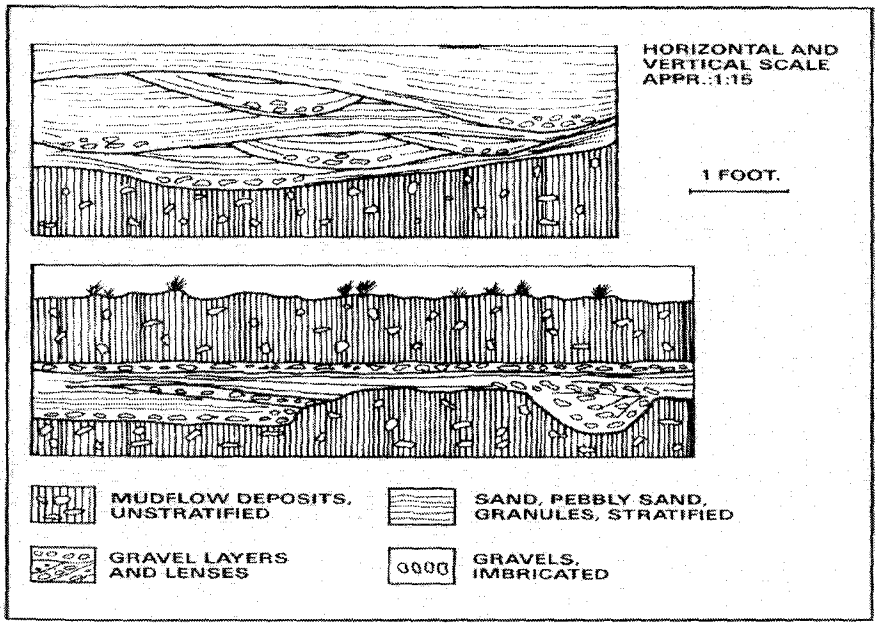


Fig. 5.2-8. Characteristic sedimentary structures in an alluvial fan (from Blissenbach, 1954; in Spearing, 1971).

Paleontology

- More common spores, pollen, often oxidized
- Rare vertebrated bones, plant debris

Paleontology

- As the result of sudden burial due to flooding
- Microfossils, such as spores and pollen, have a better chance of being incorporated.
- Macrofossils are relatively rare however some vertebrate bones and plant fragments may exist.
- Percolating groundwater within the fan has a strong chance to oxidized, acidic, dissolved and altered these fossils.

Geometry

- Fan shaped in plan view
- Wedge shaped in radial profile
- Concave upward in transverse profile
- Often lense-shaped in subsurface

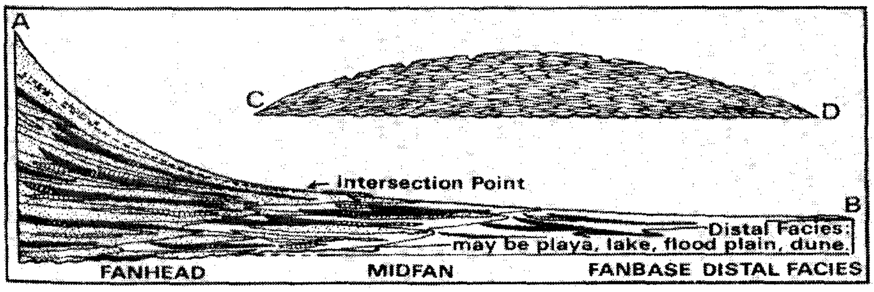


Fig. 5.2-10. Schematic cross-sections in an alluvial fan (from Spearing, 1971).

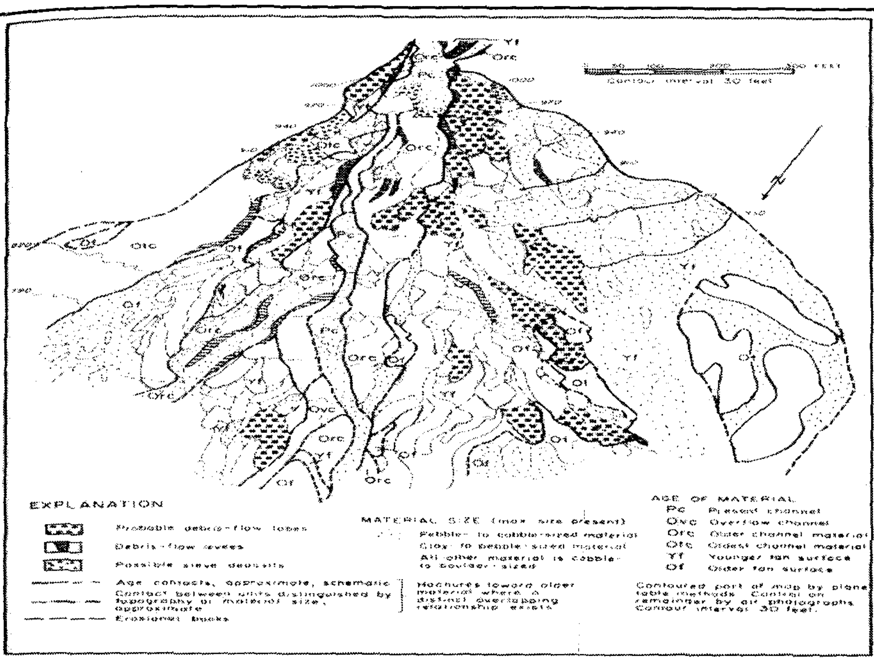
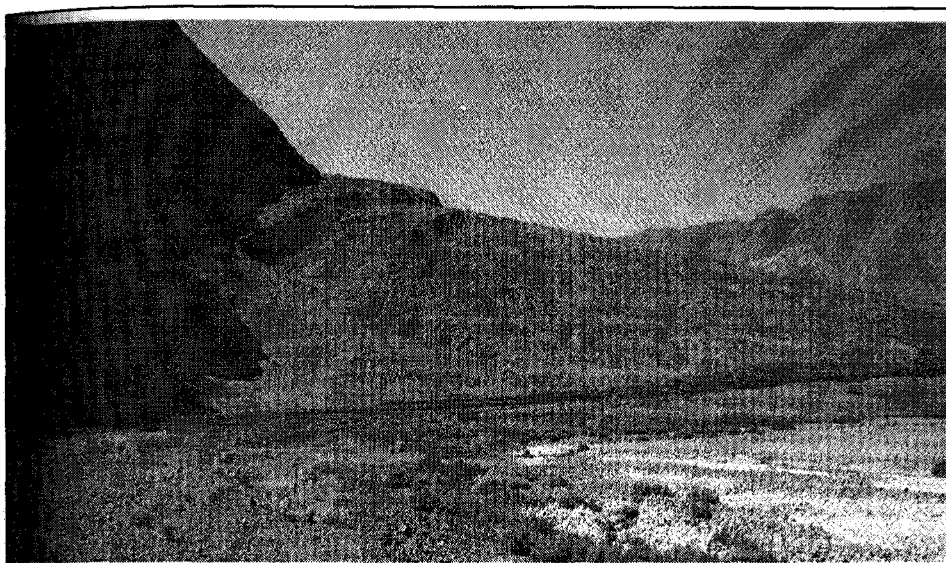


Fig. 5.2-9. Distribution of various types of sediments in the Trollheim alluvial fan (from Hooke, 1967).

Geometry

- Fan/cone-shape of long narrow body, extending radial down slope from fan apex. (fig.9) Concave upward in radial profile, convex-upward in transverse profile. (fig.10)
- Semi-arid climate (small fan) Debris flow (muddy) with high discharge but shot duration
- Humid climate (large fan) Perennial stream flow in low stream gradient
- Glacier climate (steep gradient fan) High level of spring run-off causing sediment transport



...this photograph an alluvial fan in Death Valley, California, is ...several faults expressed as low cliffs close to the mountain front. The fault scarps are obviously younger than the part of the fan they cut, indicating a tectonic event after deposition.

...re 8.5 **Crosscutting relations** indicate the relative ages of rock bodies and geologic structure.

Associated facies

- Fault generated mountain fronts
- Mountain stream valley
- Alluvial plains (braided stream)
- Playa lakes and aeolian facies

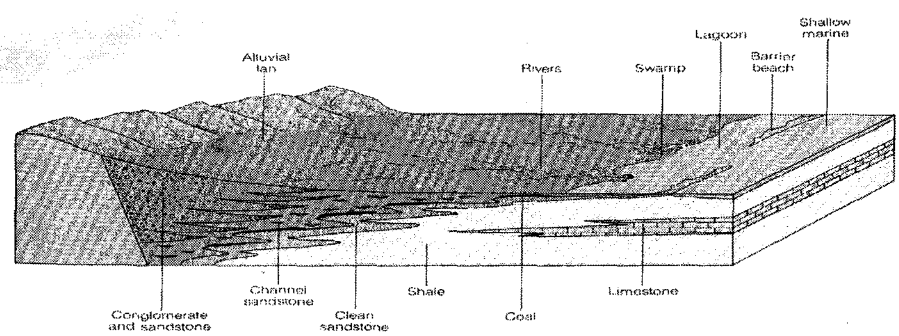
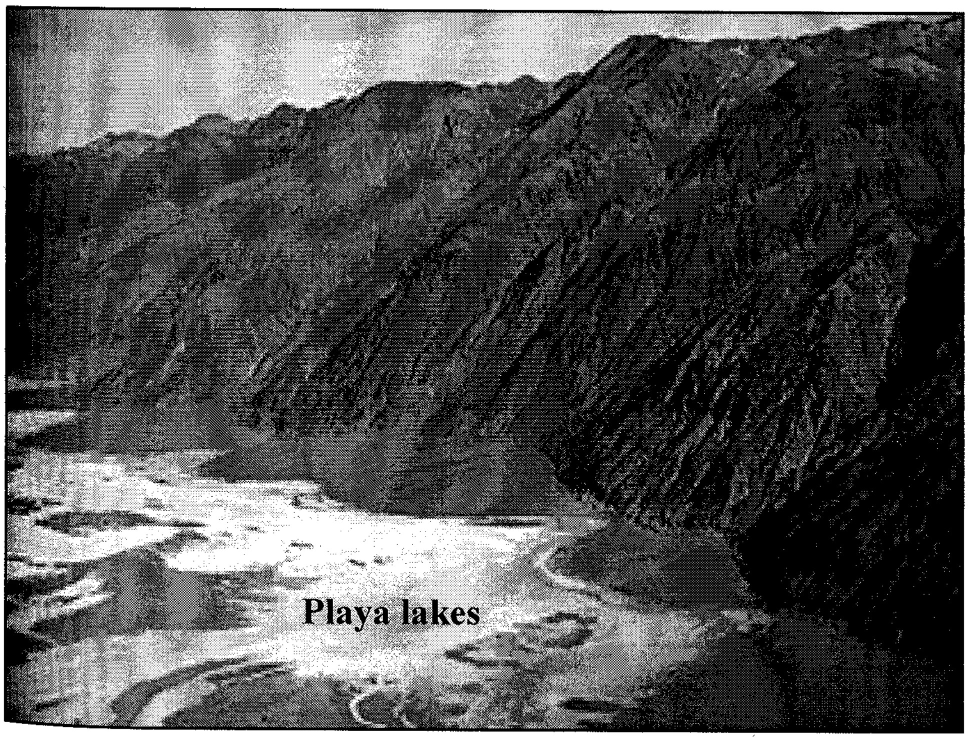


FIGURE 6.11
Interpretation of ancient sedimentary environments based on sedimentary rocks and their vertical and lateral relationships. The major sedimentary environments are shown on the top of the diagram: alluvial fans, river systems, deltas, lagoons, barrier bars, and shallow marine. The rock sequences—conglomerate, sandstone, coal, shale and limestone—are shown on the sides of the diagram. They were formed in a vertical sequence as each environment shifted back and forth as the sea expanded and contracted with time.

Associated facies

- Rapid vertical and lateral change, commonly red bed. It may inter-finger up-slope with talus deposits and down-slope with alluvial plain or less common playas lake, sea and aeolian facies.
- Boundaries: An irregular erosion lower boundary is present and gradational contact toward the top.
- Sequence, fundamentally, fining upward but coarsening upward may present if tectonic uplifts occur. In cases where the fan is situated on the down-thrown side of an active fault, great thickness of sediment may accumulate.
- Rhythmic of several sequences can be observed.



Core

- Upper fan:
- Coarse grained (conglomerate?)
- Poor sorting
- Angular
- Immature
- Lower fan:
- Finer grained (sand?)
- Cross stratified/ flat bedded channel sandstone associated with thin shale (mud flow), sand-silt bed (sheet flood) and gravel layer.

Wire line log

- Upper fan: Massive conglomerate shows Monotonous GR/SP/R curve & Random Dip
- Lower fan: Alternation of sand and conglomerate show Saw-tooth GR/SP/R & Green Dip (low angle)
- Immature sediment: Th & K content are M-H
- Pb vs. $\varnothing n$ points: Fall between sand & shale line
- Grain supported conglomerates: High R with low amplitude and Random Dip
- Matrix-supported conglomerates: Isolated R with high amplitude (several shale layers)
- Aeolian sand: Green Dip (high angle)

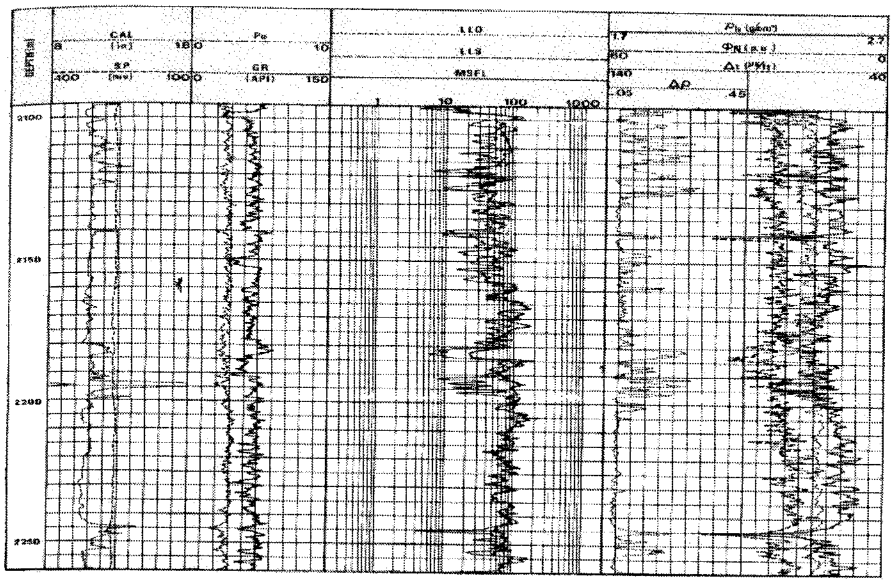


Fig. 5.2-12. Typical log responses in an alluvial fan deposit as shown by this composite-log. Logs reflect a certain heterogeneity continuing on a thick interval.

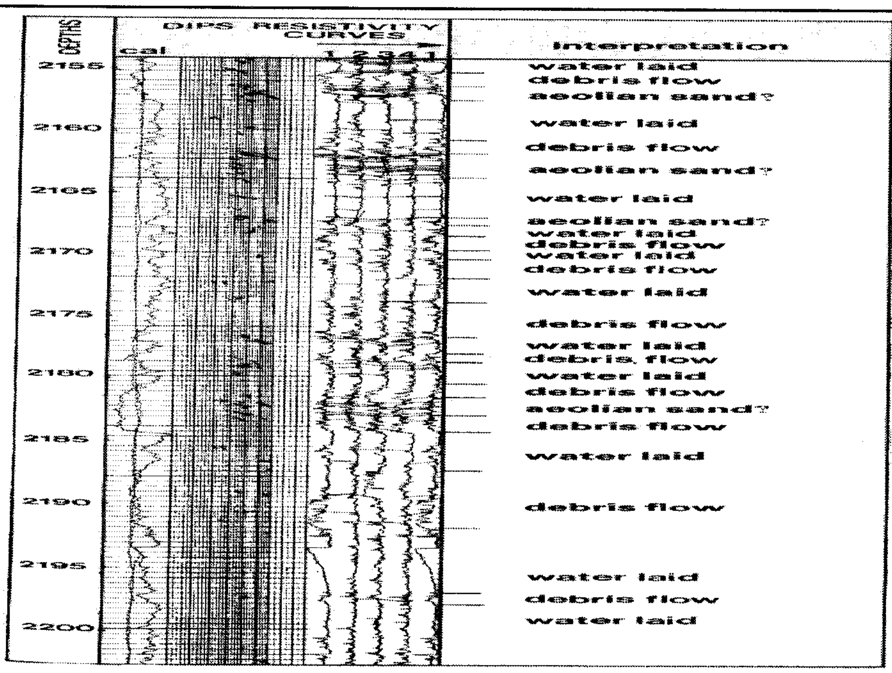


Fig. 5.2-13. Typical GEODIP response in an alluvial fan, and its interpretation. It corresponds to a short interval of the previous composite log.

Petroleum aspect

●Not good reservoir: They are not good reservoir but often serve as an important indicator of tectonic setting and source area composition.

●Proximal fan: Best porosity and permeability are usually confined to the proximal area. Further away from the proximal the grain sizes and fairly well sorted gravel are usually decrease down slope.

●Fan delta: To date, there are only a few, clear-cut examples of petroleum fields producing from terrestrial fans. However, fan deltas are productive in N-Texas and S-Oklahoma.

Seismic

●Discontinuous: Alluvial fan typically shows discontinuous internal reflectors. This should be expected given the great lateral and vertical variation in lithology.

●Distorted geometry: Further more the concave upward geometry often subdued in the subsurface, due to post-depositional compaction and tectonic tilting.

BRAIDED STREAM ENVIRONMENT

Definition

▪Low sinuosity: A continental deposits resulting from a river system of an interlaced network of low sinuosity channels.

▪Steep slope: They form on relative high slope, low discharge with large amount of coarse sediments and make many shallow channels, bars with no separate floodplain. Braided stream often begin on the alluvial fan itself.

▪Common: In Late Paleozoic and Mid Mesozoic – Early Tertiary, when tectonic activity was extensive over large regions of arid or semi-arid.

FIGURE 11.20
A braided stream pattern commonly results if a river is supplied with more sediment than it can carry. Deposition occurs, causing the river to develop new channels. *(U.S. Department of Agriculture, ASCS Western Aerial Photo Lab., Salt Lake City, Utah.)*

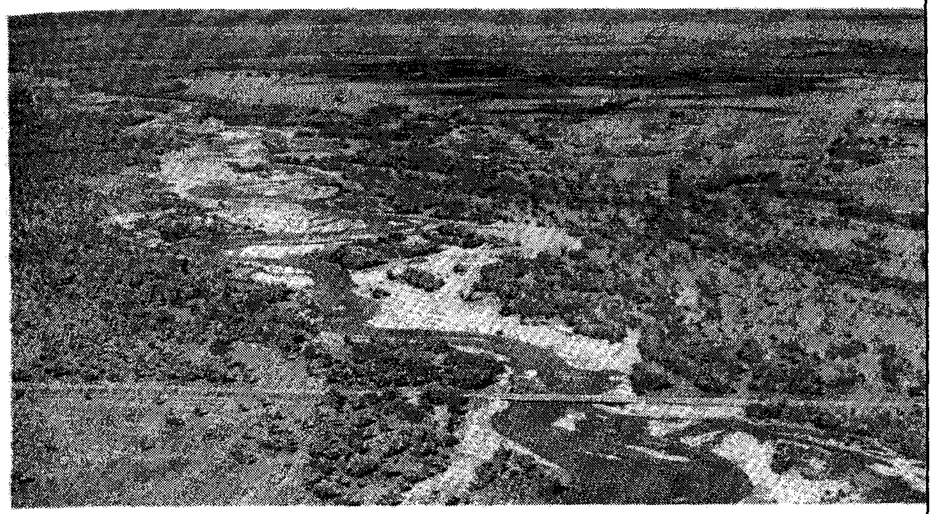
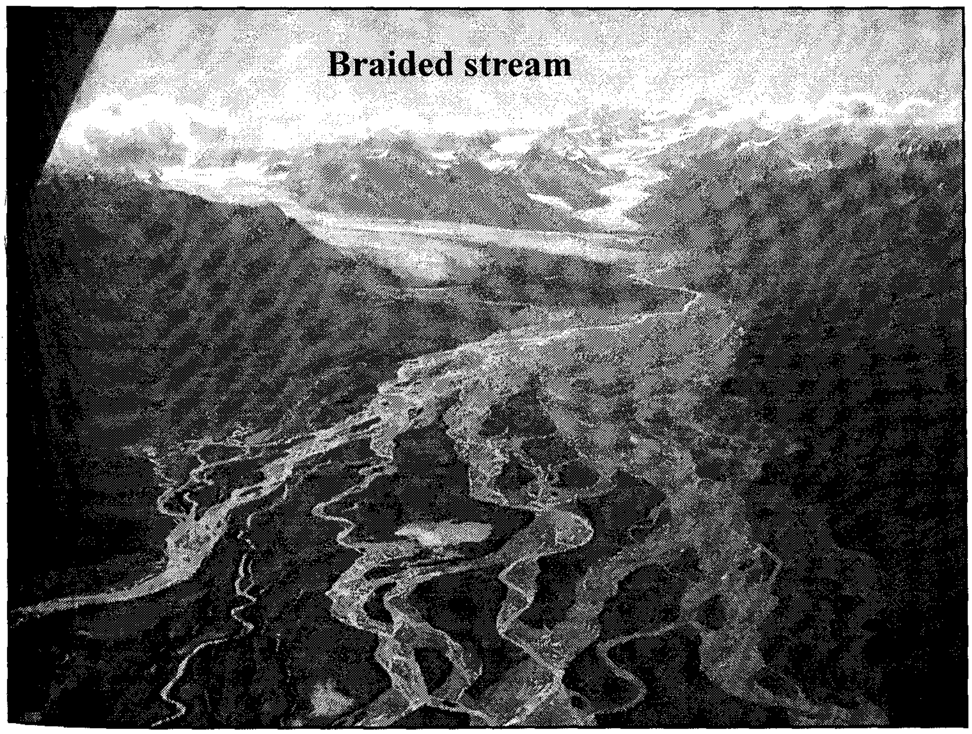


Figure 12.25 A braided stream pattern commonly results if a river is supplied with more sediment than it can carry. Deposition occurs, causing the river to develop new channels.



Lithology

- Up to 90% of gravelly/ pebbly sandstone
- Highly variable grain sizes

Fig. 5.4-1. Aerial photograph of a braided stream choked with erosional debris, near the edge of a melting glacier (Photo by B. Washburn, in Press & Siever, 1978).

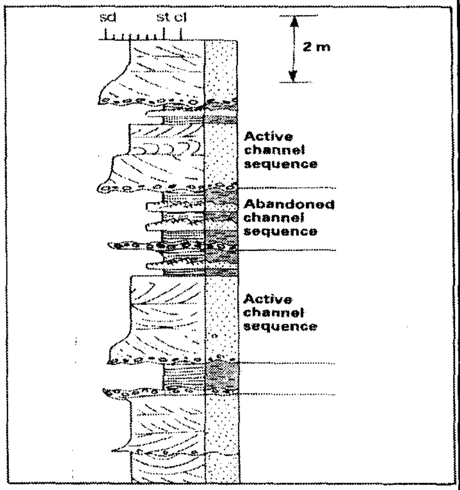
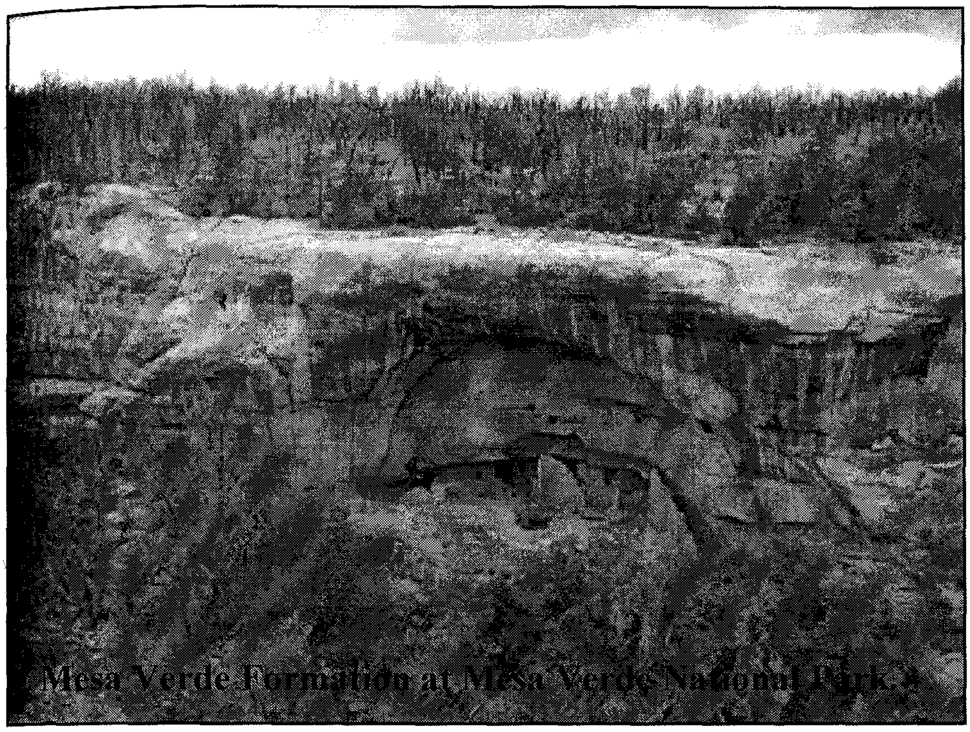


Fig. 5.4-2a. Theoretical vertical cross-section in braided river deposits (from Selley, 1976).

Lithology

- Gravelly sandstone: A homogeneous section of up to 90 % is cross-bedded gravelly sandstone with diverse range of grain sizes.
- Low discharge: The overall discharge is low compared to the supply of sediment and sporadic punctuation ranging from no water to flooding discharge.
- Stacked channels: Flooding will quickly overflow the old shallow channels, during this time; new channels will be cut and fill. Thus, sequences are commonly comprised of multiple, stacked channels.
- Preservation: Preservation of this environment requires a region of subsidence.



Composition

- Immature Gravel & Sand: It is composed of immature gravel and sand, range from lithic arenites to lithic wackes.
- Common: Common minerals are quartz/feldspar pebble, mica with absent of glauconite and rare carbonaceous however, shale pebble and reworked clay-ironstone concretion may also present.
- Minor: Minor amounts of silt are found and correspond to abandoned channel deposits.

Texture

- ■Sand/Shale > 1: Up to 90% of gravelly/ pebbly sandstone
- ■Channel: Fining up, poor sorting near the base to moderate sorting at the top with low sphericity is observed.

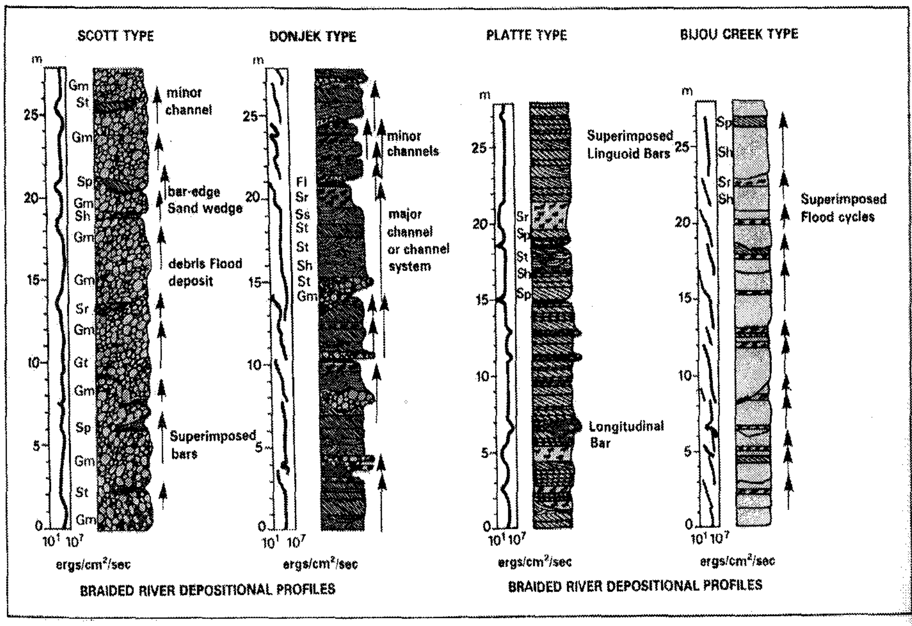


Fig. 5.4.2. (b) Four braided river depositional profiles (Miall, 1977).

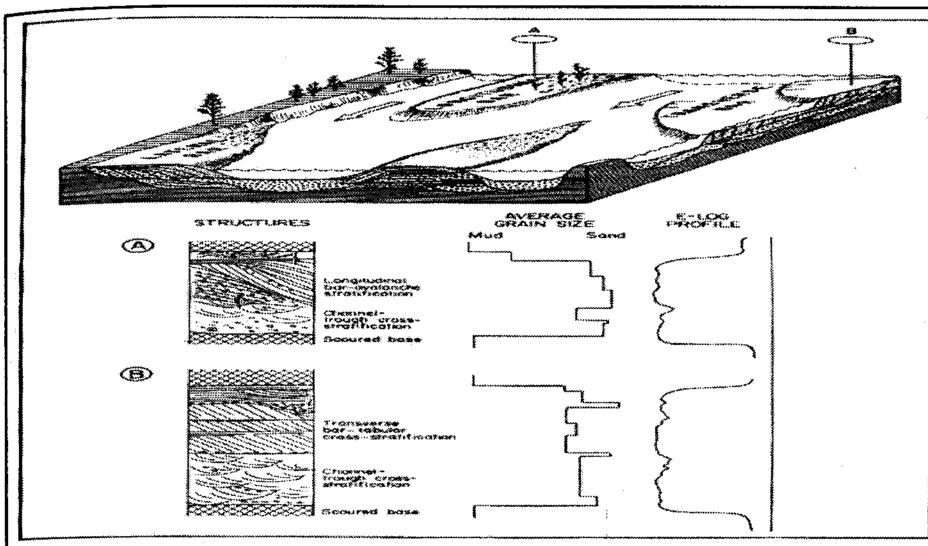


Fig. 5.4-10. Generalized depositional model, vertical sequences of grain size and sedimentary structures, and S.P.log profiles produced by a low-sinuosity, braided channel. Sequence (A) is dominated by migration of a gravelly longitudinal bar. Sequence (B) records deposition of successive transverse bar cross-bed sets upon a braided channel fill (from Galloway & Hobday, 1983).

Structure

- Table 5.4-1 summarizes braided deposits
- Flood plain?: Soft sediment deformation due to rapid changes in water level, are common and results in convoluted (de-watering), recumbent or collapse cross bedding.
- Bar?: Abundant tabular/ trough cross bedding commonly one direction are observed. The bedding may be either massive/ graded.
- Channel floor?: Beds trend to be lenticular sand with erosion scour, track and trail.

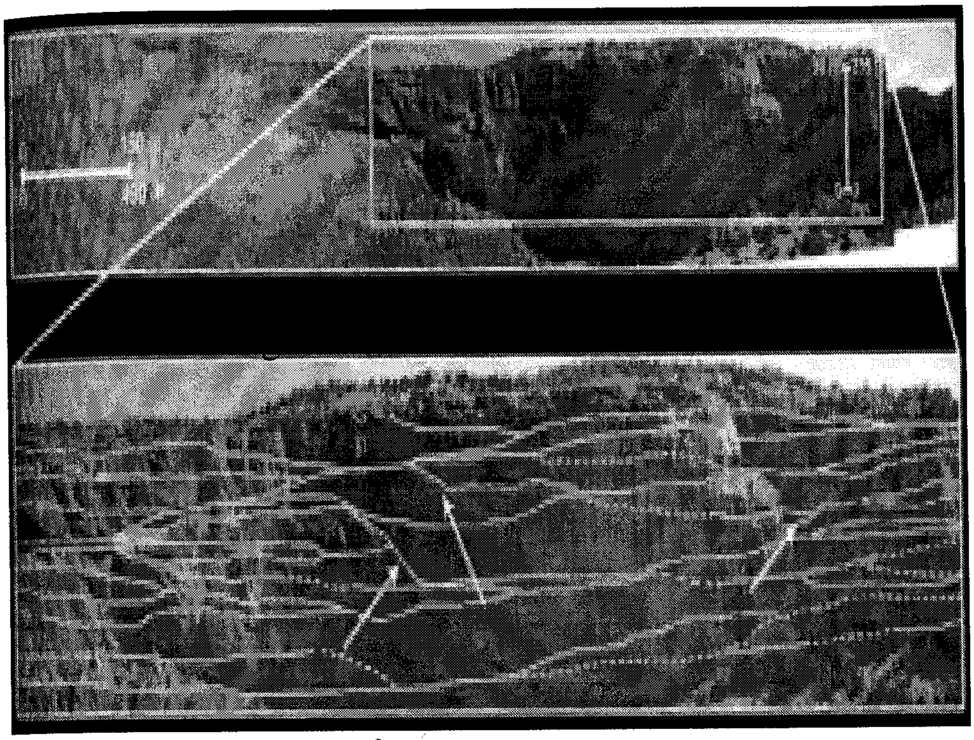
Table 5.4-1. *Principal sedimentary structures and their relative abundances*

Level/ Stream Channel	Lamination, Cross-Lamination				Ripples: Small-Scale					Ripples: Large-Scale		Bedding		Large-Scale Structures: Erosional		Large-Scale Structures: Depositional		Small-Scale Structures: Surface								Small-Scale Structures: Cross Section				
	Parallel	Lenticular	Small Scale X-L	Large Scale X-L	Straight	Sinuous	Lunate	Linguoid	Wave	Lunate	Linguoid	Massive	Graded	Scour Hollows	Channels	Bar Avalanche Face	Bars	Rill Markings	Current Crescents	Grain Lineation	Plant Lineation	Rain Pits	Desiccation Cracks	Silt Volcanoes	Tracks and Trails	Bedded Organics	Color Banding	Bioturbation	Imbrication	Bank Slippage
4	O	R										O		R	C		C								R	A	C	A		
3	C	O	A	O			A				O	O	O	C	A	O	A	R	C	R	R	O	C		C	C	C	C	O	
2	C	R	A	C			A				R	O	O	C	A	R	A	R	A	O	R	C	O	O	C	R		R	O	R
1	O	R	A	C			A				R	O	R	C	A	O	A	R	A	O	R	C	O	O	R	R		R	O	O
Overall (1-4)	C-O	O-R	A	C	O	A	A	A	C	R	R	O	O-R	C-R	A	O-R	A	R	A	O-R	R	C-O	C-O	O	C-R	A-R	C-R	A-R	O	O-R

A = Abundant, C = Common, O = Occasional, R = Rare.

Paleontology

- Sudden flooding:
- Some plant and animal debris may have settled on the immediate alluvial plain. They are often highly oxidized red, orange or yellow color by varying amounts of ferric iron.
- Some burrow and rootlet horizons may be preserved in shale layers but commonly barren.



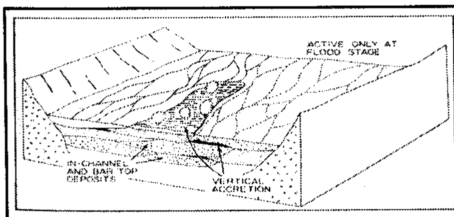


Fig. 5.4-6. Block diagram of a braided sandy system with low sinuosity channels. Vertical accretion can occur during flood stage (from Walker, 1969).

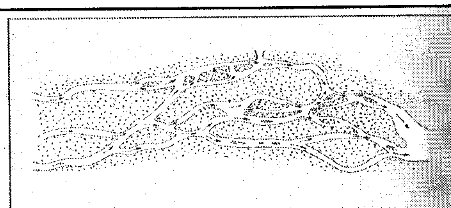


Fig. 5.4-7. Aerial distribution of a braided system showing hierarchical organization of channels and bars (from Allen, 1965).

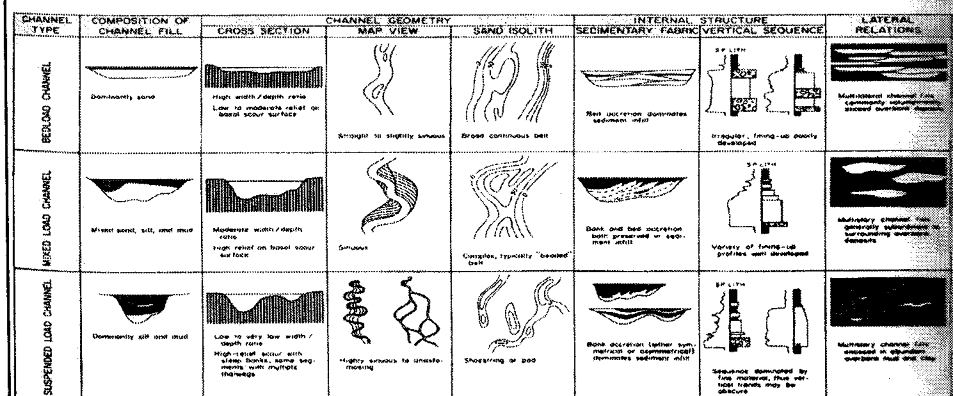


Fig. 5.4-8. Geomorphological and sedimentary characteristics of bed-load, mixed-load, and suspended-load stream channel segments (from Galloway, 1977).

Geometry

- Sheet like/ wedge:
- Braided stream migrate laterally leaving thick sheet like or wedge of channel and bar complexes cover large area preserving only minor amounts of floodplain.
- Not well developed vertical succession because:
- Rapid shifting channels erode any vertical succession.
- Braided tract is commonly wide zone so flood plain are less common.
- It is generally bed load. However vegetated islands may accumulate peat.

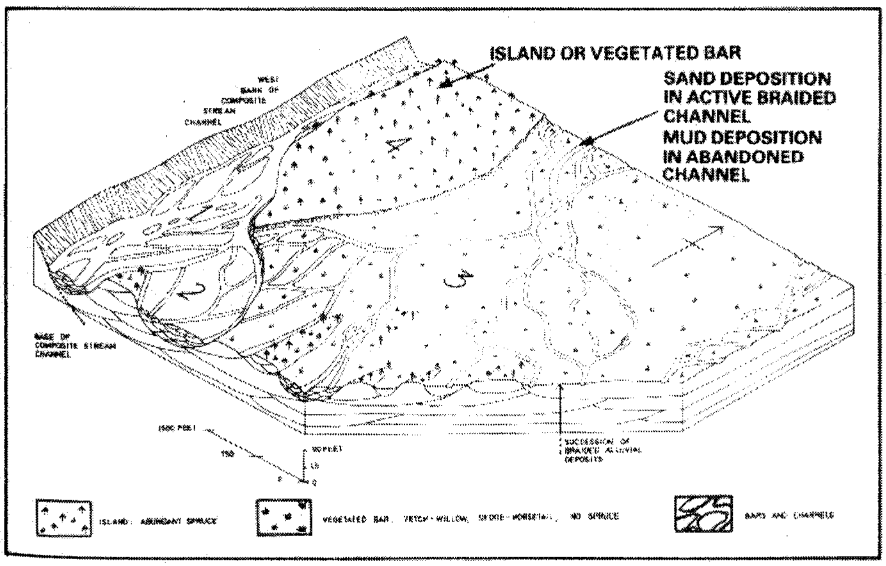


Fig. 5.4-5. Composite model of a braided river deposit (from Williams & Rust, 1969).

▪Geomorphology:

▪Channel is divided into several small channels which meet and re-divide during low flow but often submerged during high flow.

▪Bars are present in 3 types: the major (95%) is longitudinal with minor transverse & point bars.

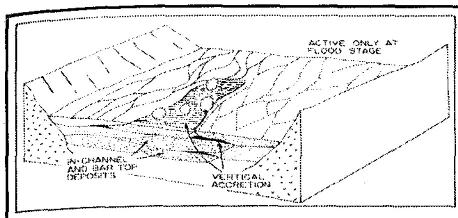
▪Vegetated Island are the most permanent features within a braided system. Root or carbonaceous material can be evidences.

Associated facies

▪Upper: alluvial fan

▪Lower: meandering streams, alluvial plains, aeolian dunes, playa lakes, sabkha, and possible transition to marine delta

▪Boundaries: lower contact of the sand is erosion and upper contact is also frequently abrupt.



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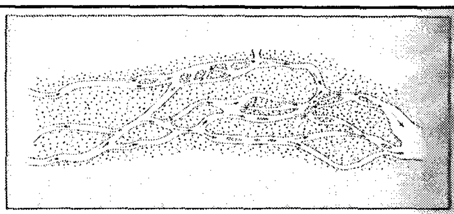


Fig. 5.4-7. Aerial distribution of a braided system showing hierarchical organization of channels and bars (from Allen, 1965).

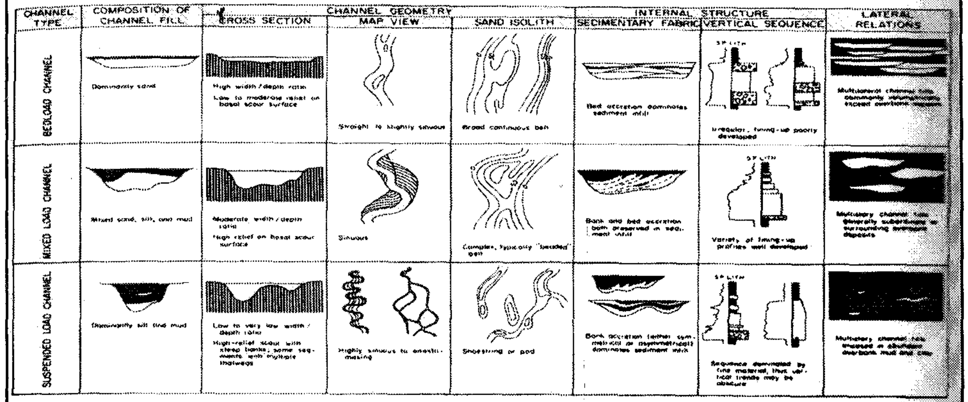


Fig. 5.4-8. Geomorphological and sedimentary characteristics of bed-load, mixed-load, and suspended-load stream channel segments (from Galloway, 1977).

- Sequences: fining up

(Top)

- Unit 4 F-Sd + Mud…horizontal/ convolute bed (Abandoned channel)
- Unit 3 F-Sd…small-ripple bed

(Recent abandoned channel)

- Unit 2 M-Sd…mega-ripple cross bed (trough/ tabular) (Migrated channel bars)
- Unit 1 C-Sd + Gravel…large cross bed (trough) with imbricate pebble & erosion base (no bedding)

(Channel floor?)

(Bottom)

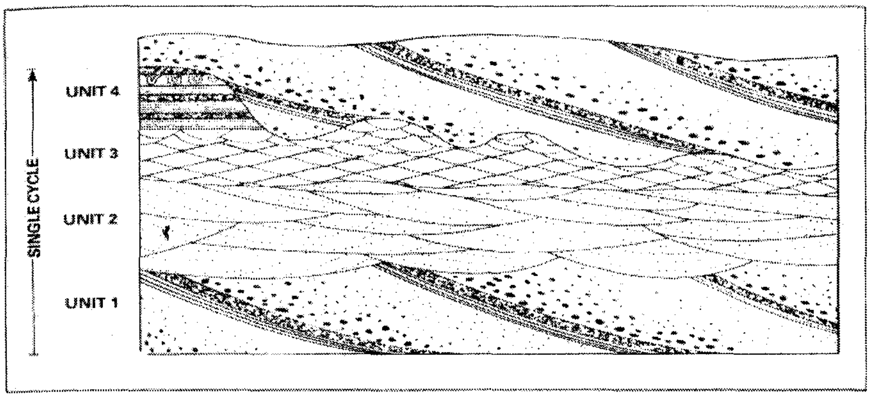
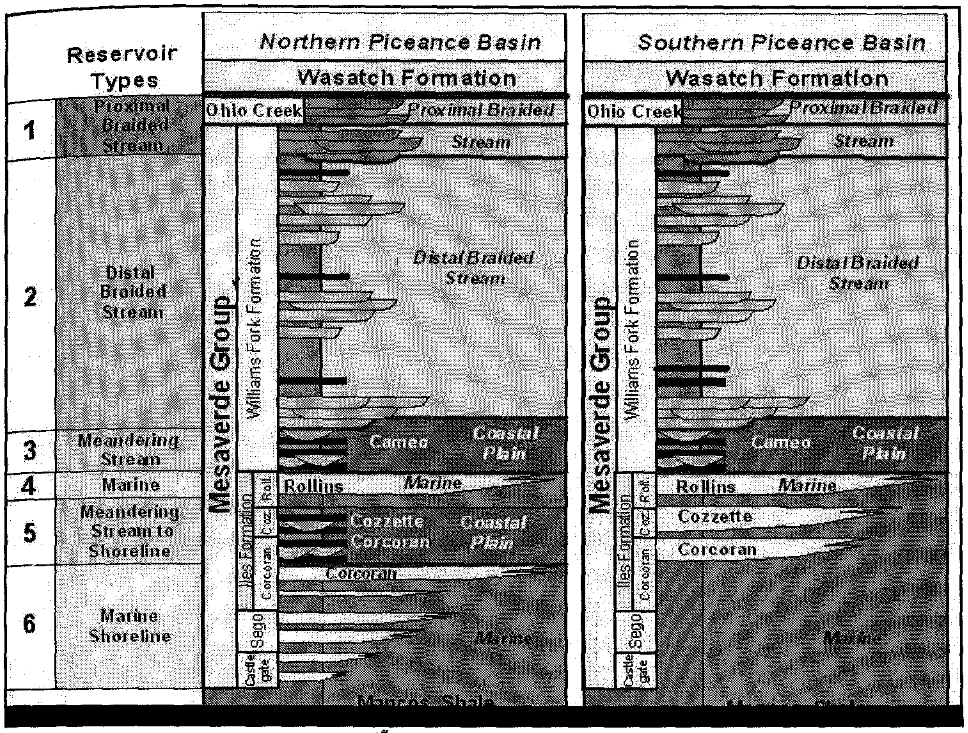


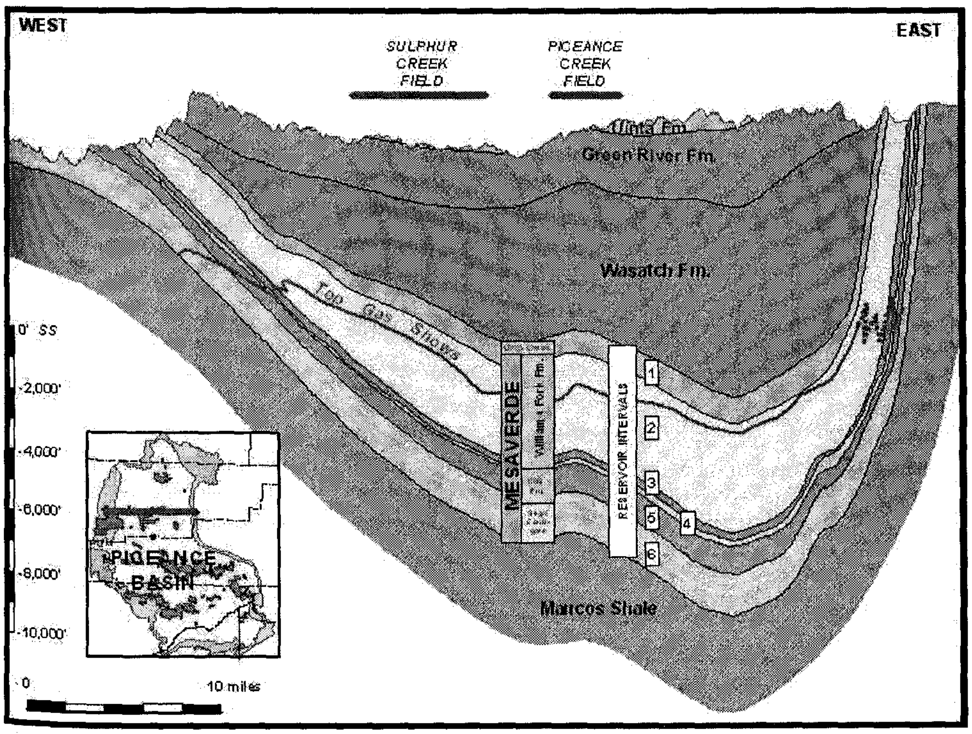
Fig. 5.4-3. Schematic vertical sequence of a braided river deposit. Unit 1: large scale cross-bedding with pebbles. Unit 2: medium sand megaripple bedding. Unit 3: fine sand small ripple bedding. Unit 4: fine sand and mud horizontal bedding, occasional convolute bedding (from Reineck & Singh, 1975, based on data of Doeglas, 1962).

Core

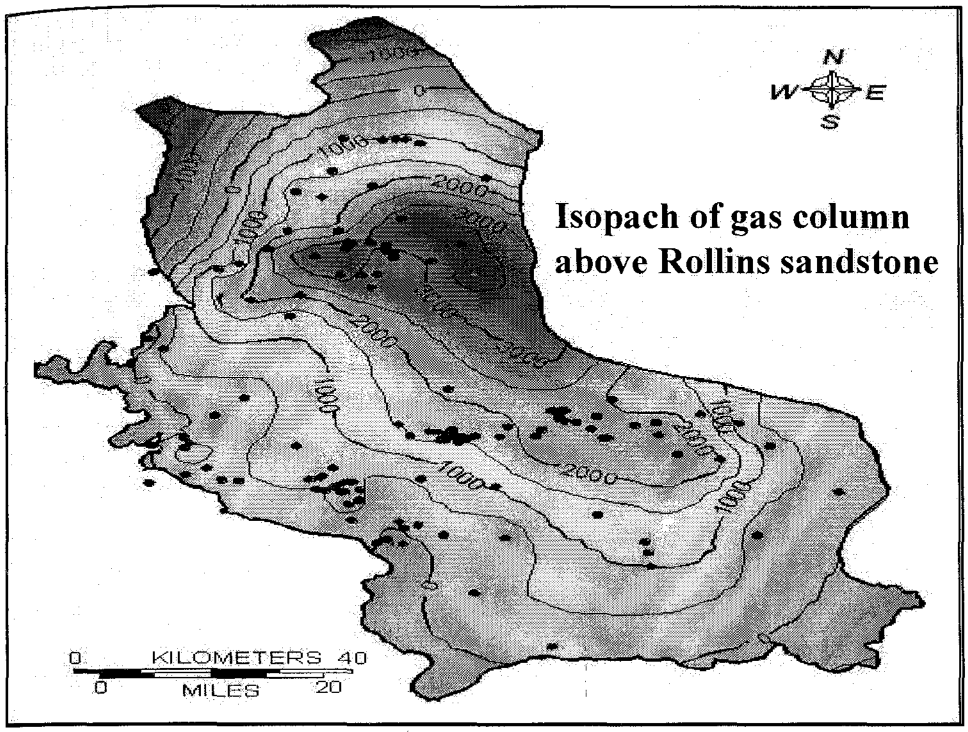
- It can be either a homogenous of coarse, cross bedding and gravelly sandstone or diverse range of grain sizes and sedimentary structures.
- Individual sequence begin with erosion base and is overlain by fining upward of grain sizes and sedimentary structures.



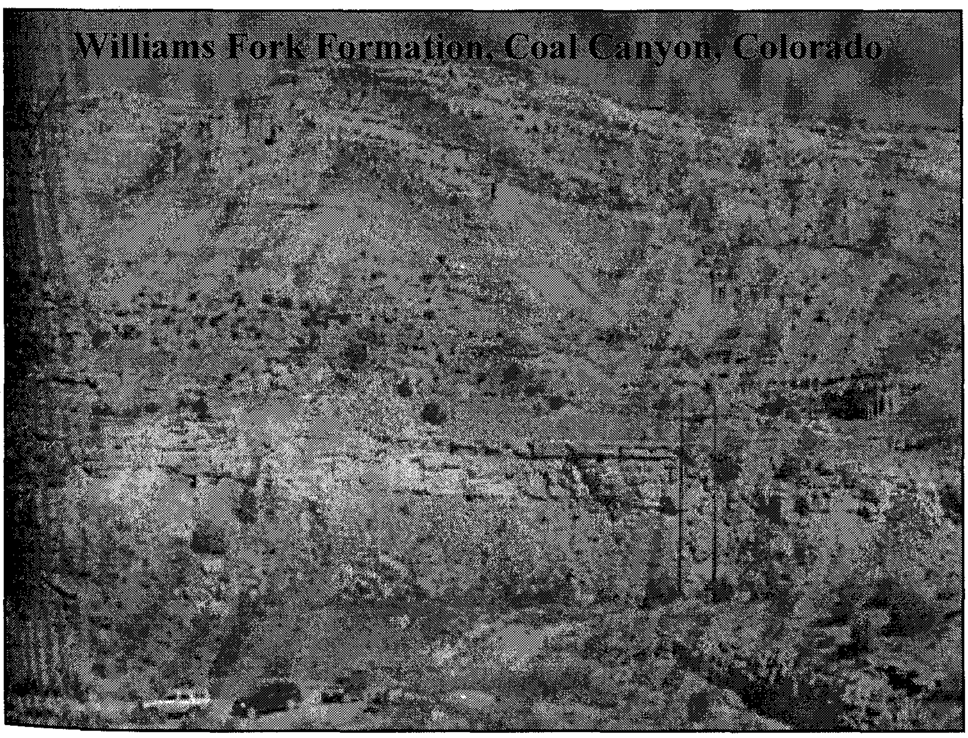
Reservoir Types
Northern Piceance Basin
Southern Piceance Basin
Wasatch Formation
Wasatch Formation
1
Proximal Braided Stream
2
Distal Braided Stream
3
Meandering Stream
4
Marine
5
Meandering Stream to Shoreline
6
Marine Shoreline
Ohio Creek
Proximal Braided Stream
Distal Braided Stream
Mesaverde Group
Williams Fork Formation
Iles Formation
Cameo
Coastal Plain
Rollins
Marine
Cozzette
Corcoran
Coastal Plain
Corcoran
Sego
Castlegate
Marine
Marcos Shale



WEST
EAST
SULPHUR CREEK FIELD
PICEANCE CREEK FIELD
Uinta Fm.
Green River Fm.
Wasatch Fm.
Top Gas Shows
MESAVERDE
Williams Fork Fm.
RESERVOIR INTERVALS
1
2
3
4
5
6
0' SS
-2,000'
-4,000'
-6,000'
-8,000'
-10,000'
PICEANCE BASIN
0
10 miles
Mancos Shale



Isopach of gas column above Rollins sandstone
N
W
E
S
0 KILOMETERS 40
0 MILES 20



Williams Fork Formation, Coal Canyon, Colorado

Wire line log

- Blocky shape: Grain size variation is often blocky (C) GR/SP with occasional spikes (F).
  - Upper: thin laminations
  - Middle: massive with few resistive peaks
  - Lower: start with an abrupt erosion surface
- Immature: High K confirms feldspar and high Th confirms heavy radioactive mineral both indicating immature sediment.
- Stacking channels: Dipmeter within each channel, azimuth & angle are clustered into separate group
- Paleo-current: Usually remain within 90*

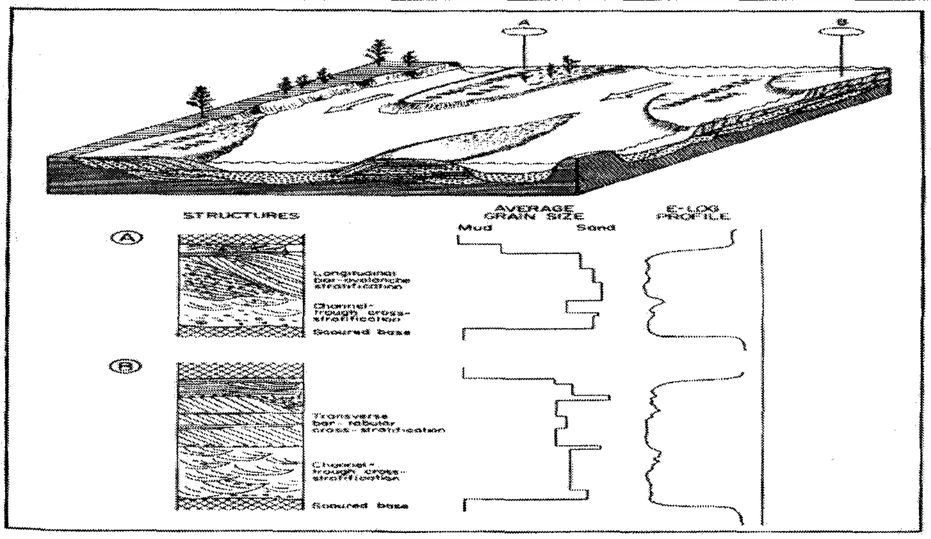


Fig. 5.4-10. Generalized depositional model, vertical sequences of grain size and sedimentary structures, and S.P.log profiles produced by a low-sinuosity, braided channel. Sequence (A) is dominated by migration of a gravelly longitudinal bar. Sequence (B) records deposition of successive transverse bar cross-bed sets upon a braided channel fill (from Galloway & Hobday, 1983).

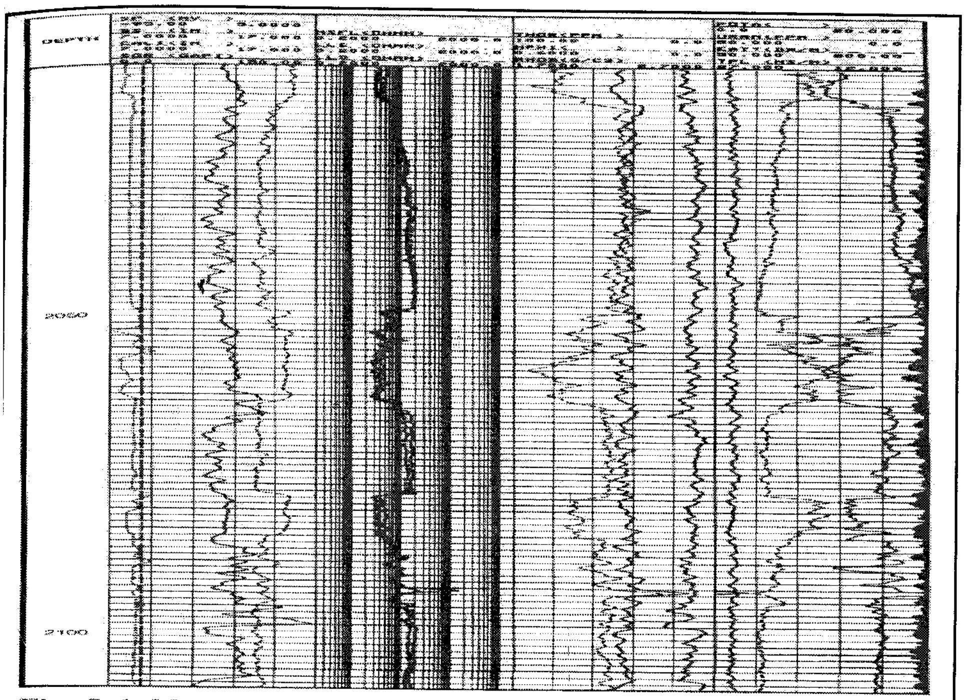


Fig. 5.4-11. Typical log responses over a braided river system.

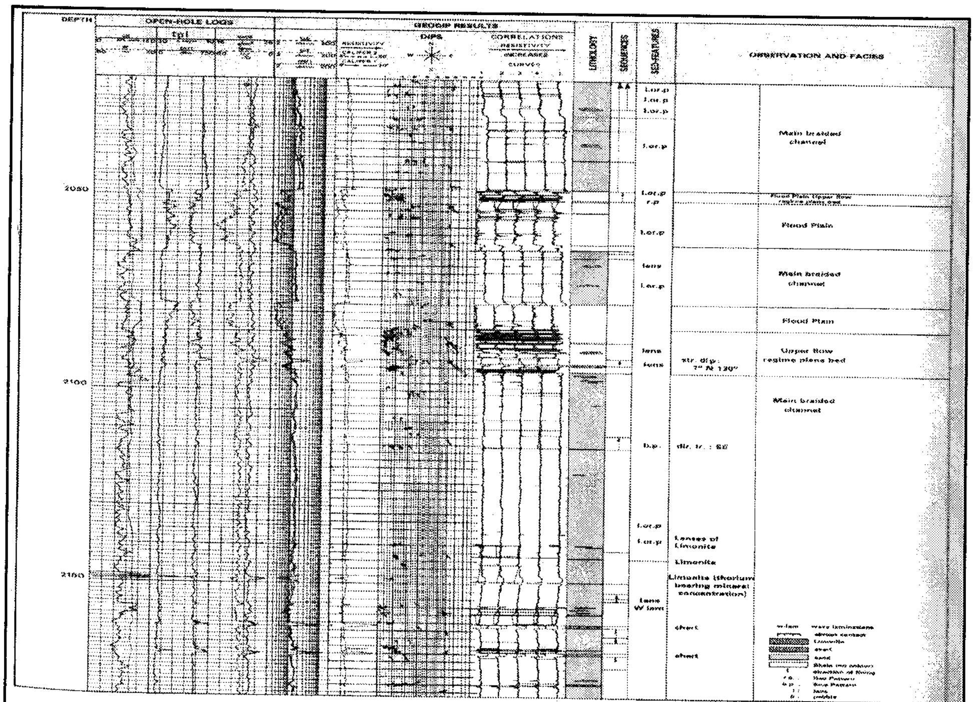


Fig. 5.4-16. GEODIP arrow-plot on the same well and its interpretation.

Petroleum aspect

- They are <u>good to excellent reservoir</u> potential because of large sheet of sand geometry.
- <u>Intercommunication</u> between individual channels is excellent due to 90% coarse grain size.
- Ideal reservoir is normally capped by major <u>unconformity</u> and top up by <u>marine transgression</u>.
- Percolation of acid meteoric water may <u>destroying</u> primary porosity by mineral precipitation or may <u>enhancing</u> it through dissolution.

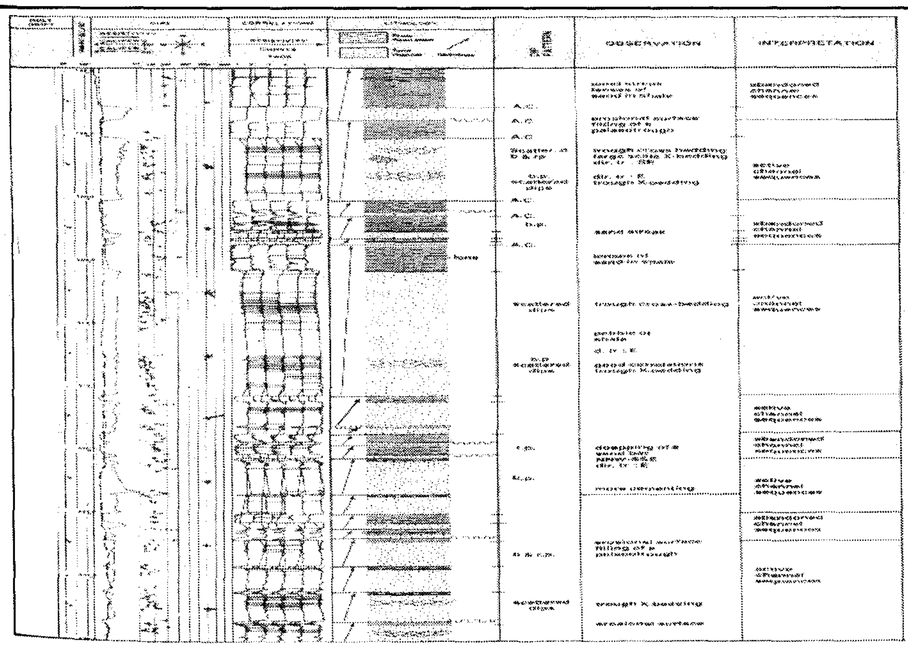


Fig. 5.4-17. Other example of a braided river system from Africa as it can be interpreted from GEODIP display.

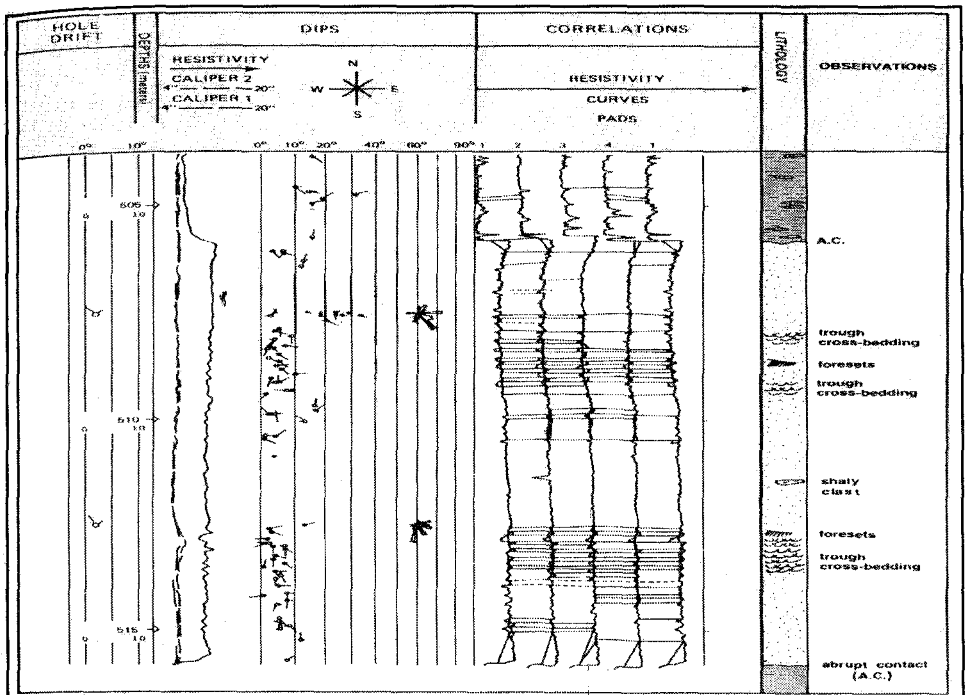


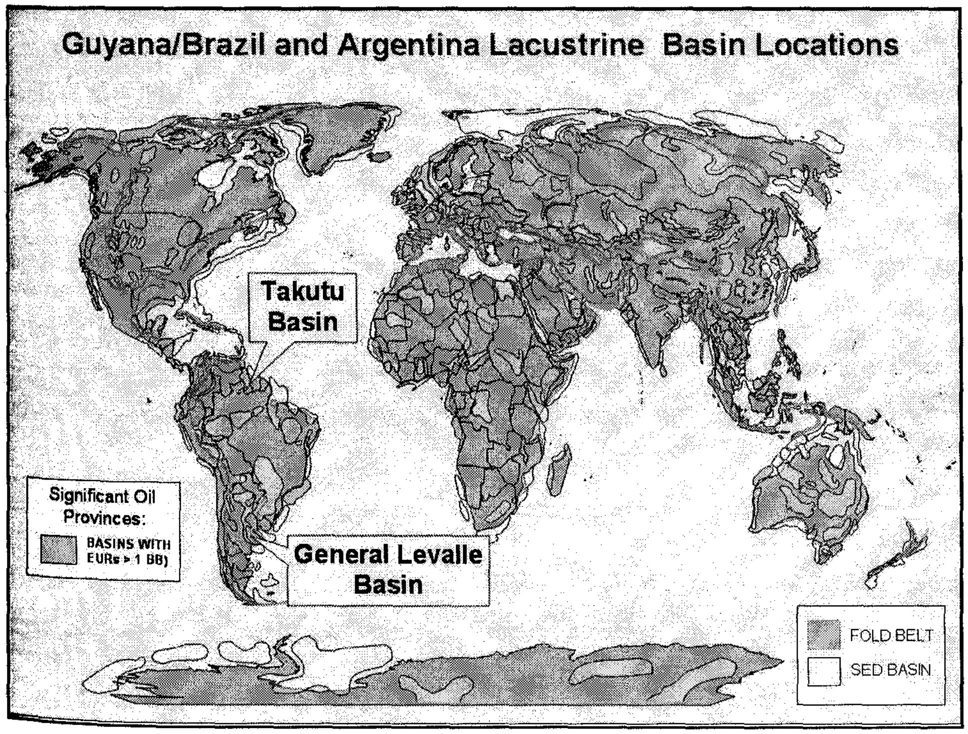
Fig. 5.4-18. Detailed sedimentary features observed on one sequence of the braided river system illustrated by Fig. 5.4-17.

Seismic

- Transparent reflection: Due to homogeneity, Braided stream deposits do not often show internal reflections.
- Continuous reflection: If the facies is thick enough, certain large scale depositional changes will generate continuous reflections.

LACUSTRINE ENVIROMENT

- **Definition**
- Lacustrine/Inland seas:
- Lakes that have occupied continental basins can be considered as small inland seas, hence better be considered as a facies group (marginal & central).
- Distinguishing lacustrine from marine facies:
- Tectonic setting as rift can be a strong evident.
- Fossils but reworking of non-marine fossil in marine facies is common.
- Associated facies but may confused with marine transgression



▪**Lithology**

▪Factors: influence sedimentation, paleontology, and composition of lake deposits

- Climate (precipitation) paleo-latitude/ climate
- Tectonic relief (local slope)
- Water salinity
- Source area (rock type)

▪Climate (humid): perennial lake

- Tectonic (high relief):
- marginal = delta (w/fluvial), beach (clastic sand)
- central = mud
- Tectonic (low relief):
- marginal = peat swamp (or carbonate mud flat), beach (skeleton sand)
- central = mud (or marl)

- Climate (arid): ephemeral lake
  - Tectonic (high relief):
  - marginal = alluvial fan (w/braided), dune
  - central = evaporite (or reddish silt)
  - Tectonic (low relief):
  - marginal = carbonate mud flat
  - central = evaporite
- Lamination: Lacustrine sediments are often more laminated and contain better preserved plant debris than marine setting (except lagoon).
- Delta: They may be form deltas at river mouths, which turbidity currents transport sediment into the basin center, creating sub-aqueous fans.

- Sensitive to climate: Their hydrological status or lake-water chemistry can be determined from the terrigeneous clastic versus chemical & biochemical sedimentation in the lake.
- Preservation: Preservation results from sediment filling in the original lake will demonstrates an overall regressive sequence.
  - <u>Humid</u>
  - margin: coarser (delta, beach, swamp)
  - basin: finer (shale)
  - <u>Arid</u>
  - margin: coarser (alluvial fan, dune)
  - basin: finer (evaporite)

▪Closed lake:

▪Tectonic: Closed lakes commonly form in the centers of the continental (sag, rift, pull apart basin).

▪Climate: They are dominated by detrital sediments and where discharge is negligible they are dominated by chemical/ biochemical sediments.

▪Water level: Closed lakes such as Dead Sea lake, Great Salt lake and Eyre lake are smaller size, more saline and less animal species comparing to the past as a result of climatic fluctuations (water level).

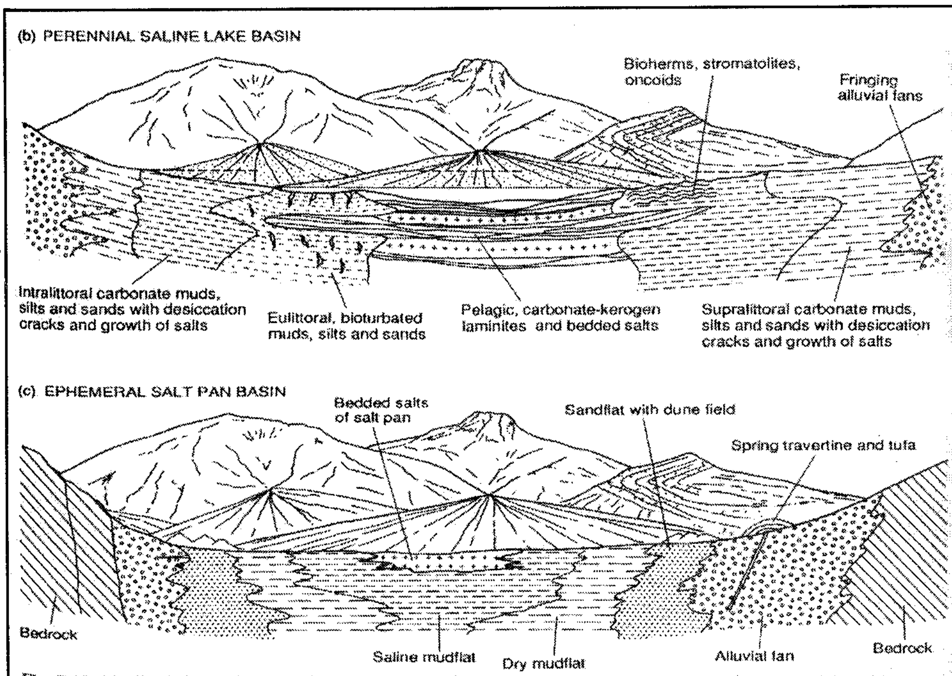


Fig. 7.13. Idealized depositional environments and facies in lacustrine systems. (a) Open freshwater lake with through drainage; (b) Hydrologically closed perennial salt lake; (c) Hydrologically closed ephemeral salt pan. After Eugster and Kelts (1983), modified from Allen and Collinson (1986).

▪Allen and Collinson, 1986

▪**Central facies:**

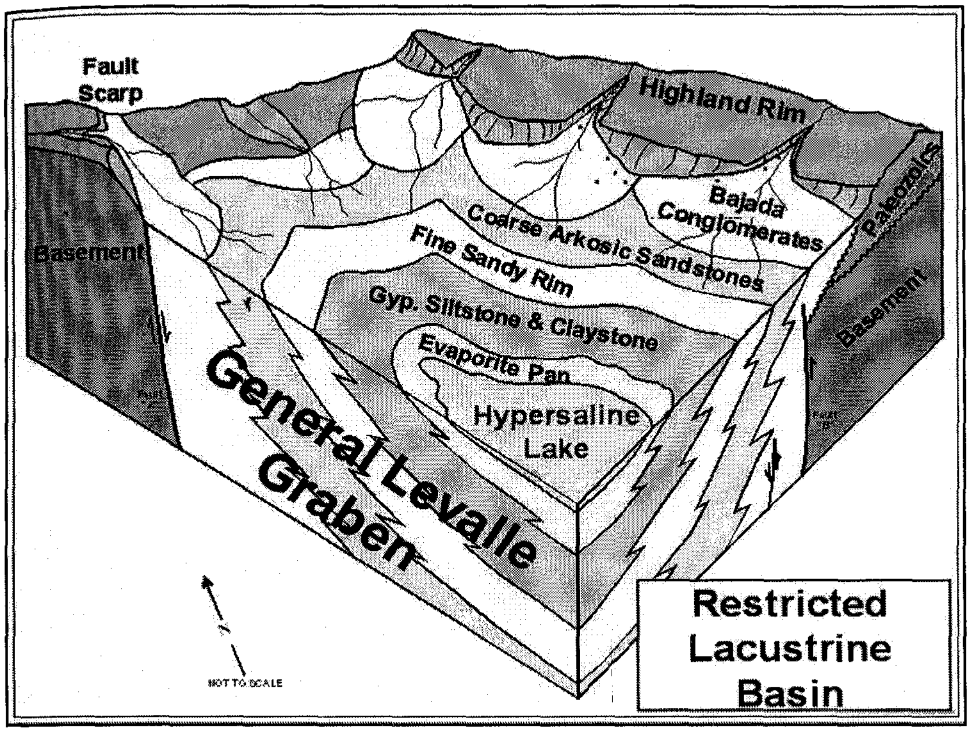
▪Perennial salt?:

▪Oil shale representing the remain of algae and marl input from fringing mud-flats.

▪Laminated carbonate-gypsum caused by seasonal changes in water chemistry.

▪Ephemeral salt?:

▪Evaporite precipitated from concentrated lake.



▪**Marginal facies:**

▪Perennial salt?:

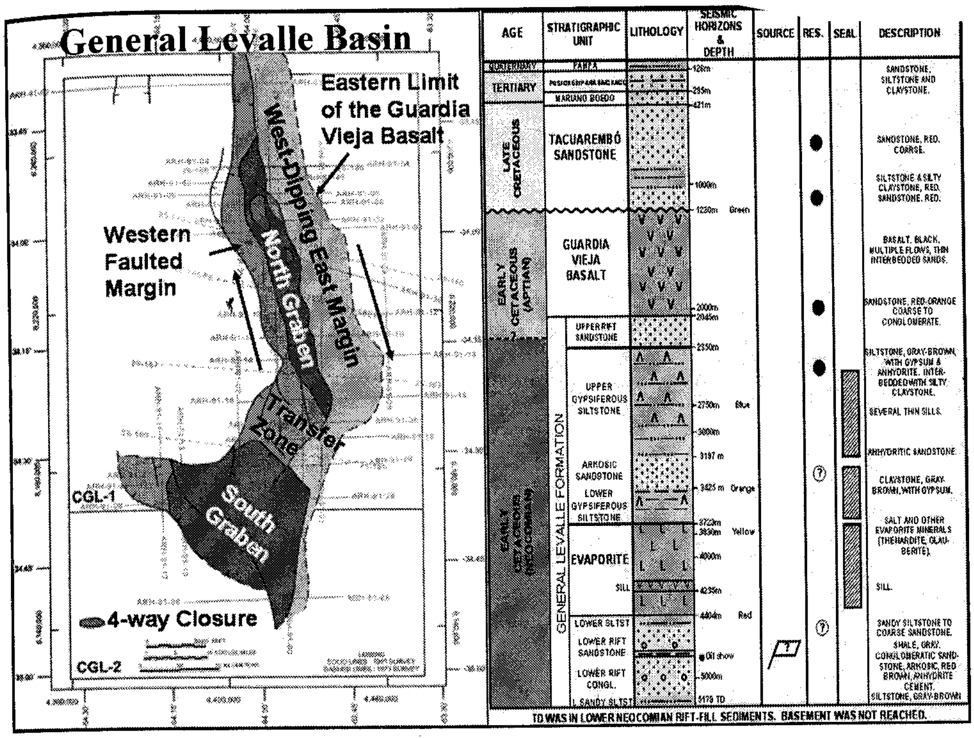
▪Siliciclastic sandstones deposited in small beach zones close to river entry points.

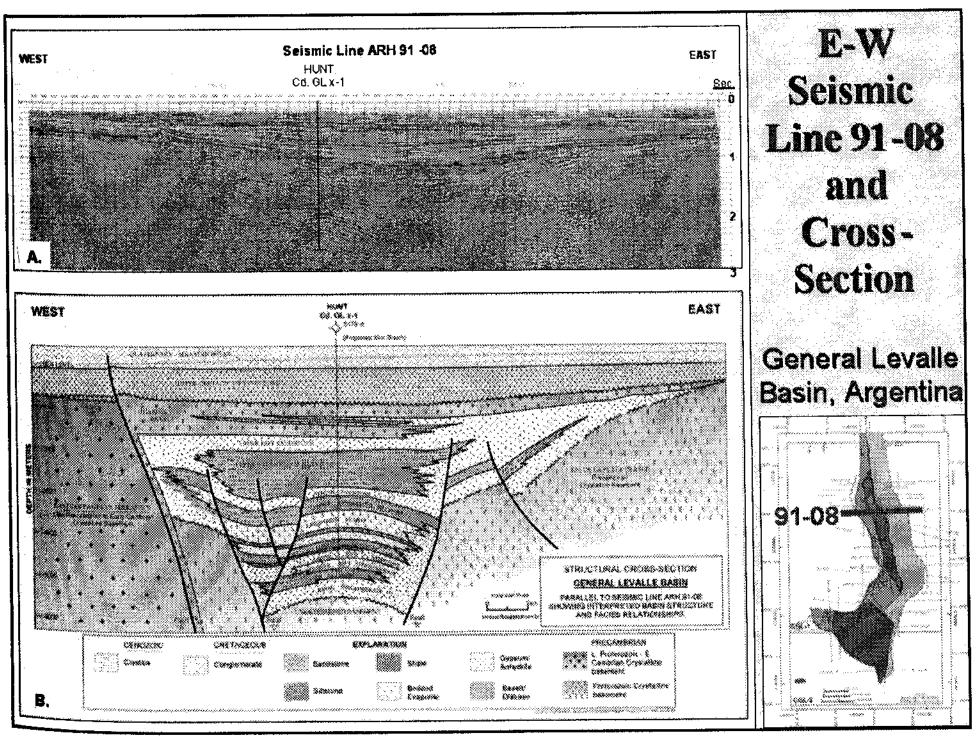
▪Stromatolitic limestone and oolitic-pisolitic grain-stones promoted by algal activities.

▪Ephemeral salt?:

▪Laminated limestone with desiccation cracks.

▪Gypsum marls with nodular sabkha-like gypsum.


General Levalle Basin
Eastern Limit of the Guardia Vieja Basalt
West-Dipping East Margin
Western Faulted Margin
North Graben
Transfer Zone
South Graben
4-way Closure
CGL-1
CGL-2
AGE
STRATIGRAPHIC UNIT
LITHOLOGY
SEISMIC HORIZONS & DEPTH
SOURCE
RES.
SEAL
DESCRIPTION
TERTIARY
MARIANO BOEDO
LATE CRETACEOUS
TACUAREMBÓ SANDSTONE
EARLY CETACEOUS (APTIAN)
GUARDIA VIEJA BASALT
EARLY CETACEOUS (NEOCOMIAN)
GENERAL LEVALLE FORMATION
UPPER RIFT SANDSTONE
UPPER GYPSIFEROUS SILTSTONE
ARKOSIC SANDSTONE
LOWER GYPSIFEROUS SILTSTONE
EVAPORITE
SILL
LOWER SLTST
LOWER RIFT SANDSTONE
LOWER RIFT CONGL.
L SANDY SLTST
128m
295m
421m
1000m
1230m Green
2000m
2045m
2350m
2750m Blue
3000m
3197 m
3425 m Orange
3723m
3830m Yellow
4000m
4235m
4404m Red
Oil show
5000m
5175 TD
SANDSTONE, SILTSTONE AND CLAYSTONE.
SANDSTONE, RED, COARSE.
SILTSTONE & SILTY CLAYSTONE, RED. SANDSTONE, RED.
BASALT, BLACK, MULTIPLE FLOWS, THIN INTERBEDDED SANDS.
SANDSTONE, RED-ORANGE COARSE TO CONGLOMERATE.
SILTSTONE, GRAY-BROWN, WITH GYPSUM & ANHYDRITE. INTER-BEDDED WITH SILTY CLAYSTONE.
SEVERAL THIN SILLS.
ANHYDRITIC SANDSTONE.
CLAYSTONE, GRAY-BROWN, WITH GYPSUM.
SALT AND OTHER EVAPORITE MINERALS (THENARDITE, GLAUBERITE).
SILL.
SANDY SILTSTONE TO COARSE SANDSTONE.
SHALE, GRAY.
CONGLOMERATIC SANDSTONE, ARKOSIC, RED BROWN, ANHYDRITE CEMENT.
SILTSTONE, GRAY-BROWN
TD WAS IN LOWER NEOCOMIAN RIFT-FILL SEDIMENTS. BASEMENT WAS NOT REACHED.


WEST
Seismic Line ARH 91-08
HUNT
Cd. GL x-1
EAST
Sec
0
1
2
3
A.
WEST
EAST
STRUCTURAL CROSS-SECTION
GENERAL LEVALLE BASIN
CENOZOIC
CRETACEOUS
EXPLANATION
PRECAMBRIAN
B.
E-W Seismic Line 91-08 and Cross-Section
General Levalle Basin, Argentina
91-08

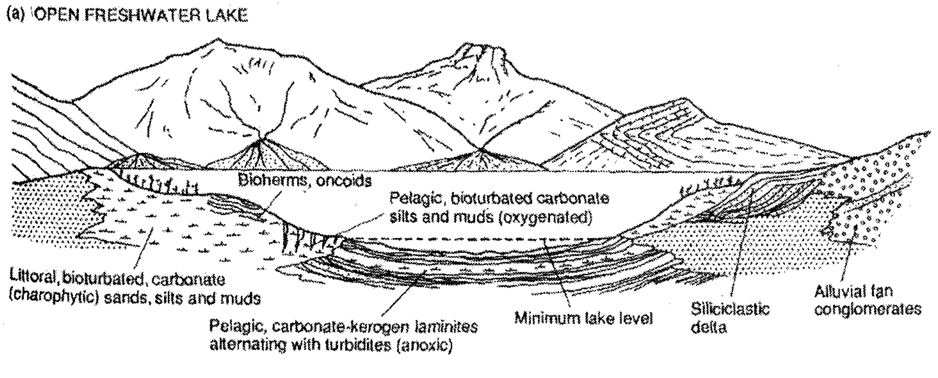
▪Opened lake

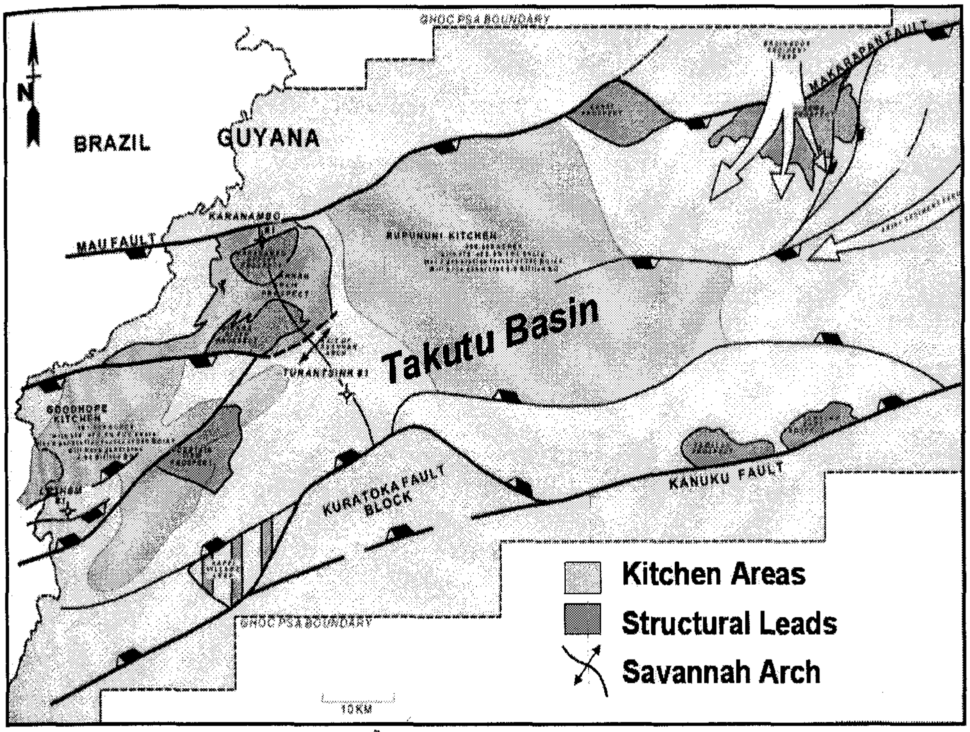
▪Tectonic: Hydrological status of opened lake may change completely over a short period of time.

▪Climate: Opened lake, often show seasonal variation in both thickness and composition of individual layers.

▪Water level: Climate fluctuation effects water level in opened lake with a smaller amplitude than in closed lake, so facies are commonly less finely interbedded.

(a) OPEN FRESHWATER LAKE



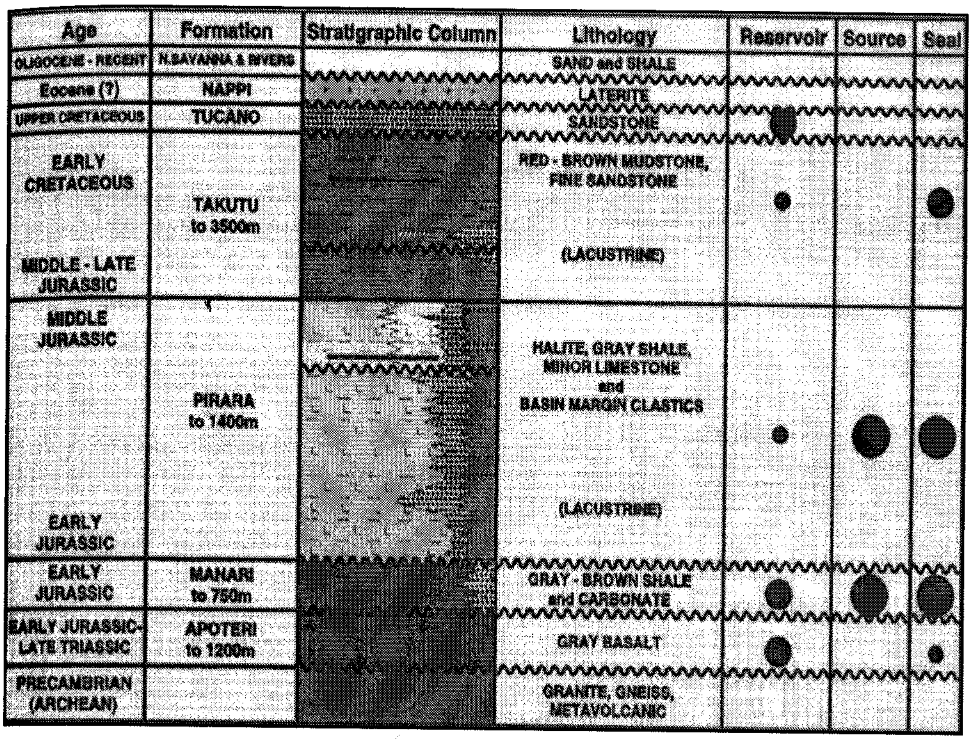


▪**Off-shore facies:**

▪Perennial fresh?:

▪Laminated layers of clastic (mud), organic and carbonate deposited below the thermocline of stratified lake.

▪Thin graded bedding of silt and mud derived from turbidity current.



▪Near-shore facies:

▪Perennial fresh?:

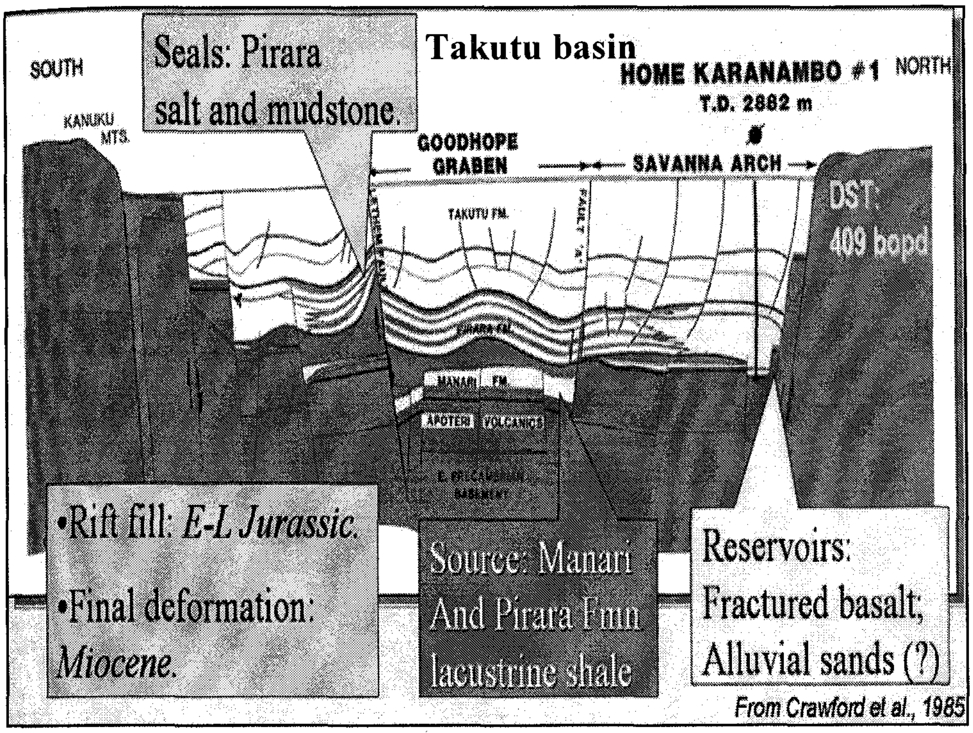
▪Sandstones deposited in beach zones (with ripple marks), channel fill or mouth bars (with cross bed).

▪Coals & silts deposited in inter-distributary bays or swamps.

▪Bioherms including stromatolites

▪Coated grain of oncoids, pisoids and ooids.

▪Chalks are in marl or throughout the littoral zone.



▪**Structure**

▪Diversity of structures: Because of the range of lacustrine facies, a corresponding diversity of sedimentary structure exists for lake deposits.

▪**Paleontology**

▪Non-marine fossils: In general non-marine fossils and lack of marine fossils together indicate the probability of lacustrine.

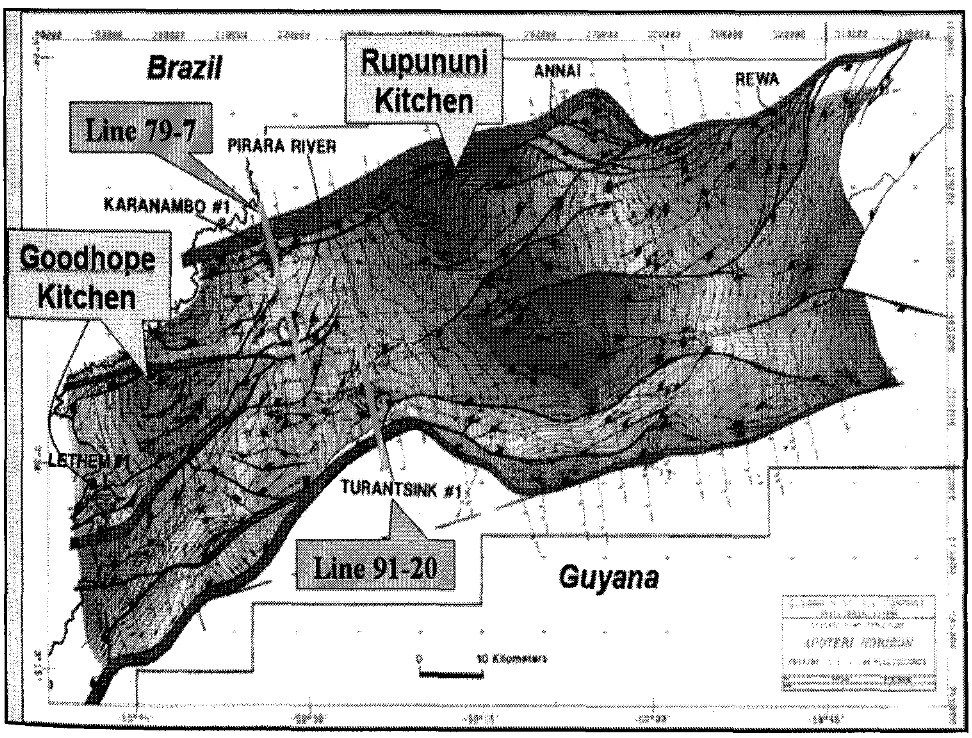
▪Common fossils: Common fossils found in lake bottom mud/ lower zone (Hypolimnian = dark, cold & anoxic) have likelihood been transported from near shore areas by turbidity currents or have settled from the upper zone (Epilimnion = light, warm & well oxigenated).

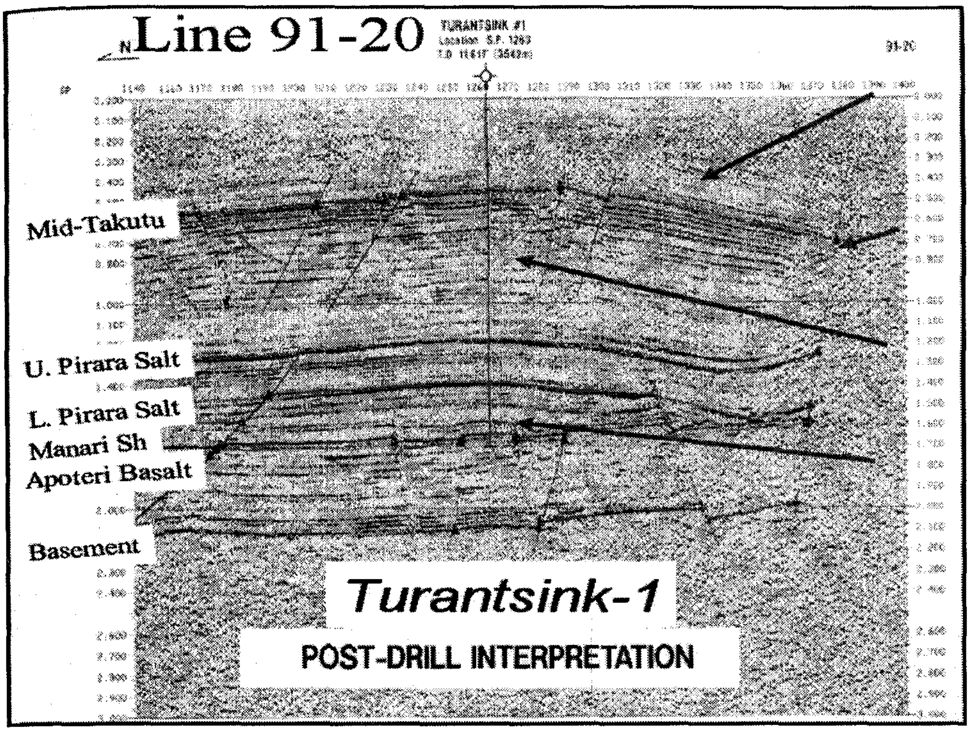
▪Common fossils:

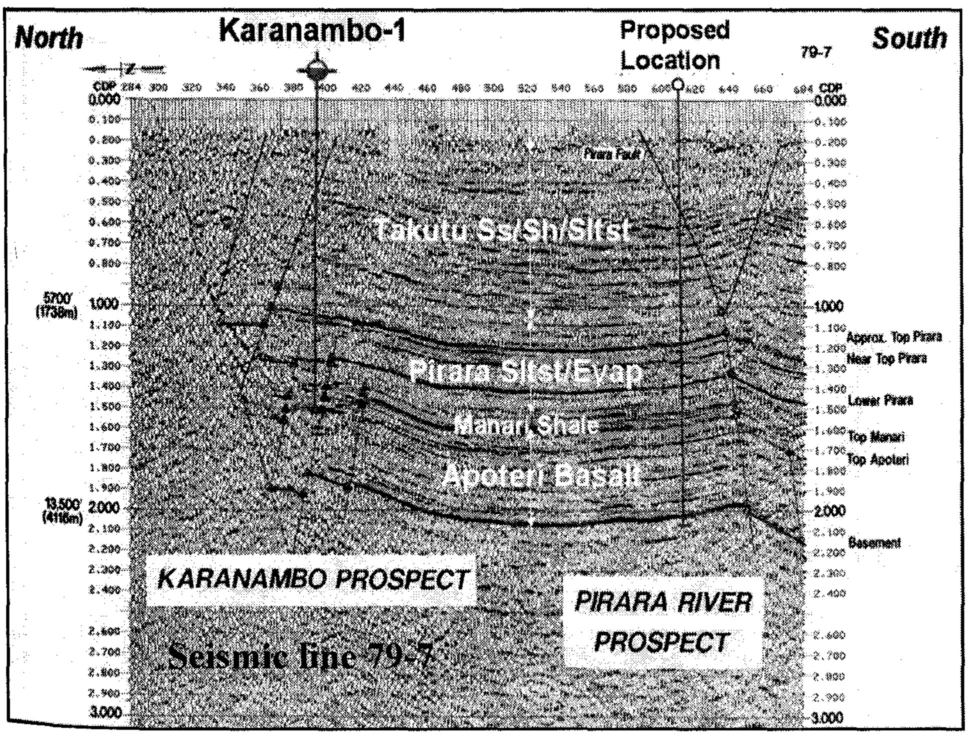
▪Central: aquatic vertebrates, planktonic/ benthic algae, mollusks and some species of ostracods.

▪Marginal: greater diversity of bivalves, gastropods, diatoms, various forms of algae, aquatic & terrestrial vertebrates, plans, spores and pollen.

- **Geometry**
- Diversity of geometry: Because of the range of lacustrine facies, a coresponding diversity of geometry exists for lake deposits.
- **Associated facies**
- Regressive sequence: As the result of regression sequence, fine-bedded basin shale/silt should be succeeded by delta, fluvial/swamp deposits in a humid environment, and evaporitic, fine grained sediment should be overlain by coarser, braided streams/ alluvial fans.




Line 91-20
TURANTSINK #1
Mid-Takutu
U. Pirara Salt
L. Pirara Salt
Manari Sh
Apoteri Basalt
Basement
Turantsink-1
POST-DRILL INTERPRETATION


North
Karanambo-1
Proposed Location
79-7
South
Takutu Ss/Sh/Slfst
Pirara Fault
Pirara Sltst/Evap
Manari Shale
Apoteri Basalt
Approx. Top Pirara
Near Top Pirara
Lower Pirara
Top Manari
Top Apoteri
Basement
5700' (1738m)
13,500' (4116m)
KARANAMBO PROSPECT
PIRARA RIVER PROSPECT
Seismic line 79-7

▪**Wire-line logs**

▪Because of the range of lacustrine facies, a coresponding diversity of wire line log exists for lake deposits.

▪**Seismic**

▪Because of the range of lacustrine facies, a coresponding diversity of seismic exists for lake deposits.

▪**Petroleum aspect**

▪Source & Reservoir:

▪In general lacustrine deposits, which have formed in humid climate, have the best chance to become petroleum source shale in lake centers and up dip stratigraphic trap at lake marginal sands.

▪Shale in lake center contain largely of algal/ type I kerogen, while lake margin contain largely of coal in swamps/ type III kerogen.

▪Lacustrine oils in general often tend to be waxy, low in sulphur, and of high gas to oil ratio.

- Stratified: Permanent lakes are usually stratified, with upper (epilimnion) & lower (hypolimnion).
- Epilimnion includes the photic zone, warm and oxygenated. Phytoplankton live here and provide the base for food chains.
- Hypolimnion is dark zone, cool and anoxic/ reducing. Organic fall out from the epilimnion settles in the lake floor mud.

MEANDERING STREAM ENVIRONMENT

Definition

▪High sinuosity: A continental environment characterized by deposits resulting from a river system of high sinuosity channels generated by a mature stream swinging from side to side across its flood plain on a gentle slope.

▪Low slope: Flood plains cut by meander streams characterized by low gradients areas, F-M grain with perennial discharge.

▪Common: They are often created/associated with deltas at their mouth.

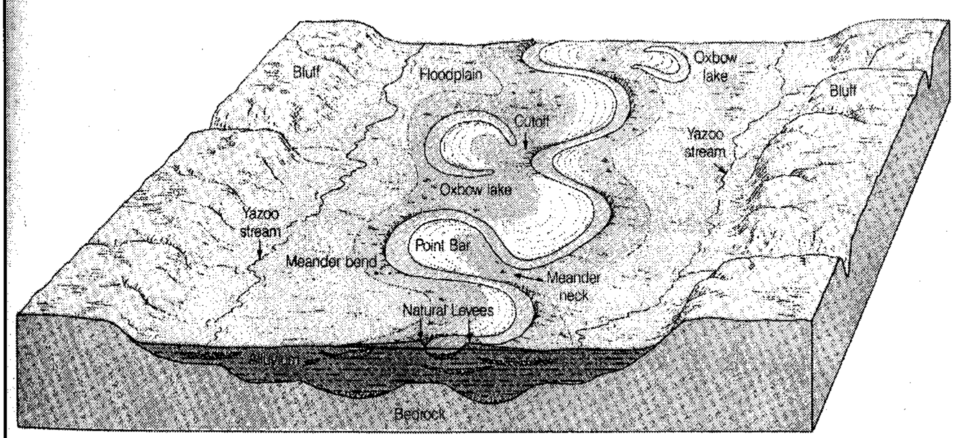
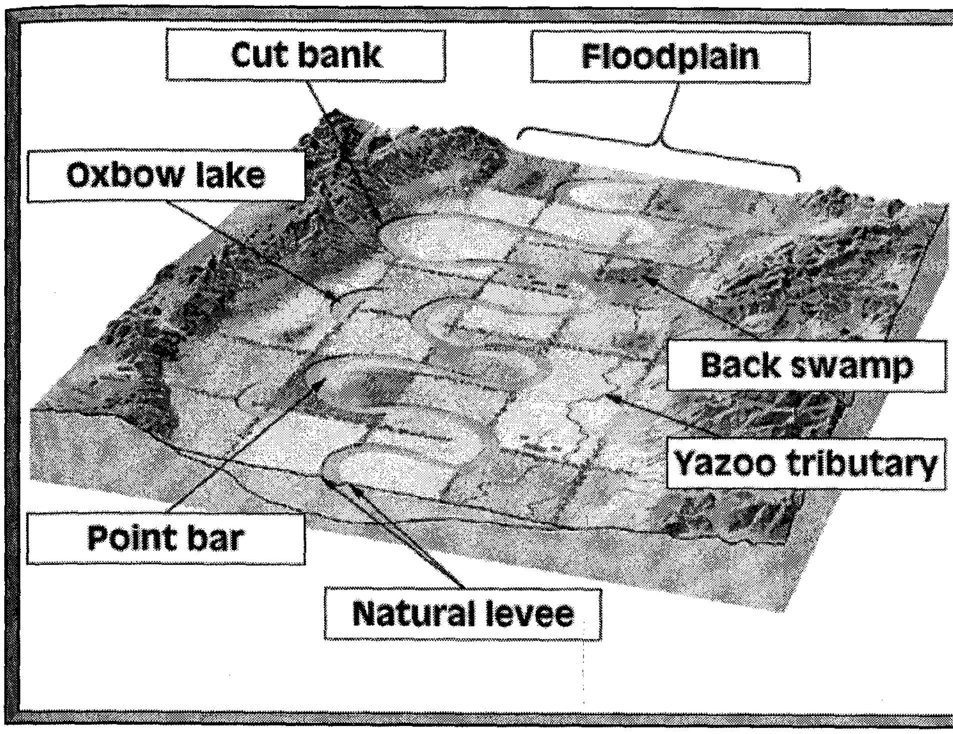


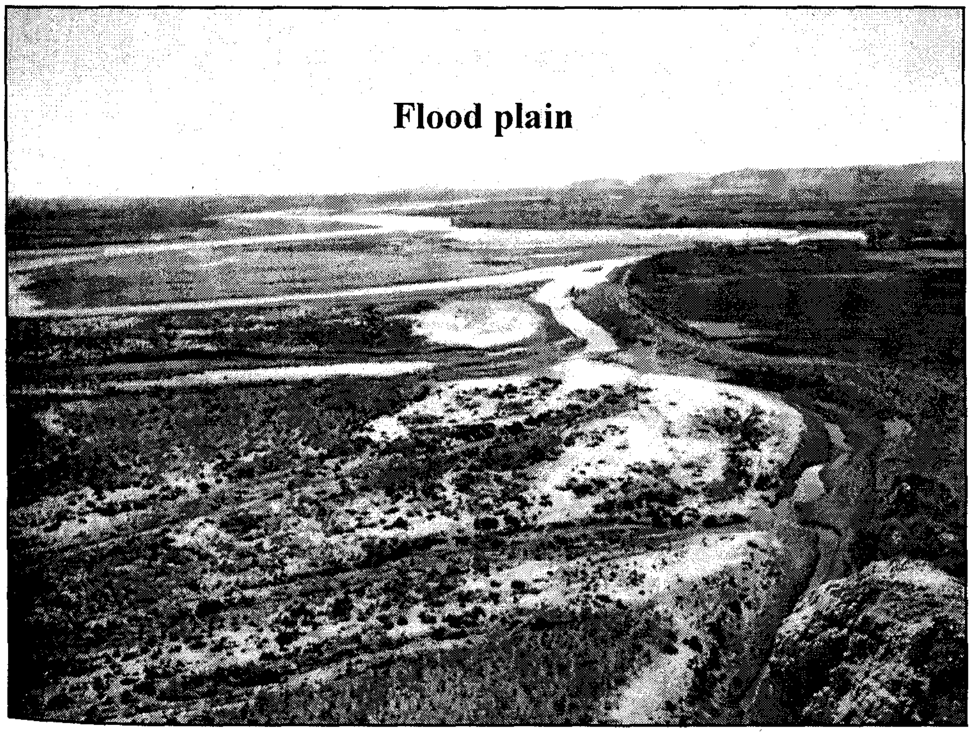
FIGURE 11.17
The major features of a floodplain include meanders, point bars, oxbow lakes, natural levees, backswamps, and yazoo streams. A stream flowing around a meander bend erodes the outside curve and deposits sediment on the inside curve to form a point bar. The meander bend migrates laterally and is ultimately cut off, to form an oxbow lake. Natural levees build up the banks of the stream, and backswamps develop on the lower surfaces of the floodplain. Yazoo streams have difficulty entering the main stream because of the high natural levees and thus flow parallel to it for considerable distances before becoming tributaries. Slope retreat continues to widen the low valley, which is partly filled with river sediment.



Lithology

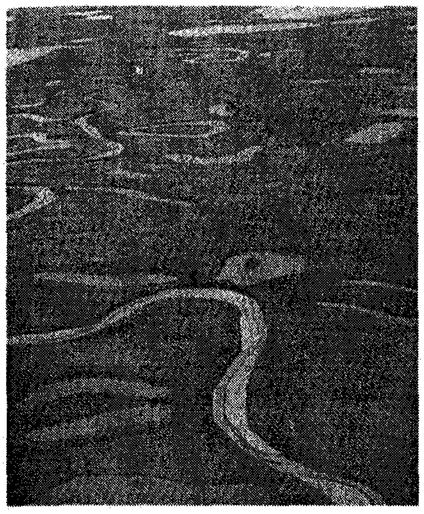
- Sand/Shale: 1
- Active channel: (migration stage?)
  - Flood plain: coal (swamp), siltstone/ shale (levee, crevasse splays)
  - Point bar: M-F sandstone, well sorted, fining up
  - Channel floor: pebble lag
- Abandoned channel: (end stage?)
  - Flood plain: coal (swamp), siltstone/ shale (levee, crevasse splays)
  - Oxbow lake: coal (oxbow lake), siltstone/ shale
  - Channel floor: pebble lag


Point bar

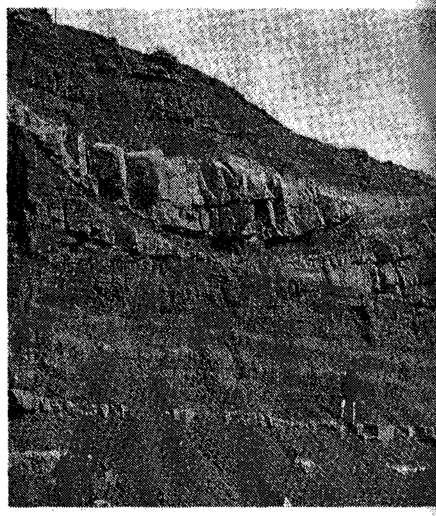

Flood plain


Channel Pebble
Close-up view of the Budleigh Salterton Pebble Bed. The pebbles are well-rounded but sometimes cracked through in situ.
A matrix of firm, speckled, coarse sand holds the bed in a vertical cliff. Reddish mud staining obscures surface details.


Oxbow lake



(A) Point-bar deposits in a modern river.



(B) Ancient stream channel in central Utah.

Figure 5.10 The fluvial environment. The great rivers of the world are the major channels by which erosional debris is transported from the continents to the oceans. Before reaching the ocean, most rivers meander across flat alluvial plains and deposit a considerable amount of sediment. Within this environment, sedimentation occurs in stream channels, on bars, and on floodplains. Perhaps the most significant type of sedimentation occurs on bars on the insides of meander bends (see Figure 12.22). Stream deposits are characterized by channels of sand or gravel cut into horizontal layers of silt and mud.

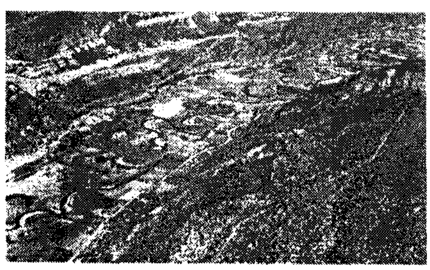


Fig. 5.5-1. Aerial photograph of meander bed and floodplain of the Animas River a few miles above Durango, Colorado (from Shelton, 1966).

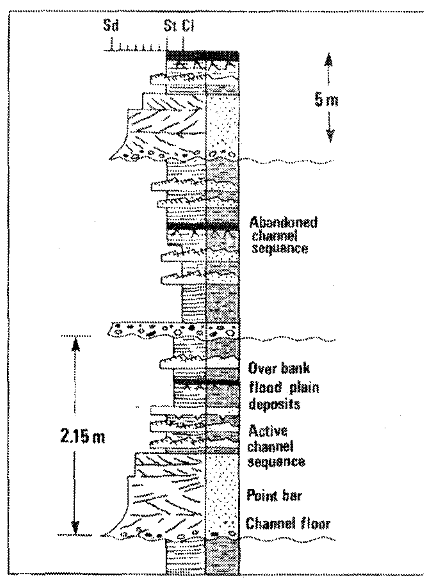


Fig. 5.5-2. Generalized section of fining-upward sequence in a meandering system in Devonian Catskill facies, U.S.A. and south Wales (from Selley, 1978).

- <u>Composition</u>
- Low-moderate immature sandstone consists of quartz, altered feldspar, and mica with range from quartz arenites to lithic arenites.
- Common: Common cement is siliceous/ calcareous. In bed-load channel, clay pebbles may come from levees slumping.
- Humid?: Glauconite is absent but coal is present as beds in flood plain and as small fragments in channel.
- Arid?: Carbonate & iron concretions may be formed in area of high evaporation rate on flood plain.

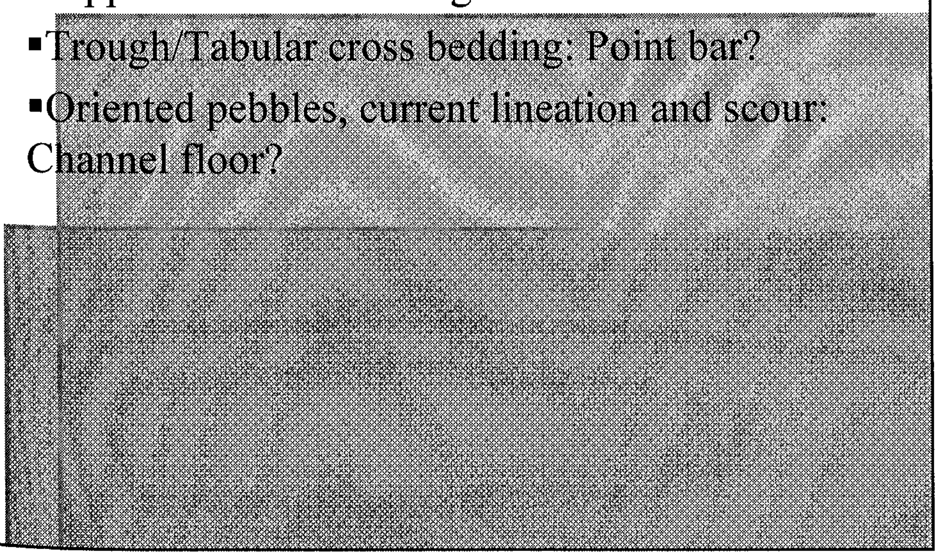
- <u>Texture</u>
- Sand-shale ratio < 1: more clay
- Channel: Fining & well sorting upward are developing in channels

Table 5.5-1. *Physical characteristics of fluvial or valley-fill model. Line weight is suggestive of abruptness of transition between units (adapted from Visher, 1965).*

	MEAN GRAIN SIZE	SORTING	GRAIN SIZE RANGE	SEDIMENTARY STRUCTURES	GEOMETRY	SEQUENCE
CHANNEL FILL	FINE	POOR-FAIR	SILT-CLAY	HORIZONTAL LAMINATION MUD CRAKS PLANTS-ROOTS	IRREGULAR (P)	
BACK SWAMP	VERY FINE	POOR	SILT-CLAY	HORIZONTAL LAMINATION PLANTS-ROOTS-COAL	IRREGULAR	
FLOOD PLAIN			SILT-CLAY	HORIZONTAL LAMINATION SLUMP STRUCTURES MUD CRAKS NEAR TOP	ARCUATE	
NATURAL LEVEE			FINE SAND-SILT	SMALL SCALE X-BEDS HORIZONTAL LAMINATED	WEDGE SHAPED (P)	
RIPPLE X-BED ZONE			FINE SAND-SILT	CLIMBING RIPPLES RIPPLE X-BEDDING	WIDTH TO 30 MI	
LAMINATED ZONE			SAND-SILT	HORIZONTAL BEDDING OR LAMINATION	WIDTH TO 30 MI	
MEGA-RIPPLE ZONE		VERY GOOD	SAND	FESTOON OR PLANAR X-BEDDING	WIDTH TO 30 MI	
BEDLOAD ZONE	COARSE	POOR-GOOD	CLAY CHIPS PEBBLES COARSE SAND	POORLY BEDDED	WIDTH TO 30 MI	

Structure

- Surface exposure features: Flood plain?
- Ripple & Planar bedding: Chute bar?
- Trough/Tabular cross bedding: Point bar?
- Oriented pebbles, current lineation and scour: Channel floor?



Structure

▪Channel floor:

▪Channel floor commonly has scour, oriented pebbles and current lineation. The oriented pebbles are only moved at maximum flood velocities.

▪Bar:

▪During average discharges sand is moved in dunes on the channel floor (large trough?) and in ripples higher on the point bar (ripple?).

▪Sand bars are normally restricted to the main channel with its point bars/ chute bars (tabular/ small trough?).

▪Flood plain:

▪Flood plain & natural levees accumulate fine grained sediments after floods. (ripples, planar bed and surface exposure?).

▪These are represent by the action of plants and animals in humid climate and by calcretes in semi arid climate.

▪The sequence:

▪Starts with an erosion troughs, followed by cross bed which are related to point bar or chute bar with small trough sets.

▪Flood plain shows horizontal or convolute bed and may be bioturbation and rootlet.

▪Fore set:

▪Fore set in point bar is dipping to the channel axis or *thalweg*. These are termed *epsilon* cross beds.

▪Meander loops can be abandoned either

▪(1) by chute cut off causing gradual abandonment and the deposition of thick ripple cross laminated sands or

▪(2) by neck cut off causing sudden abandonment and deposition of muddy sediments by vertical succession over the channel deposits.

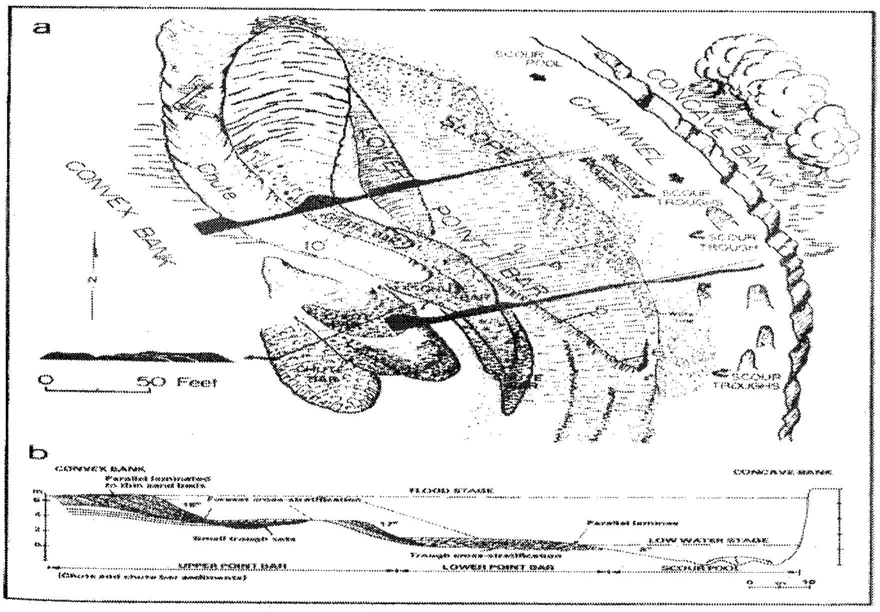


Fig. 5.5-3. Topographic features and internal structure of a coarse-grained point bar. (a) Plan, (b) cross-section (after McGowen & Garner, 1970).

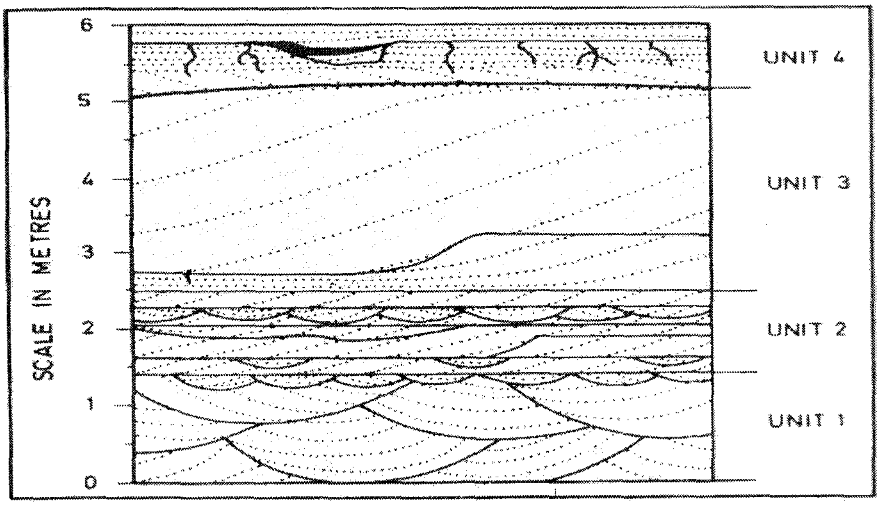


Fig. 5.5-4. Vertical sequence of coarse-grained point bar deposits, showing various bedding features. Four units can are distinguished: Unit 1 - scour pool deposit; unit 2 - lower point bar deposit; unit 3 - chute bar deposit; unit 4 - flood plain deposit (from McGowen & Garner, 1970).

Paleontology

▪Diversity: vertebrates, plant remains, non-marine mollusks, gastropod shells, abundant spores, pollen,

▪Swamp: coal

▪Surface exposure: rootlet, burrows, footprints, rain drop impressions and desiccation cracks.

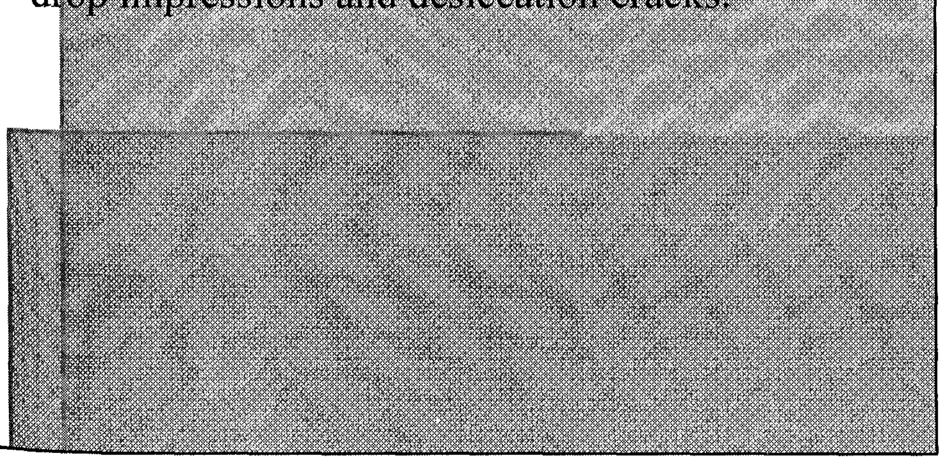
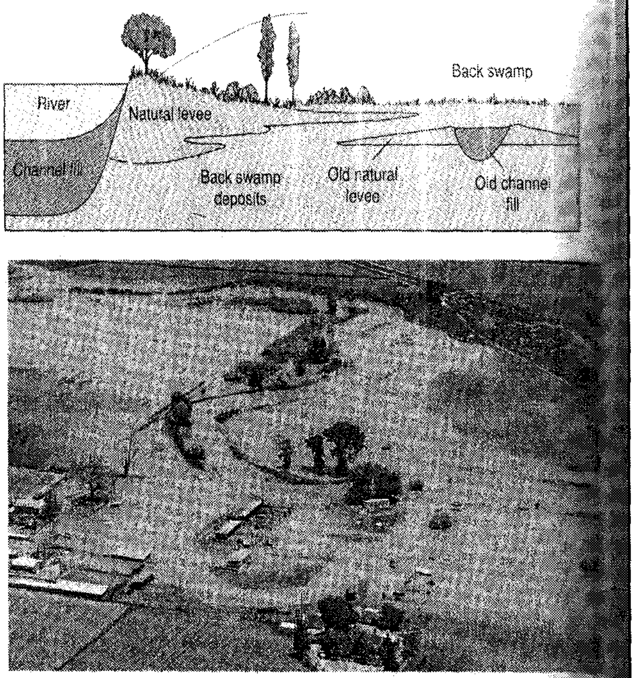


Figure 12.23 Natural levees are wedge-shaped deposits of fine sand, silt, and mud that taper away from the stream banks toward the backswamp (Top right). They form during flood stages because, as the stream overflows its banks, the velocity of the water is reduced and silt is deposited (Bottom right). As the levees grow higher, the stream channel also rises, and thus the river can be higher than the surrounding floodplain. *(Courtesy of Michael Collier)*



Geometry

- Channels:
- Continuous/ discontinuous shoestrings bodies are long & narrow or tabular geometry.
- Point bars:
- Isolated lenticular, stacked/ sheets point bars should be elongated in the longitudinal direction and lateral migration in the transverse direction.
- Lateral migration will be determined by climate, slope and sediment supply.
- Meander belts = 2 * average meander amplitude
- Point bar width > 10 * channel width or > 200 * thickness (water depth of the channel during flood)

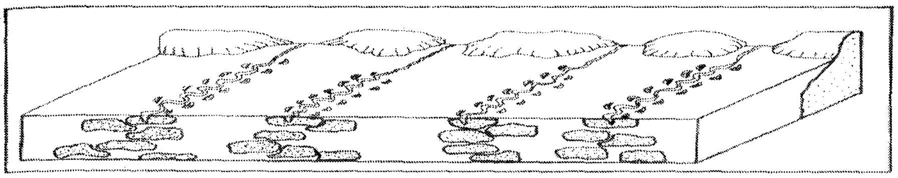
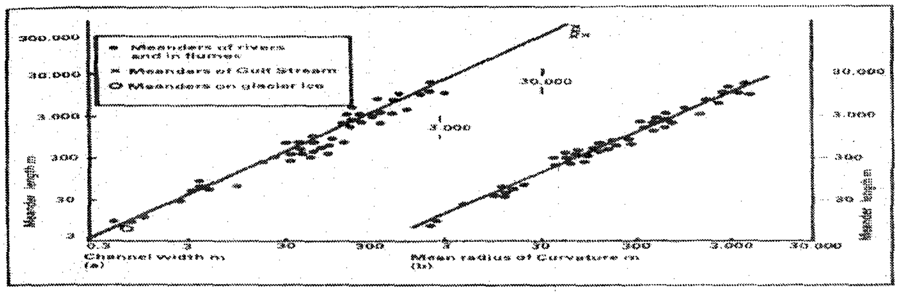


Fig. 5.5-6. Conceptual models of fluvial channel geometry (adapted from Allen, 1965, by Visher, 1977).

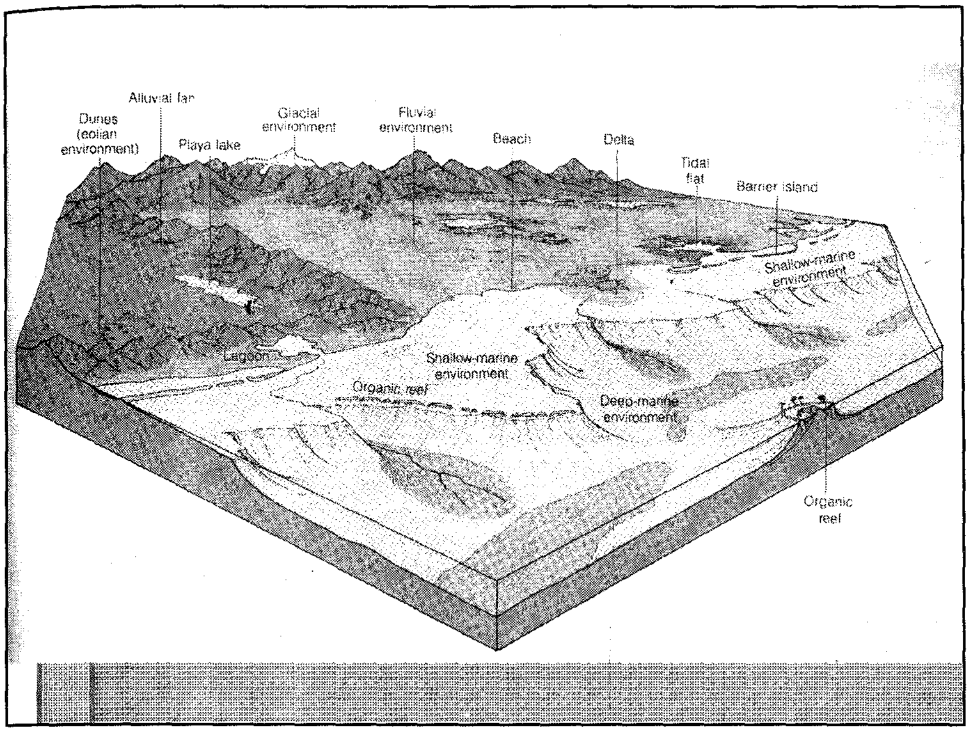
Length of the meander increases with the widening meandering stream and the mean radius of curvature of the meander (Fig. 5.5-7).

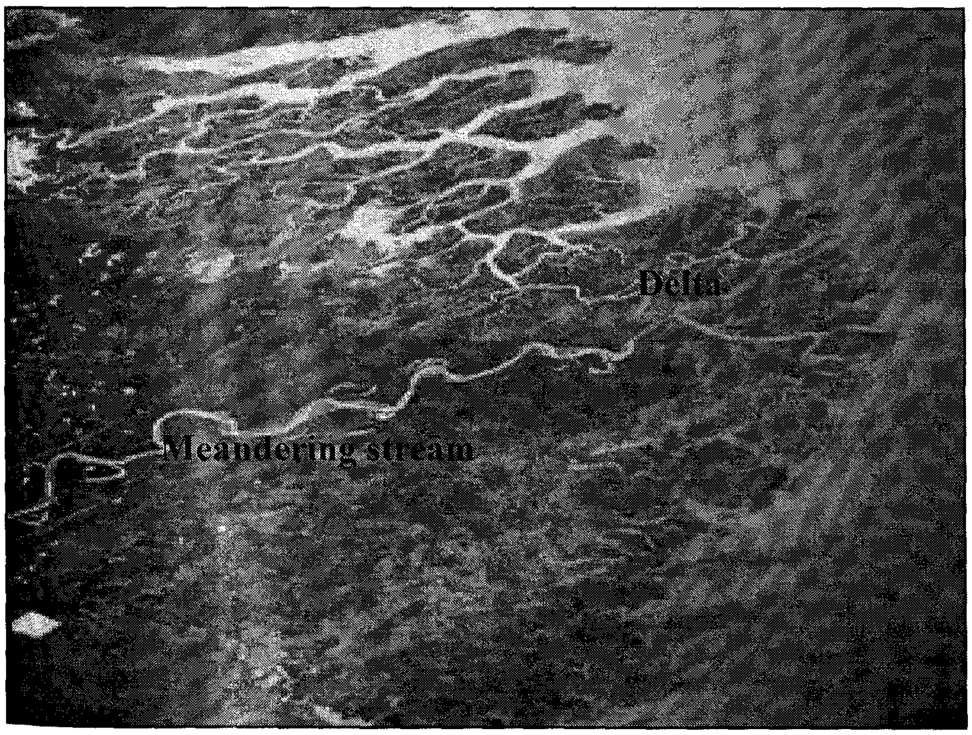


Fg. 5.5-7. Relationship between meander length and (a) channel width, (b) mean radius of curvature (from Leopold & Wolman, 1960, in Leet et al., 1978).

Associated facies

- Most common:
  - Land-ward into lacustrine/braided (shallower)
  - Marine-ward into delta/shore-line (deeper)
- Boundaries: abrupt, sharp, erosion lower and lateral contacts are observed, they are gradation toward the top.
- Sequences: fining up, starts with channel (lateral) and topped by flood plain (vertical).


Alluvial fan
Dunes
(eolian
environment)
Playa lake
Glacial
environment
Fluvial
environment
Beach
Delta
Tidal
flat
Barrier island
Shallow-marine
environment
Lagoon
Shallow-marine
environment
Organic reef
Deep-marine
environment
Organic
reef


Delta
Meandering stream

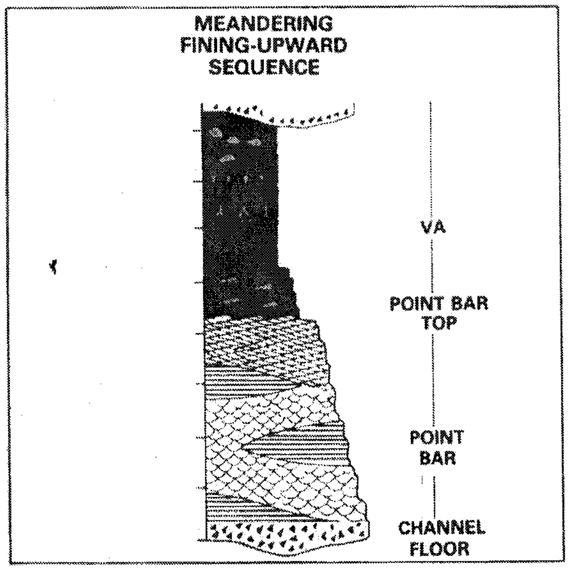


Fig. 5.5-5. Theoretical sequence of facies in a meandering system. VA = vertical accretion (from Allen, 1970).

- *Lateral succession*: Channel floor & Bar
- Lag deposits cover erosion surface and are capped by trough cross bedding (sand), which is overlain by small scale, trough cross lamination (silt).
- Several lamination can occur with in this sequence

▪ *Vertical succession*: Flood plain

▪ After the lateral succession, it is continues with vertical succession (silt/mud) indicating flood stage.

▪ Root trace and desiccation crack can be observed.

▪ In humid region vegetation may grow sufficiently to form coal seam.

▪ In arid region the fluctuation water table & drying at the surface may form caliche-like concretion.

Core

▪ Reservoir continuity:

▪ Sand/Shale (Sand = point bar; Shale = flood plain)

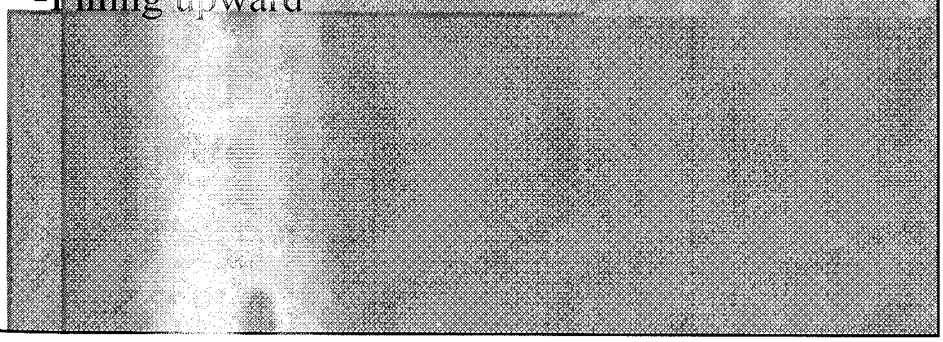
▪ Equal chance: Sand/Shale = 1

▪ Connected channels: Sand/Shale > 1

▪ Unconnected channels: Sand/Shale < 1

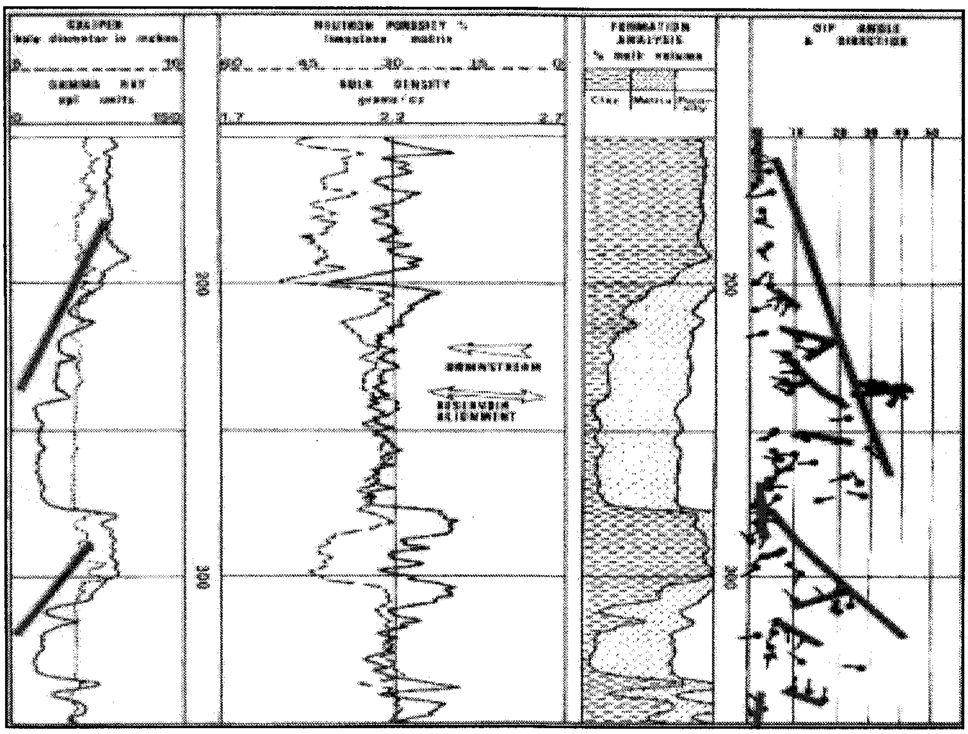
▪ Point bar sands:

▪ Fining upward



Wire line log

- Bell shape: Usually, point bars (sand) are surrounded by over-bank flood plain (shale). GR/SP shows abrupt change from shale to sand at the bottom channel and fining up bell shape curve as point bar sand grades into flood plain at the top channel.
- Dipmeter pattern (fig.13,15)
  - Random/None: trough cross bedding (channel)
  - Red & Blue: same azimuth (chute bar on point bar)
  - Red & Blue: 90* difference azimuth (point bar)
  - Green: regional slope (flood plain)



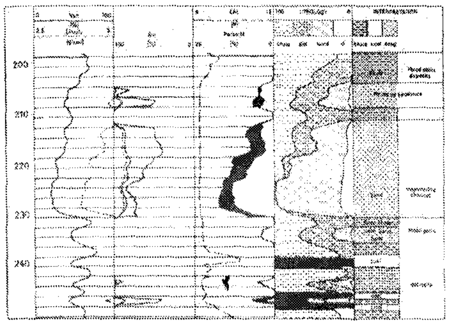
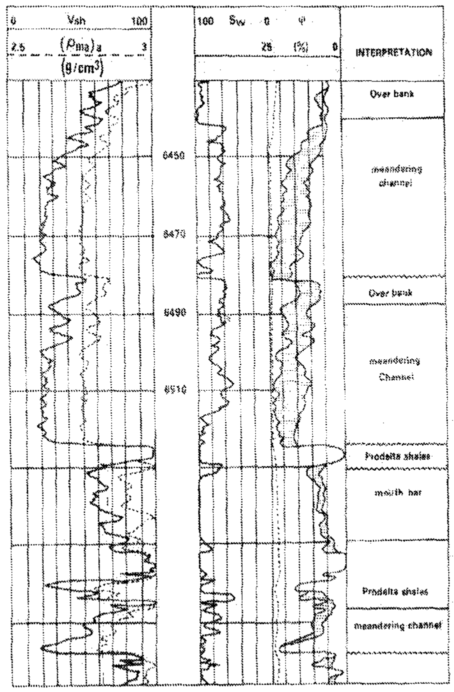


Fig. 5.5-12. One meandering channel as illustrated by a SARABAND result display.

Fig. 5.5-14. Three meandering channels as they can be recognized from a SARABAND result display. ▶

Fig. 5.5-13. GEODIP display on the same interval shown in Fig. 5.5-12, and its interpretation in terms of facies.



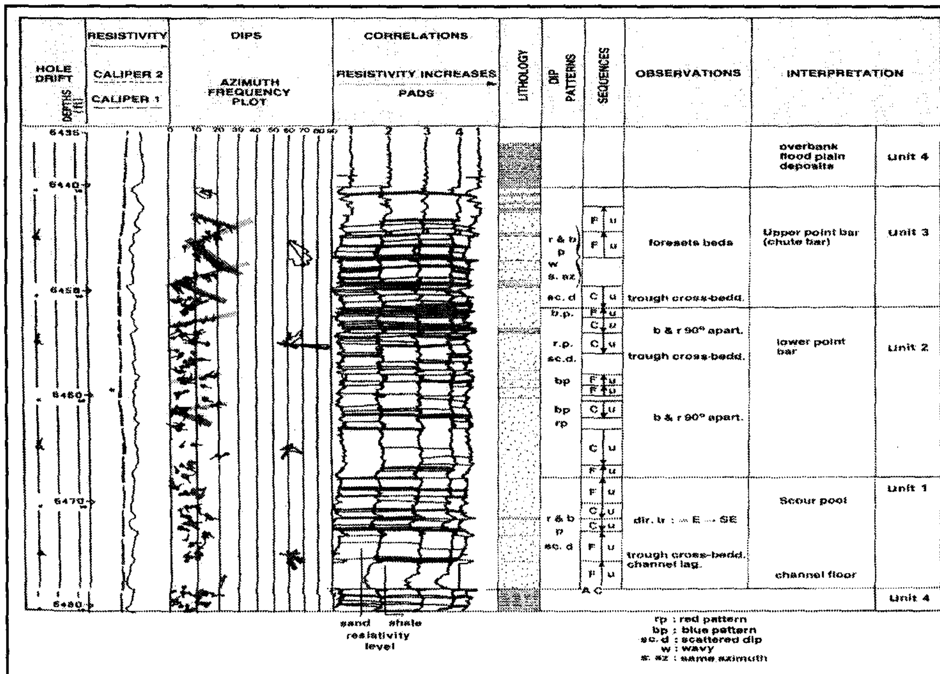


Fig. 5.5-15. GEODIP display on the upper meandering channel shown in Fig. 5.5-14, and its interpretation in terms of facies.

▪Paleo-current: Current direction will change as much 180*-270* between locations. Therefore limited predictions can be made on one well dipmeter.

▪Isopach maps combined with paleo-current data are often usẽd in predictions.

▪It is sometimes useful to outline the general location of valley and plain which the channel cut.

▪Sub-environments are represented in fig.9-11

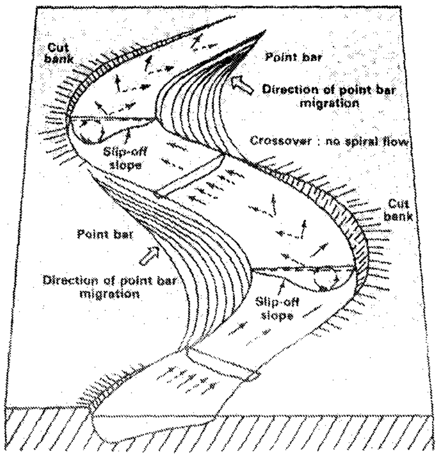


Fig. 5.5-8. Downstream schematic block diagram of two meander bends and intervening crossover. Solid arrows indicate direction of surface current; dashed arrows indicate bottom current along; circular arrows with one barb, direction of spiral flow in plane of shaded transverse sections (from Friedman & Sanders, 1978, based on Friedkin, 1945).

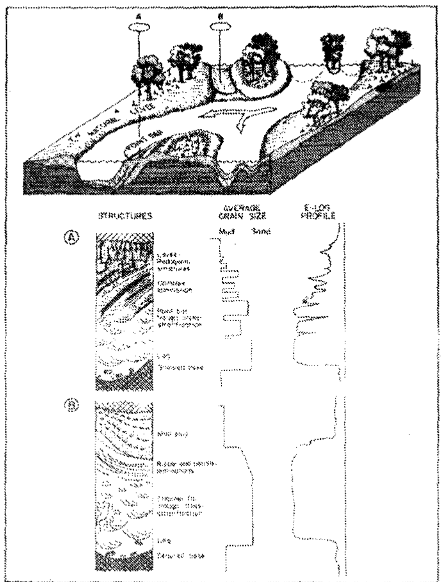


Fig. 5.5-9. Generalized depositional model, representative vertical sequences, and idealized S.P. log profiles through laterally accreting (A) and symmetrically-filling channel segments (B) of an anastomosed channel system (from Galloway & Hobday, 1983).

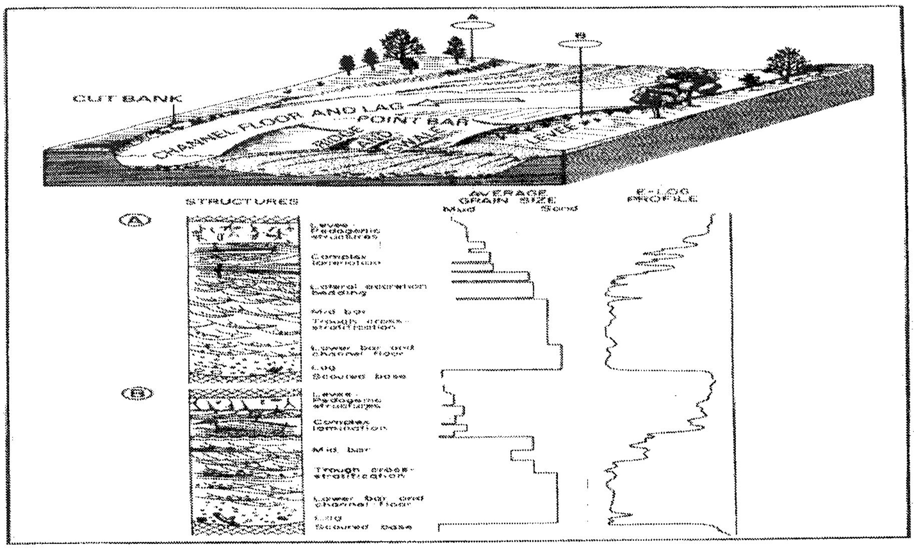


Fig. 5.5-10. Generalized depositional model, representative vertical sequences, and idealized S.P. log profiles of a meanderbelt sand body produced by a high-sinuosity channel. Sequence (A) illustrates a complete fining-upward sequence typical of the mid- or downstream point bar. Section (B) illustrates the truncated vertical sequence commonly found in the upstream end of the bar (from Galloway & Hobday, 1983).

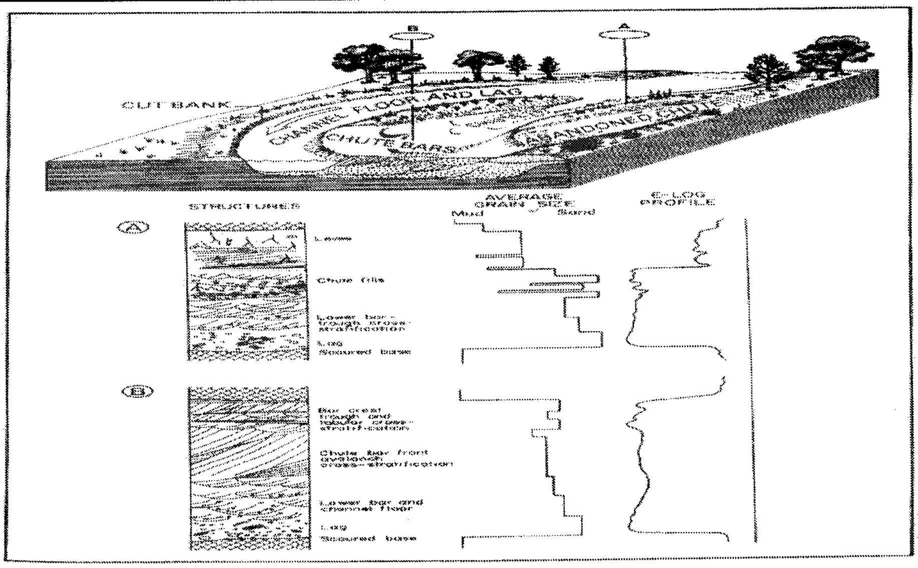
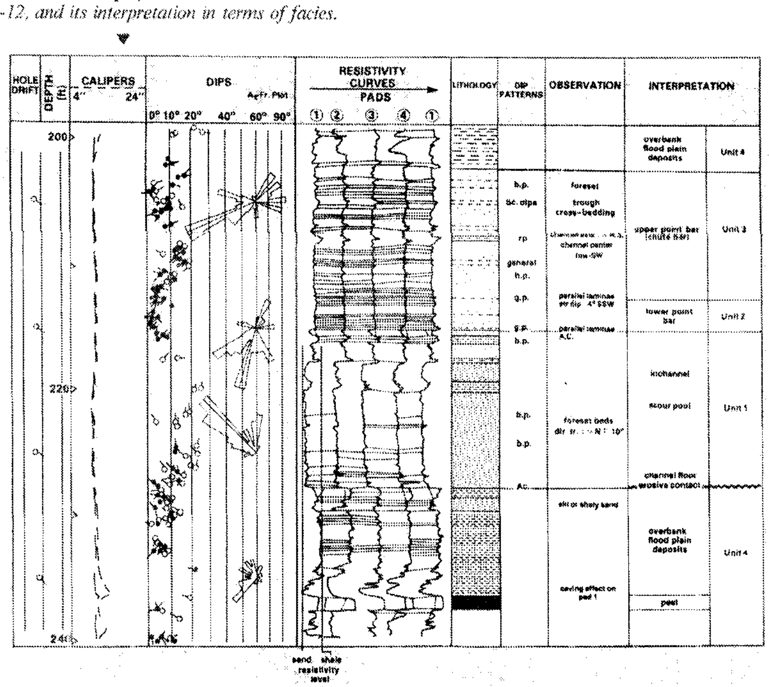


Fig. 5.5-11. Generalized depositional model, representative vertical sequences, and idealized S.P. log profiles of a chute-modified point bar. Upstream portions of the point bar are capped by chute-channel deposits (A). Downstream, the channel and lower point bar deposits are capped by chute-bar sediments (B) (from Galloway & Hobday, 1983).

- Spectrum GR: radioactivity depends on chemical immaturity fsp & mica
  - K: < 1% = mature
  - Th/K: > 10 = mature
  - U: low in oxidizing condition but high in organic flood plain
- FDC-CNL points fall between sand & shale only few points may indicate carbonate (caliche-like).
- Pe generally does not exceed 3, unless heavy minerals (limonite, pyrite) are abundant.
- Coal beds are well identified by log responds.

Fig. 5.5-13. GEODIP display on the same interval shown in Fig. 5.5-12, and its interpretation in terms of facies.



Petroleum aspect

- Trap: Petroleum fields are small localized stratigraphic or combination because of:
- High shale content & small size of point bars
- Lateral fluid flow is limited by
  - Surrounding flood plain shale
  - Local abandoned channel clay plugs
- In subsidence region: It has built complexes of well sealed channel sand that possess moderated to excellent quality reservoir properties.

Seismic

- Channel base: In the subsurface, the lower part channel generally create erosion surface and filled up with abrupt changes in lithology, makes good velocity contrast while the upper part channel grades fining up into flood plain shows poor velocity contrast
- As the result: Most channels show lens shape in 2D and meandering stream in 3D.

DELTA ENVIRONMENT

Definition

- Transition: A transition environment characterized by sediments that have been transported to the end of a channel by a current of continental water and deposited mostly sub-aqueous but partly sub-aerial at the margin of the standing water into lake, sea or ocean.
- Geomorphology of delta is depend on the interplay between river factors (sediment load, climate) and basin factors (wave, tide).
  - Where basin energy is low = River dominate
  - Where basin energy is strong = Marine dominate

- River dominate:
- Distributary channel can be build out into the sea without coastal erosion. However, distributary mouth bars sand may be reworked into barrier island bars by marine processes.
- Surround these channels are fine grained bay fill, often containing coarsening up of crevasse sand.

- Marine (wave, tidal) dominate:
- Winnowing of fine grained material by waves, currents, and tidal current creates a variety of channel sand deposits over the entire delta plain (or along the shoreline), in the form of barrier island bars, tidal channels, and tidal sand sheets.
  - Wave dominate: Sediment delivered to the sea is deposited into curved ridges at the delta front and prograde slowly due to the destructive nature of waves. Sand trends are generally parallel to shore and some is redistributed along the shore as beaches, spits.
  - Tidal dominate: Effective tidal channels cut deep into the coastline with associated tidal sand ridges or shoals elongated in the same direction of tidal flow.

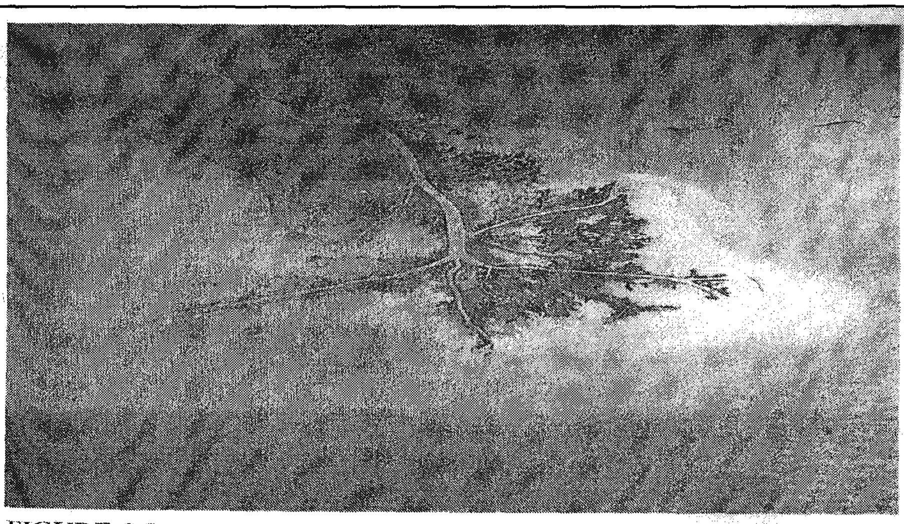


FIGURE 3.3
The Mississippi Delta, like deltas of other major rivers, is a record of erosion due to the hydrologic system. Sediment eroded from the land is transported by a river system and deposited in the sea. The dynamics of delta building are displayed vividly in this photograph. The cloud of mud and silt delivered to the ocean colors the water a lighter tone around the mouth of the river. This material is deposited as banks of mud, sand, and clay over the continental shelf as the delta grows seaward at a rate of nearly 20 km per 100 years. Measurements indicate that the Mississippi River pours more than a million metric tons of sediment into the Gulf of Mexico each day. In the process of deltaic growth, the river builds up a projection of new land into the ocean. Eventually, the river finds a shorter route to the ocean and abandons its active distributary channel for the shorter course. The abandoned distributary ceases to grow and is eroded back by wave action. Abandoned river channels and inactive subdeltas can be seen clearly on each side of the present river. *(Courtesy of National Space Data Center, NASA.)*

Fig. 5.6-1. Aerial photograph of the modern Mississippi river delta (Photo from NASA, extracted from Friedman & Sanders, 1978).

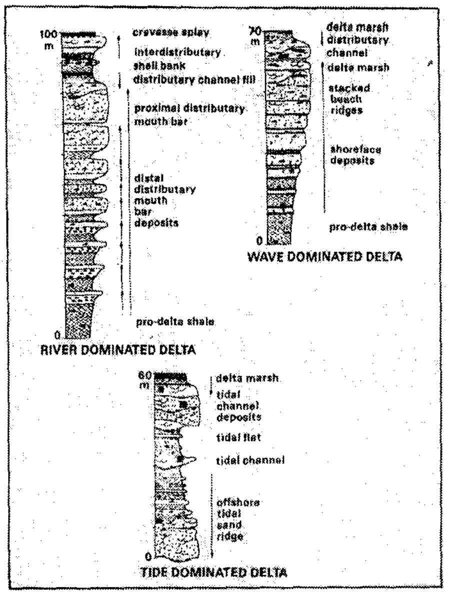


Fig. 5.6-2. Theoretical vertical cross-sections in the three types of deltas (from Walker, 1979).

Sub-environment

▪**Delta plain**

▪It is sub-aerial, which comprises active and abandoned channels separated by shallow water.

▪*Upper delta plain (high energy)*

▪Distributary channel (braided/ meandering), levee, point bar, and lacustrine (inter-distributary flood plain)

▪*Lower delta plain (low energy)*

▪Inter-distributary bay, levee, marsh, crevasse splay and abandoned channels. Distributary mouth bar may be reworked into barrier islands

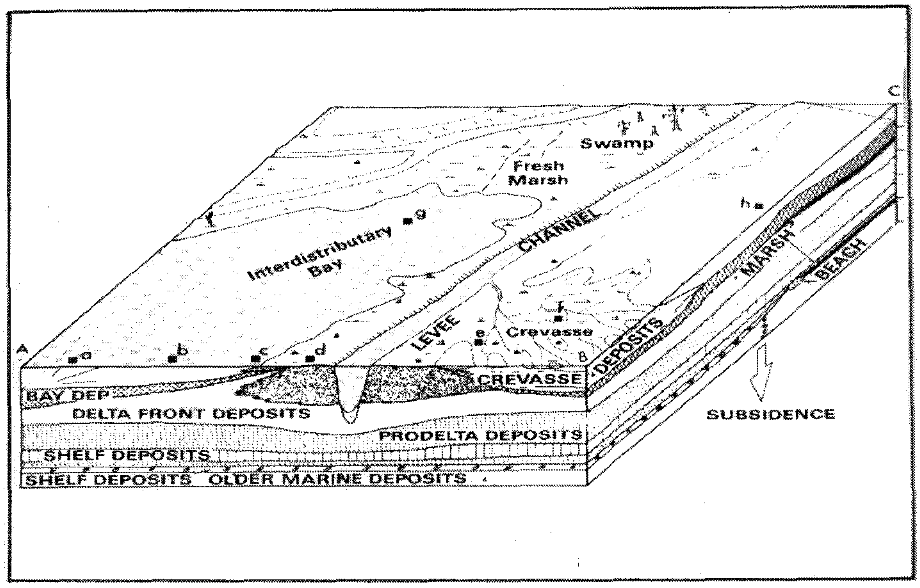


Fig. 5.6-7. Blockdiagram showing subenvironments and facies relationship of a river-dominated elongate delta (from Coleman & Prior, 1980).

▪**Delta front**

▪Delta front is high-energy area where the sediments are constantly reworked by tidal currents, long-shore currents, and wave action.

▪It is includes delta front sheet sands, distributary mouth bar, tidal range and shoreline.

▪It is represented by a coarsening up sequence, from fine grained pro-delta into coarser grained shoreline facies. On the top of delta front may be truncated by distributary channel.

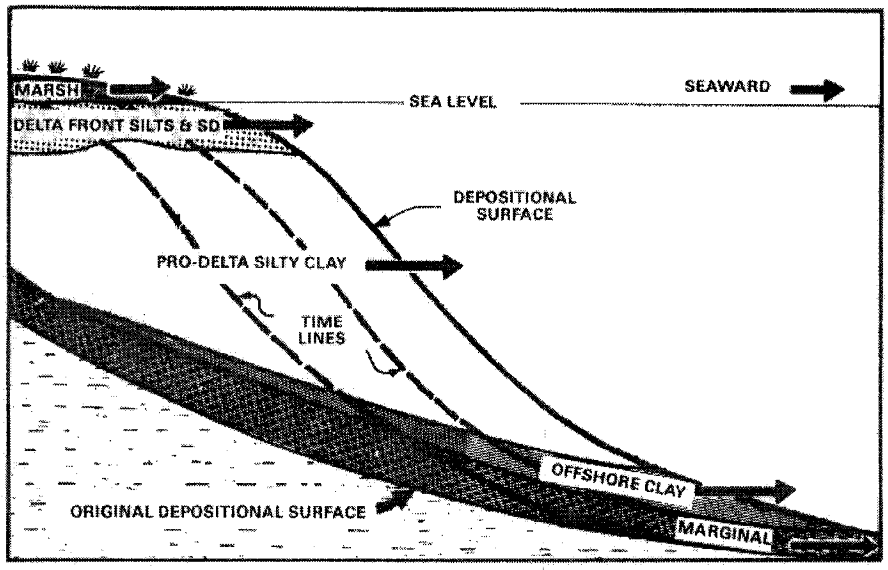


Fig. 5.6-11. The "constructional" phase of the delta cycle (from Scruton, 1960).

▪**Pro-delta**

▪Pro-delta is lying between delta front and marine shelf below the effective of wave erosion, which slope gently down to basin floor.

Classification

- The distribution, orientation and internal geometry of deltaic deposits are controlled by a variety of factors.
  - Sediment load, Climate (river factor)
  - Coastal process, Relative SL change (basin factor)
- To accommodate this factors, the deltas will be classified into three types.
  - River dominated delta
  - Wave dominated delta
  - Tidal dominated delta

Table 5.6-1. *Factors influencing deltaic sedimentation (from Morgan, 1970).*

RIVER REGIME (Variations influence sediment load and transport capacity)	Flood stage	Sediment load	Quantity of suspended load and bed load (that is, stream capacity) increases during flood
		Particle size	Particle size of suspended load and bed load (that is, stream competence) increases during flood
	Low river stage	Sediment load	Stream capacity diminishes during low river stage
		Particle size	Stream competence diminishes during low river stage
COASTAL PROCESSES	Wave Energy		High wave energy with resulting turbulence and currents erode, rework, and winnow deltaic sediments
	Tidal range		High tidal range distributes wave energy across an extended littoral zone and creates tidal currents
	Current strength		Strong littoral currents, generated by waves and tides, transport sediment alongshore, offshore, and inshore
STRUCTURAL BEHAVIOR (With respect to sea level datum)	Stable area		Rigid basement precludes delta subsidence and forces deltaic plain to build upward as it progrades
	Subsiding area		Subsidence through structural downwarping coupled with sediment compaction allows delta to construct overlapping sedimentary lobes as it progrades
	Elevating area		Uplift of land (or lowering of sea level) causes river distributaries to cut downward and rework their sedimentary deposits
CLIMATIC FACTORS	Wet area	Hot or warm	High temperature and humidity yield dense vegetative cover, which aids in trapping sediment transported by fluvial or tidal currents
		Cool or cold	Seasonal character of vegetative growth is less effective in sediment trapping; cool winter temperature allows seasonal accumulation of plant debris to form delta plain peats
	Dry area	Hot or warm	Sparse vegetative cover plays minor role in sediment trapping and allows significant aeolian processes in deltaic plain
		Cool or cold	Sparse vegetative cover plays minor role in sediment trappings; winter ice interrupts fluvial processes; seasonal thaws and aeolian processes influence sediment transportation and deposition

Table 5.6-2. *Characteristics of deltaic depositional sequences (from Galloway, 1975).*

	RIVER DOMINATED	WAVE DOMINATED	TIDE DOMINATED
GEOMETRY	ELONGATE TO LOBATE	ARCUATE	ESTUARINE TO IRREGULAR
CHANNEL TYPE	STRAIGHT TO SINUOUS DISTRIBUTARIES	MEANDERING DISTRIBUTARIES	FLARING STRAIGHT TO SINUOUS DISTRIBUTARIES
BULK COMPOSITION	MUDDY TO MIXED	SANDY	VARIABLE
FRAMEWORK FACIES	DISTRIBUTARY MOUTH BAR AND CHANNEL FILL SANDS, DELTA MARGIN SAND SHEET	COASTAL BARRIER AND BEACH RIDGE SANDS	ESTUARY FILL AND TIDAL SAND RIDGES
FRAMEWORK ORIENTATION	PARALLELS DEPOSITIONAL SLOPE	PARALLELS DEPOSITIONAL SLOPE	PARALLELS DEPOSITIONAL SLOPE

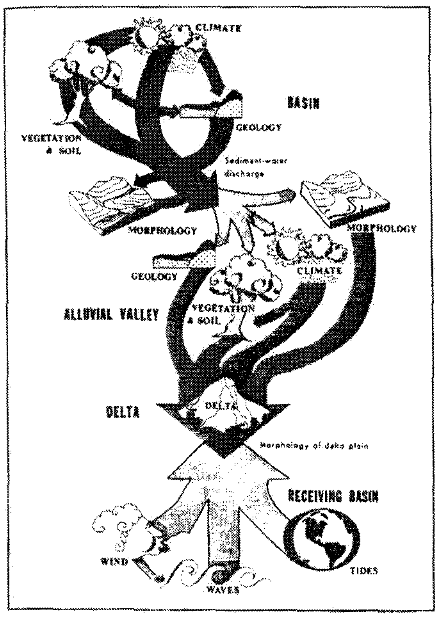


Fig. 5.6-4. Major process controls on river systems (from Coleman & Prior, 1980).

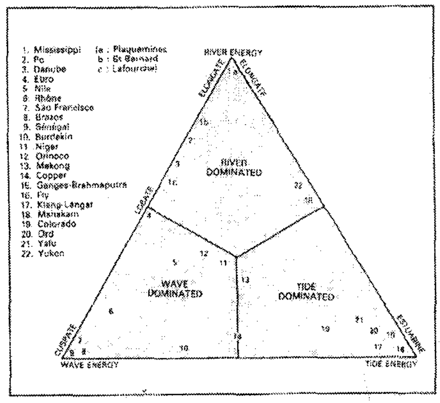
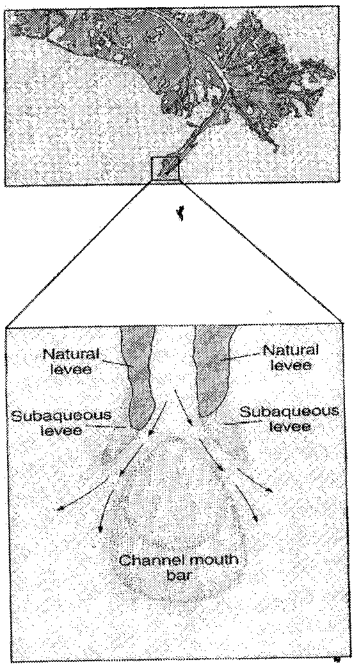


Fig. 5.6-5. Triangular classification of deltaic depositional sequences (completed from Galloway, 1975).

- **Lithology**
- Channel sands
- F to M sand
- Moderate to well sorted
- Fining up
- Mouth bar sands
- Proximal: Clean, well sorted, C to F sand
- Distal: Coarsening up of clay, silt, F sand
- Fan delta
- Fan plain: Poor sorted, C sand & gravel often highly arkosic
- Distal: Well sorted, Coarsening up of marine limestone/pro-delta shale, sand & gravel



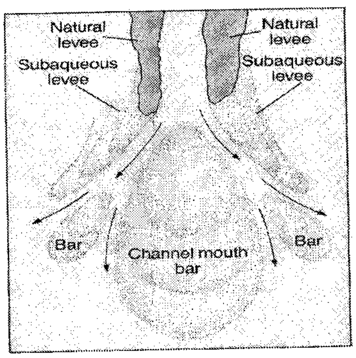
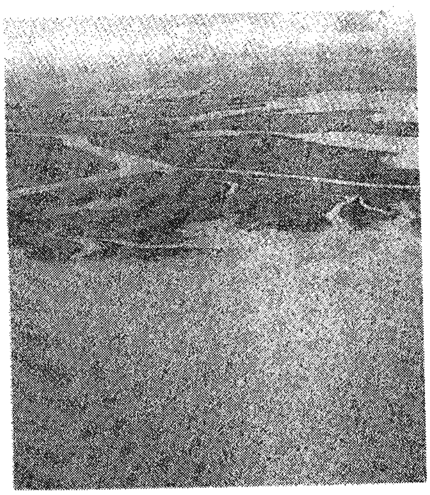
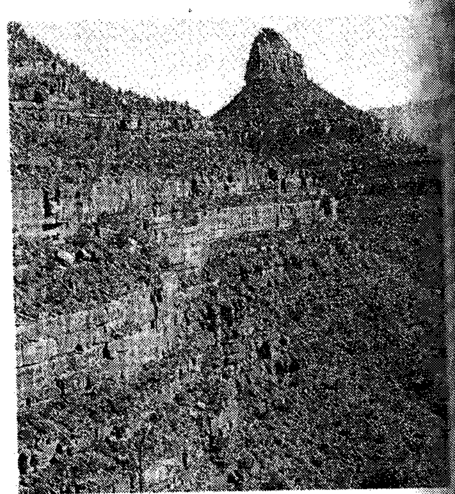


FIGURE 11.22
Distributaries develop where a stream enters a lake or the sea. A bar forms at the mouth of a river channel where water that was previously confined to the channel loses velocity, resulting in deposition as the stream enters the ocean. Subaqueous natural levees also form below water level. The bar then diverts the water coming from the main stream into two distributary channels, which grow seaward. This process is repeated, forming branching distributaries.



(A) A small delta formed in the Great Bear Lake, Canada.



(B) Ancient deltaic deposits in Tertiary rocks of the Colorado Plateau.

Figure 5.14 The delta environment. One of the most significant environments of sedimentation occurs where the major rivers of the world enter the oceans and deposit most of their sediment in marine deltas. A delta environment can be very large, covering areas of more than 36,000 km^2. Commonly, deltas are very complex and involve various distinct subenvironments, such as beaches, bars, lagoons, swamps, stream channels, and lakes. Because deltas are large features and include both marine and nonmarine subenvironments, a great variety of sediment types accumulate in them. Sand, silt, and mud dominate. A deltaic deposit can be recognized only after considerable study of the sizes and shapes of the various rock bodies and their relationships to each other. Both marine and nonmarine fossils can be preserved in a delta.

- **Lithology**
- <u>Composition</u>
- Good maturity of siliciclastic deposits is dominant lithofacies.
- Common Coal bed/fragment, frequent Mica and lenses of heavy minerals are present. (continent)
- Shell debris + thin limestone and may be Glauconite/Phosphate are present. (marine)
- Thin layer of evaporite may be present. (arid)
- <u>Texture</u>
- Grain size is mainly is sand to clay with rare conglomerate.
- Sorting and roundness is moderate to well.

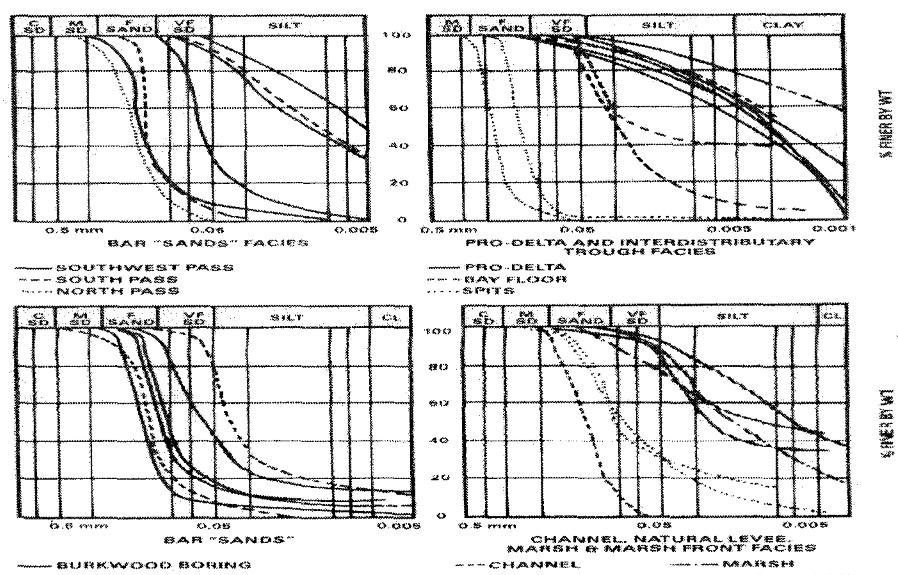


Fig. 5.6-3. Cumulative size frequency curves of selected surface and subsurface samples representative of various sedimentary facies from the bird-foot delta (from Fisk et al., 1977).

▪**Structures**

▪Channel sand

▪Contorted bedding and ripple formations

▪Planar bedding

▪Trough/tabular cross-bedding

▪Scour base

▪Mouth bar sand

▪Proximal: small scale cross lamination and ripple

▪Distal: small scour & fill, small scale cross lamination, graded sand

▪Fan delta

▪Proximal: un-bedded (fanglomerate)

▪Mid fan: trough/tabular cross-bedding with occasional planar bedding

▪Delta front: parallel lamination to massive

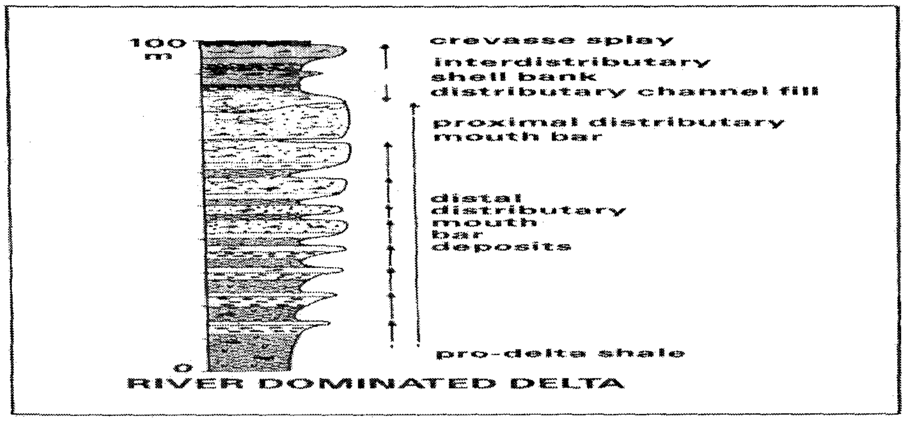


Fig. 5.6-12. Vertical sequential evolution in a river-dominated delta (from Walker, 1979).

- **Paleontology**
- Channel sands
- Burrows
- Organic plant debris
- Faunal remains usually absent
- Mouth bar sands
- Abundant microfossils in pro-delta clays at base with minor bioturbation (both microfossils & bioturbation decreasing upward)
- Proximal: laminations of organic debris
- Distal: small burrows and shell remains

- Fan delta
- Fan plain: rare vertebrate bones, plant debris
- Delta front: shall fragments
- Pro-delta: microfossils (marine or fresh water)

▪**Geometry**

▪Channel sands

▪Linear, straight to sinuous

▪10-30 m. thick and 1-5 km. wide

▪Mouth bar sands

▪Elongate in seaward directin with river dominated delta; arcuate - cuspate with wave dominated delta

▪Up to 130 m thick and 10 m wide

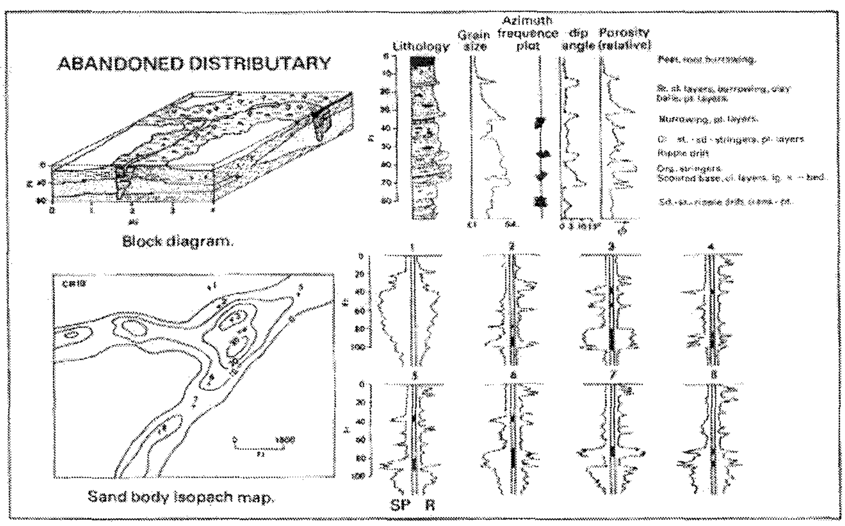


Fig. 5.6-38. Summary diagrams illustrating the major characteristics of abandoned distributary deposits (from Coleman & Prior, 1982).

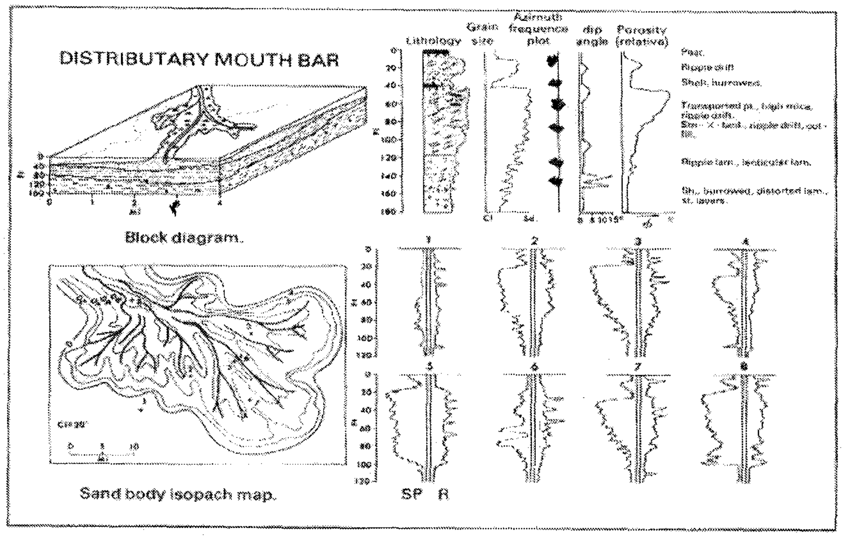


Fig. 5.6-39. Summary diagrams illustrating the major characteristics of the distributary-mouth bar deposits (from Coleman & Prior, 1982).

- Fan delta
- Overall fan shaped in plan view
- Wedge shaped in radial profile
- Convex up in transverse profile
- Subaqueous distal facies elongate in seaward direction with river dominated fan; arcuate - cuspate with wave dominate fan.

- **Associated facies**
- Channel sands
- Meandering point bars or braided bars
- Inter-bay, crevasse
- Mouth bar
- Mouth bar sands
- Delta plain & Inter-bay: silt & clay
- Channel: sand & Crevasse: silt
- Pro-delta: marine shale
- Fan delta
- Proximal: fault generated mountain fronts
- Distal: marine/lacustrine (shale & limestone)

- **Wire line log**
- GR
- Very low GR can correspond to C Sand, Coal and Limestone. Sand & Limestone can be separated by FDC-CNL and Coal by Pe or U.
- Low-moderate GR are represent to M-F Sand
- High GR can correspond to Silt (rich in Th and heavy mineral) or Shale. Silt & Shale can be separated by FDC-CNL, SP or Pe. Th & K help to define the clay type and U correlates with the OM.
- *Distributary channels*: SP/GR display blocky to bell shapes with abrupt bases
- *Mouth bar*: SP/GR display funnel shapes with abrupt tops

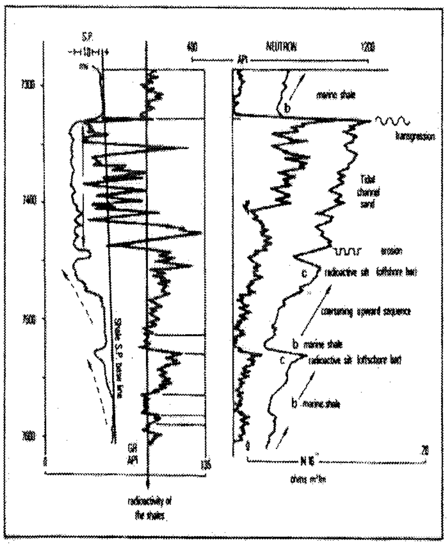


Fig. 5.6-43. Example of silt more radioactive than the shale. Silt beds are easily located on the SP and neutron curves (level c) (from Serra & Sulpice, 1975).

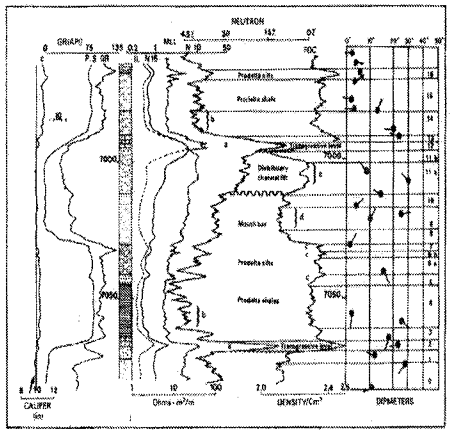


Fig. 5.6-44. The analysis of the gamma ray, neutron, density and resistivity curves indicates clearly two types of sand: the deepest (d) is finer, a little radioactive due to small amount of silt, well sorted (high porosity 35%); the sand above (e) is coarser (low radioactivity), moderately sorted (ϕ_{CP} = 22 %). This figure is an enlargement of Fig. 5.6-49, (see below).

- Texture
- Porosity:
  - High porosity (30-40%) suggests well-sorted sand. Position of FDC-CNL cross plot can also indicates the mean grain size. (more radioactive means finer and denser).
  - Medium porosity (15-25%) suggests moderate to poor sorted sand.
- Cement:
  - Silica cement if FDC-CNL cross plot point fall on the sandstone line.
  - Calcareous cement if FDC-CNL cross plot point fall on the limestone line.

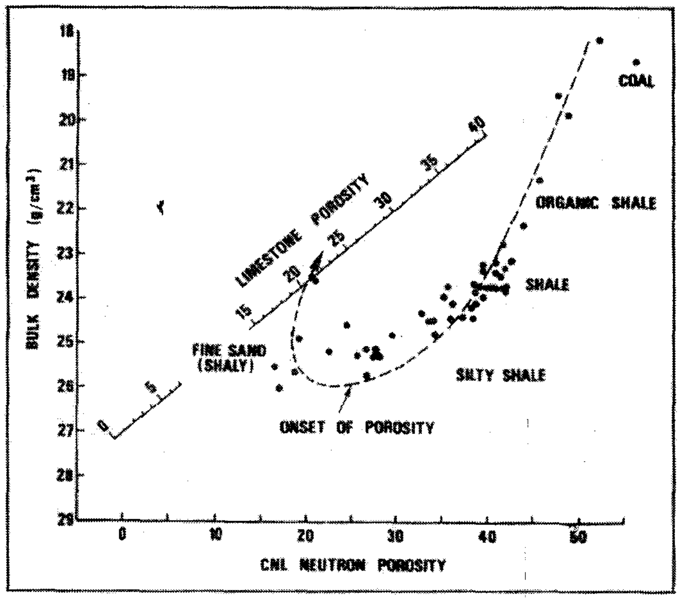
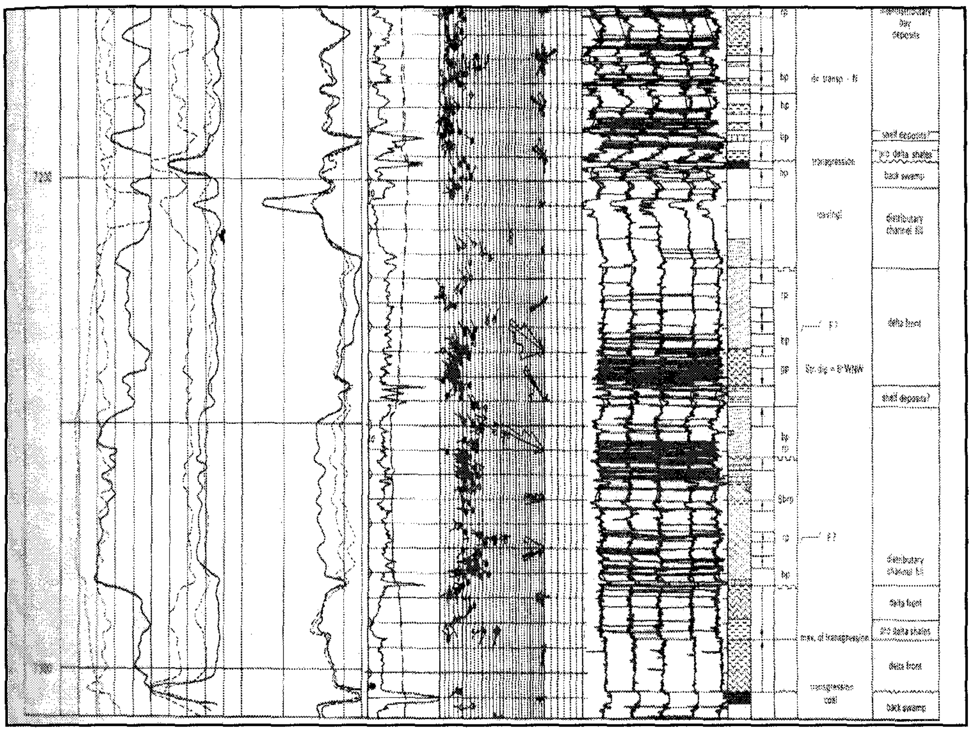


Fig. 5.6-42. Location of facies on a ρ_b *vs* Φ_N *cross-plot.*

- Dipmeter
  - No/ramdom: homogeneous or bioturbate shale
  - Green: lamination without bioturbation
  - Blue: fore-set bed of mouth bar and dip azimuths usually point in the direction of current flow
  - Red: distributary channel fill of lateral accretion and dip azimuths usually point toward the channel axis (drape-over also red)



▪**Petroleum aspect**

▪The delta reservoir of braided bar/meandering point bar sands are the same as previously lecture.

▪Braided bar sands:

▪Excellent reservoir because of large sheet geometry & inter-communication channels

▪Meandering point bar sands:

▪Small field of stratigraphic/combination trap because of small reservoir size & surrounding flood plain shale/ abandoned channel clay

- Fan delta:
- They have been recognized as important oil & gas reservoirs (Ethridge and Wescott 1894).
- Rapid facies changes and association with tectonically active basin margins create favorable stratigraphic and structural trapping.
- Furthermore, potential reservoir beds are often in close juxtaposition with marine hydrocarbon source rocks.

- **Seismic**
- Oblique configuration is the typical associated with river dominated delta.
- Sediment input is high resulting in more lateral succession than vertical succession.

River dominated delta

- Where tidal and wave energies are low, high energy distributary channels are able to build out into the sea without any erosion.
- Progradation produces a coarsening up sequence.
- The deltas are characterized by distributary channels and bays flanked with marsh.
- Where the sediment supplied to the delta is predominantly fine grained, the delta front may be failure, causing slumps and slides.

- Two types of river dominated delta:
  - *Steady discharge* with suspension load generates elongate/bird foot shape with few distributary channels.
  - *Fluctuate discharge* with bed load generates lobate shape with more distributary channels.

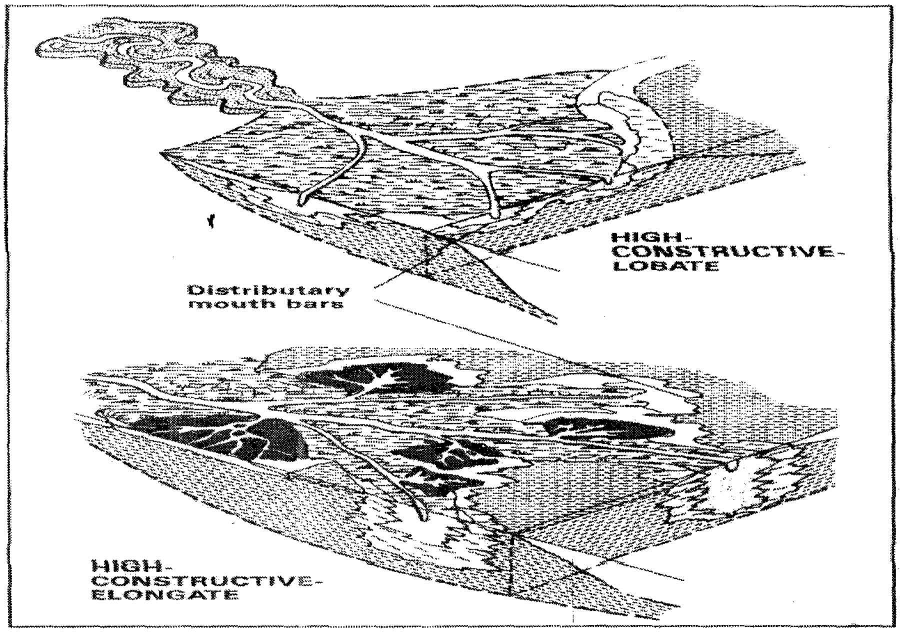


Fig. 5.6-6. Blockdiagrams of the two types of river-dominated deltas (from Fisher et al., 1969).

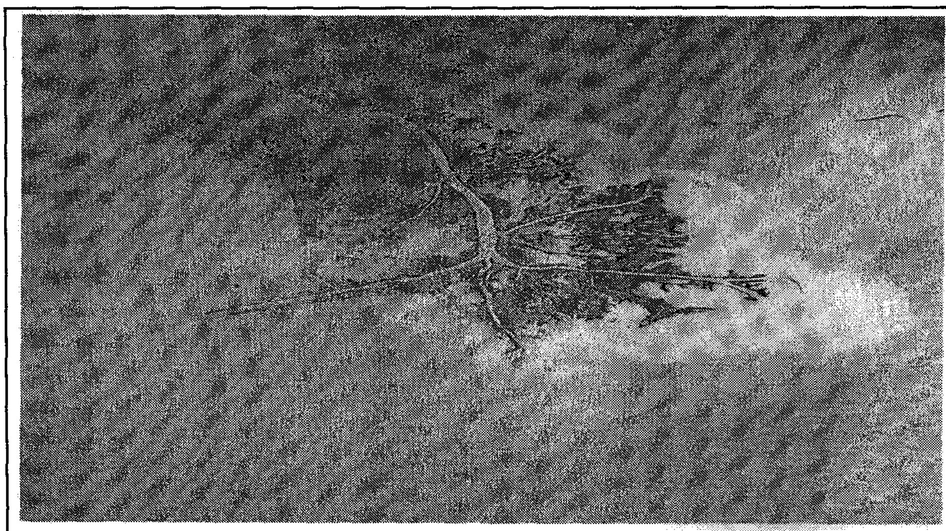


FIGURE 3.3
The Mississippi Delta, like deltas of other major rivers, is a record of erosion due to the hydrologic system. Sediment eroded from the land is transported by a river system and deposited in the sea. The dynamics of delta building are displayed vividly in this photograph. The cloud of mud and silt delivered to the ocean colors the water a lighter tone around the mouth of the river. This material is deposited as banks of mud, sand, and clay over the continental shelf as the delta grows seaward at a rate of nearly 20 km per 100 years. Measurements indicate that the Mississippi River pours more than a million metric tons of sediment into the Gulf of Mexico each day. In the process of deltaic growth, the river builds up a projection of new land into the ocean. Eventually, the river finds a shorter route to the ocean and abandons its active distributary channel for the shorter course. The abandoned distributary ceases to grow and is eroded back by wave action. Abandoned river channels and inactive subdeltas can be seen clearly on each side of the present river. *(Courtesy of National Space Data Center, NASA.)*

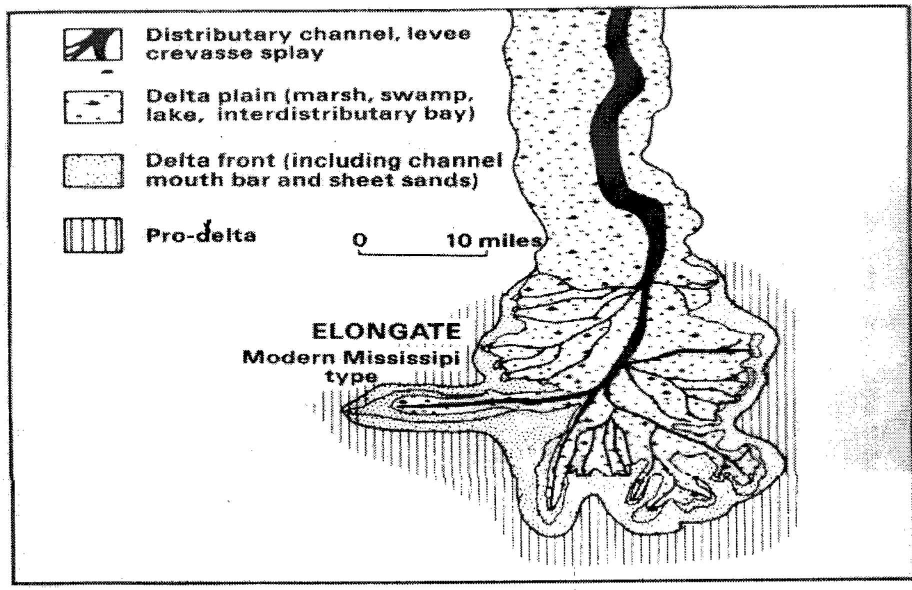


Fig. 5.6-8. Surface distribution of facies in a bird-foot type river-dominated delta (from Fisher et al., 1969).

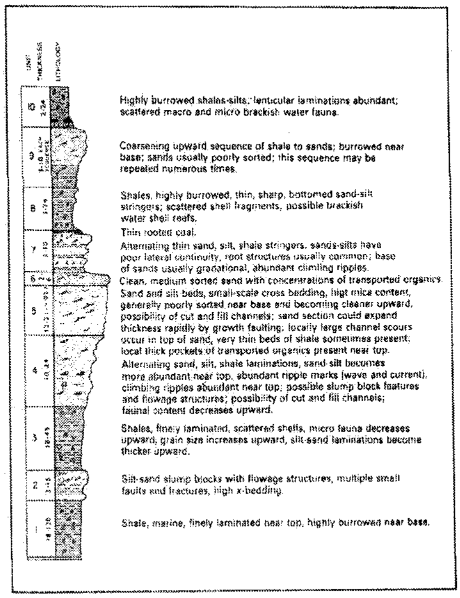


Fig. 5.6-13. Composite stratigraphic sequence of depositional environments in the Mississippi River delta (from Coleman & Prior, 1980).

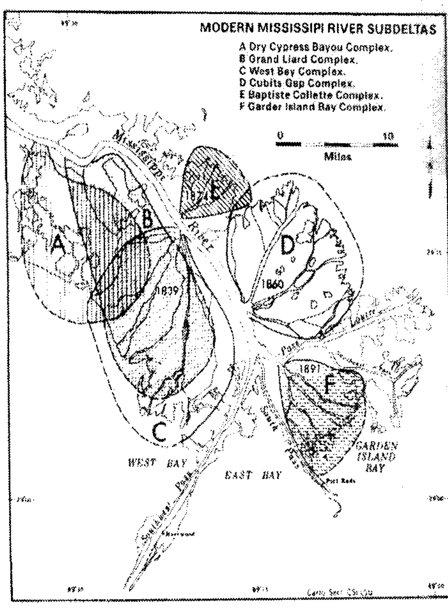


Fig. 5.6-14. Sub-deltas infilling interdistributary bays of the modern Mississippi delta (from Coleman & Gagliano, 1964).

•Structure

•Contorted bedding: Load mark, convolute, mud lump, diapiric and slump are generally related to pro-delta clays. Bioturbations are moderate to high, including flora and fauna related.

•Ripple form, Planar bed, Trough/tabular cross-bed: Lamination to thin-bed, small to large ripples (symmetrical and asymmetrical), abundant planar bed and trough/tabular cross-beds, generally high angle with unimodal current, are the most common bedding type.

•Scour bed: Massive bedding with general erosion surface. Scour with lag and iron rich concretion is common found.

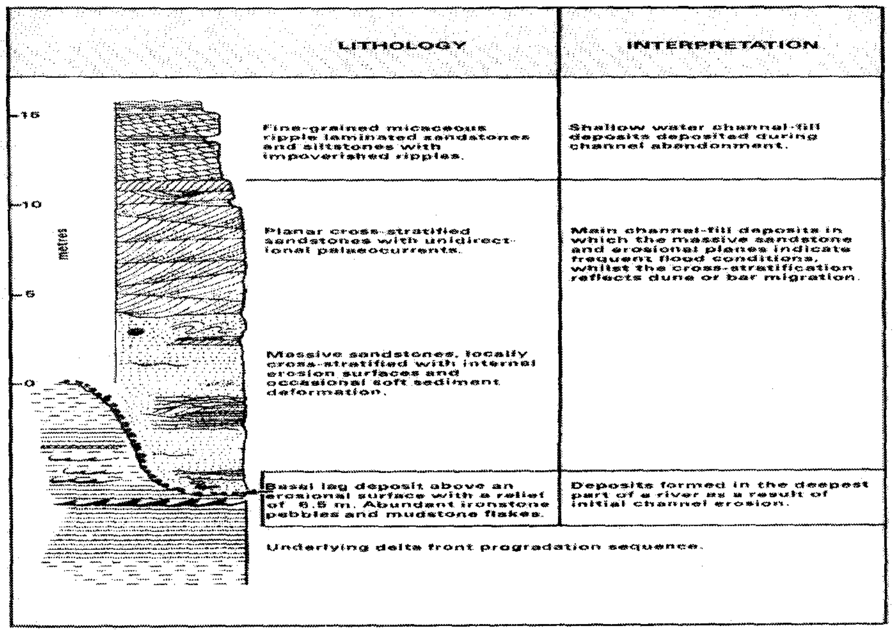


Fig. 5.6-9. Vertical sequences of sedimentary structures in river-dominated interdistributary areas (from Elliot, 1974, in Reading, 1978).

•Geometry

•The main bodies are lobate with a strong lateral accretion that generates lenticular to tabular unit of the distributary mouth bar, grading to sheet sand. Near the top, finger or shoestring shapes are described.

•Bates (1953) contrasted situations between the river waters and basin water:

- ▪Equal dense (homopycnal/inertia)
- ▪Denser (hyperpycnal/friction)
- ▪Less dense (hopopycnal/buoyancy)

•Table 5.6-3 summarizes geometrical criteria for this kind of delta.

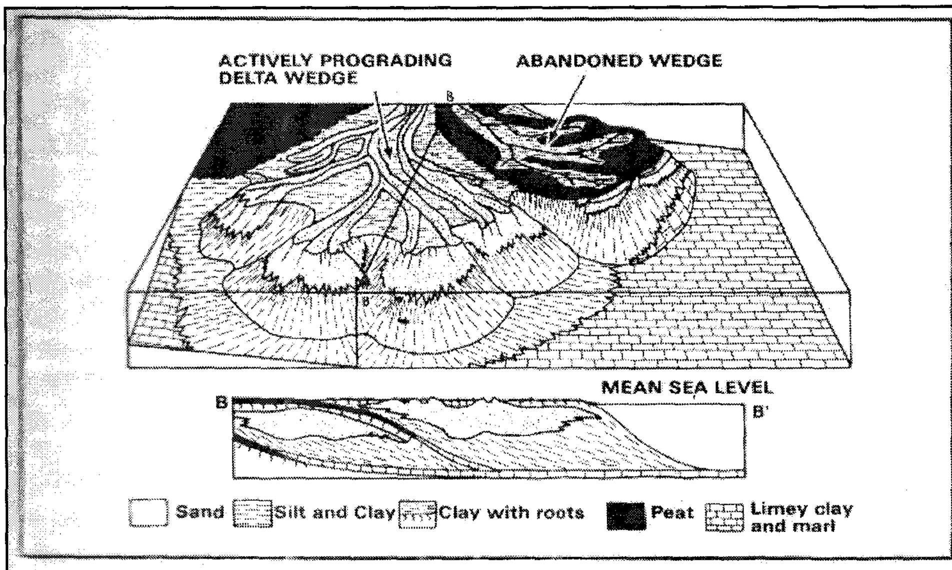


Fig. 5.6-16. Cyclical active and abandonment evolution of Carboniferous deltas in the United States (from Ferm, 1970).

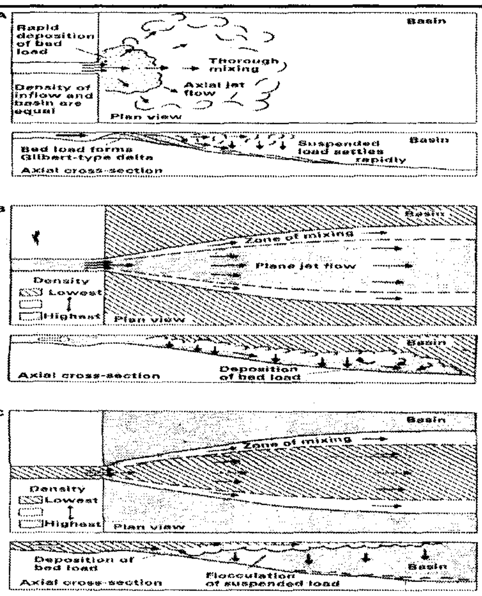


Fig. 5.6-18. Contrasted modes of interaction between sediment-laden river waters and basin waters, determined by the relative density of the water bodies: (a) homopycnal flow; (b) hyperpycnal flow; (c) hypopycnal flow (from Fisher et al., 1969; originally from Bates, 1953).

Table 5.6-3 *Geometrical and other geological parameters to identify deltaic subenvironments.*

	BAY FILL	MARSH SWAMP	DISTRIBUTARY MOUTH-BAR	POINT BAR	CHANNEL	OVERBANK
TYPE OF DEPOSIT	DETRITAL	CHEMICAL	DETRITAL	DETRITAL	DETRITAL	DETRITAL
DOMINANT ROCK TYPE	Shale & silty shale.	Seatrock, clay, coal.	Medium to fine sandstone with shale lenses.	Coarses to medium sandstone.	Medium sandstone occasional conglomerats. Shale bands.	Silty shale, siltstone Fine micaceous sandstone.
GRAIN SIZE TREND	Generally coarsening upward.	No specific trend.	Coarsening upward.	Fining upward.	Highly variable in the middle. Generally fining upward.	Cyclic, each cycle fining upward.
NATURE OF BASAL CONTACT	Generally not seen.	Gradational to sharp.	Gradational to sharp.	Highly scoured wavy.	Sharp truncation. Highly erosive.	Gradational.
VERTICAL THICKNESS	1.5 to 15 ft.	0.3 to 1.8 m.	1.5 to 4.5 m.	6 to 14 m.	3 to 4.5 m.	0.9 to 4.5 m.
LATERAL EXTENT	60 m to 73.2 Km.	In kilometres.	0.4 m to 4.8 Km.	90 m to 0.4 Km.	19 m or less, to 120 m.	Very variable.
SHAPE OF UNIT	Rectangular in Cross section.	Elongated.	Sheet-like.	Hedge shapped lenticular.	Biconvex, planeconvex.	Thin, sheet-like.
BEDDING THICKNESS	Thinly bedded laminated.		Medium bedded. 0.3 to 9 m.	Thick bedded 1.5 to 2.0 m.	Medium to thinly bedded.	Thin bedded, laminated.
SEDIMENTARY STRUCTURES	Parallel and wavy lamination.		Planar cross-beds. Composit sets common Climbing ripples on lateral extremities.	Multi-directional trough cross-beds. Solitary cross-strats common.	Small scale scour and fill.	Parallel lamination, current Ripples. Small scale cross-bed.
NATURE AND DISTRIBUTION OF ORGANIC FRAGMENTS	Small leaves and twigs along bedding planes. Brachiopods.	Mascerated plant material.	Small rounded organic fragments distributed at random.	Large leaves and stem on bedding planes. Rafted Coal lenses at base.	Oriented large stem at the base.	Small leaves and twigs along bedding planes.
MICACEOUS MINERAL	Coarse mica flakes along bedding planes.		Generally distributed at random. Some beds show unusually high concentration.	Mica distributed at random. Coarse flakes segregated along bedding planes.	Distributed at random.	Segregated along bedding planes.
POST DEPOSITIONAL MODIFICATIONS	Rooting on top only cone-in-cone burrowing.	Rooting.	Gas heave. Structure.	Convolute, laminations.	Slump features.	Rooting.
NODULES	Siderite nodules present.		Not seen.	Large disc, shaped nodules present .	Not seen.	Not seen.
PRIMARY HUES	Dark grayish, black.	Black grayish, black.	Light whistish, gray.	Dark gray.	Light grey.	Dark greenish gray grayish black.

•Associated facies

•Boundaries: large units tend to show basal gradation contacts with abrupt tops. Internally gradation or sharp contacts are randomly distributed and tend to be similar to the large units

•Sequences: The rapid seaward prograding delta is generating a large coarsening upward.

•The delta characteristics in which cyclic sequences are superimposed upon each other depend on the relative rates of sedimentation and subsidence.

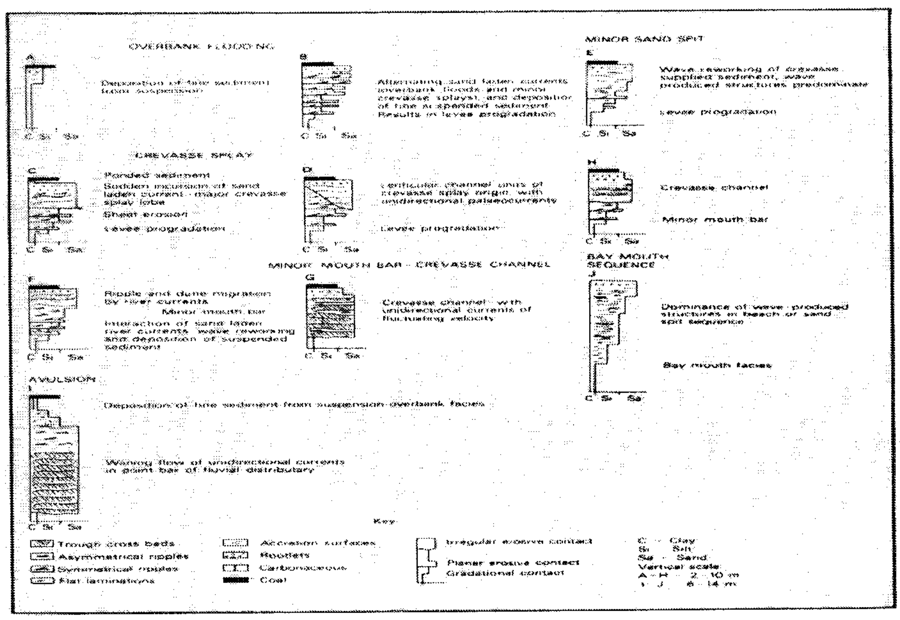


Fig. 5.6-10. Boundaries and sedimentary structures of a fluvial-distributary channel (from Reading, 1978, after Kelling & George, 1971).

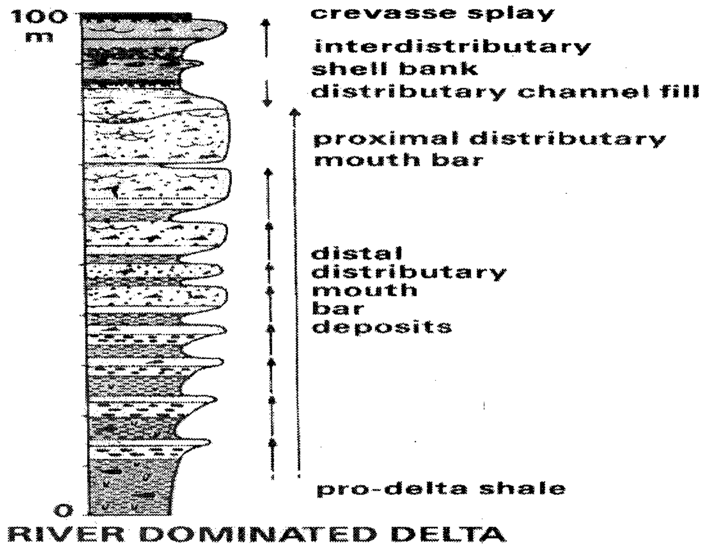


Fig. 5.6-12. Vertical sequential evolution in a river-dominated delta (from Walker, 1979).

•Scruton (1960) recognized the growth of a delta is two phases:

- *Constructive (river dominated delta)*: pro-delta (mud) is overlain by delta-front (silt/sand) then distributary mouths bar (sand) and finally tops set delta (marsh/peat).
- *Destructive (wave dominated delta, tidal dominated delta)*: delta lobe eventually is abandoned if crevasse generates a short cut to the sea. The top set delta are then attacked by waves and current activity and may be completely reworked.

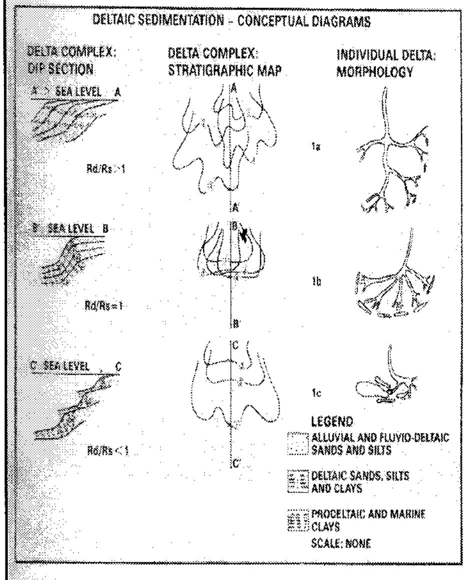


Fig. 5.6-15. Conceptual diagrams of variations in delta characteristics resulting from variations in ratio between rate of deposition and rate of subsidence (Rd/Rs) (from Curtis, 1970).

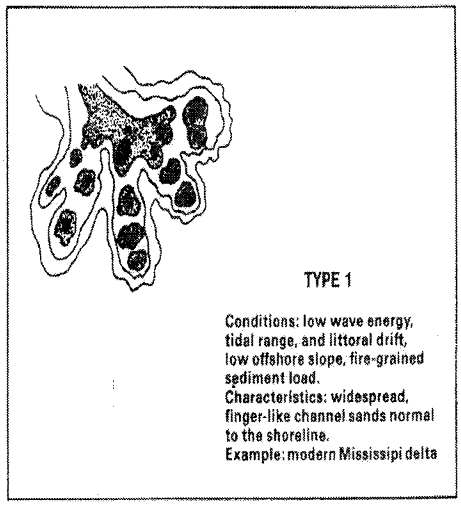
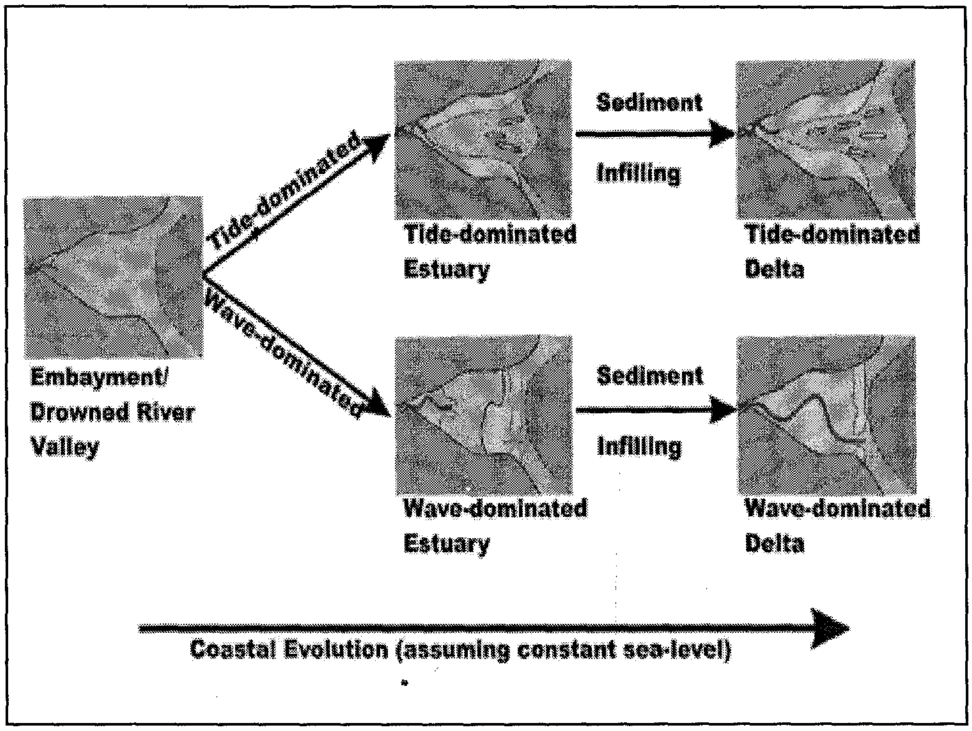
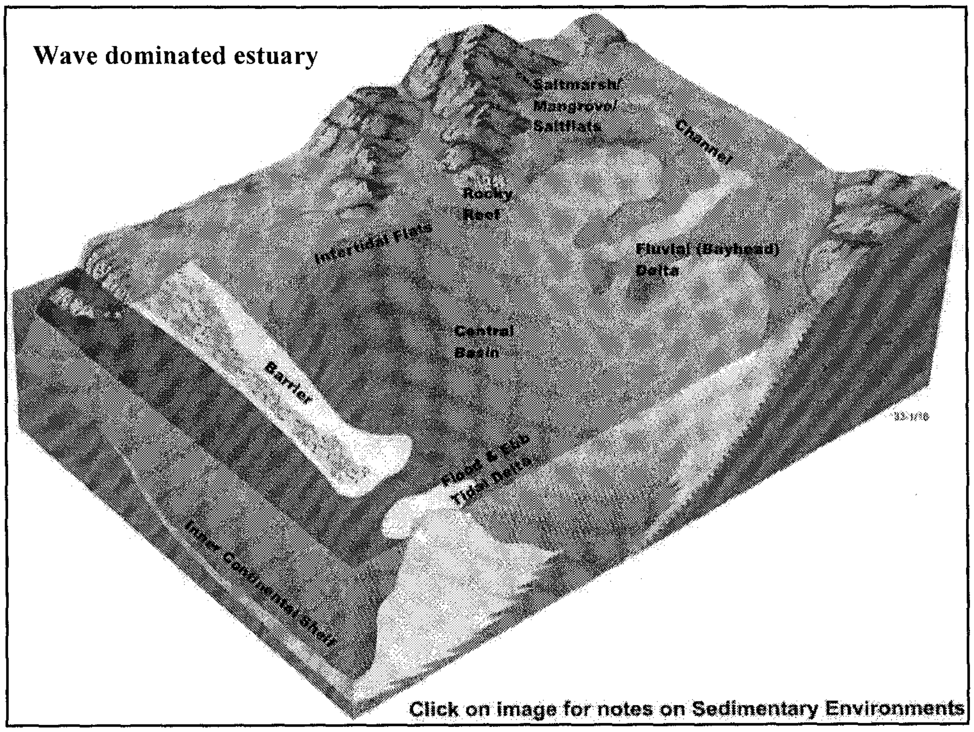


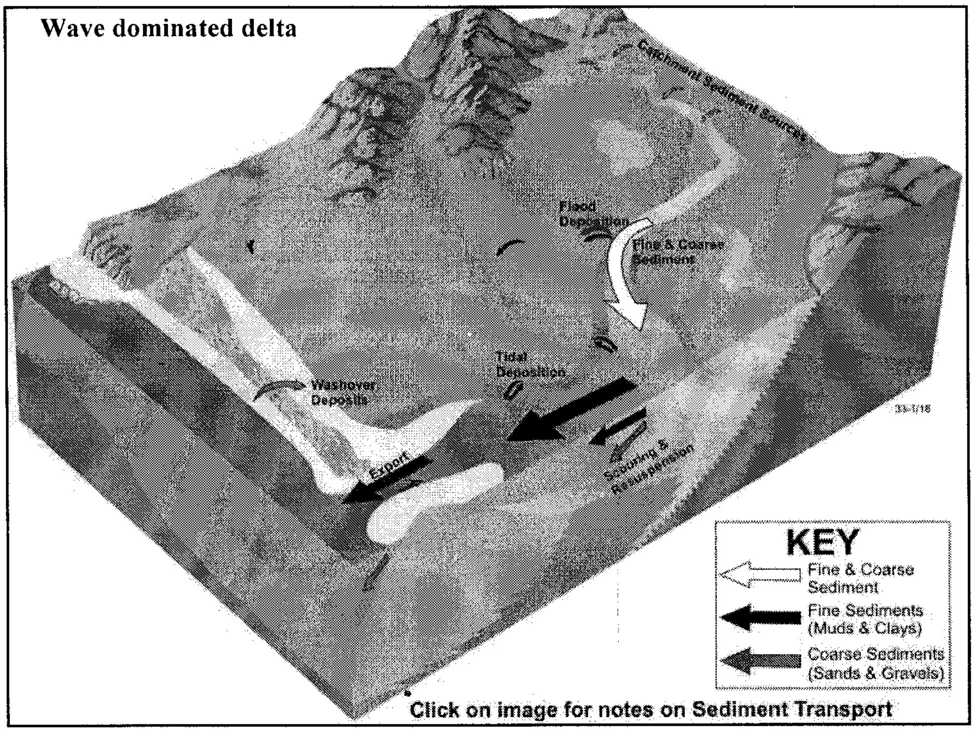
Fig. 5.6-17. Sand distribution pattern (modified from Coleman & Wright, 1975).

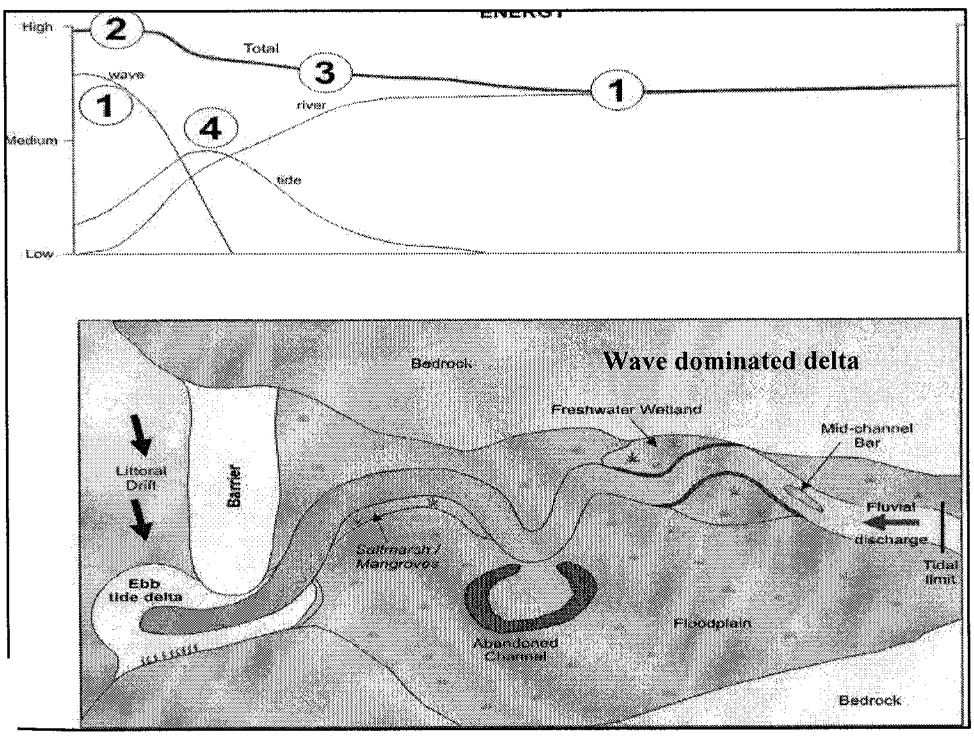
Wave dominated delta

- Where wave energies are strong compare to the river inflows and tides, the sediment delivered to the sea is moulded into curved ridges at the delta's front and some is redistributed along the shore as beaches and spits.
- The deltas are characterized by parallel beach ridge complexes in active shore lines or shallow lagoons between old beach ridges and aeolian dunes in areas of ridge reworking.


Tide-dominated
Wave-dominated
Sediment
Infilling
Tide-dominated
Estuary
Tide-dominated
Delta
Embayment/
Drowned River
Valley
Sediment
Infilling
Wave-dominated
Estuary
Wave-dominated
Delta
Coastal Evolution (assuming constant sea-level)


Wave dominated estuary
Saltmarsh/
Mangrove/
Saltflats
Channel
Rocky
Reef
Intertidal Flats
Fluvial (Bayhead)
Delta
Central
Basin
Barrier
Flood & Ebb
Tidal Delta
Inner Continental Shelf
Click on image for notes on Sedimentary Environments


Wave dominated delta
Catchment Sediment Sources
Flood Deposition
Fine & Coarse Sediment
Tidal Deposition
Washover Deposits
Export
Scouring & Resuspension
KEY
Fine & Coarse Sediment
Fine Sediments (Muds & Clays)
Coarse Sediments (Sands & Gravels)
Click on image for notes on Sediment Transport


High
Medium
Low
Total
wave
river
tide
2
3
1
1
4
Bedrock
Wave dominated delta
Freshwater Wetland
Mid-channel Bar
Littoral Drift
Barrier
Fluvial discharge
Tidal limit
Saltmarsh / Mangroves
Ebb tide delta
Abandoned Channel
Floodplain
Bedrock

•Progradation lead to a coarsening up sequence.

•The deltas appear to change from lobate/elongate to arcuate/cuspate (sub-aerial forms) as the effects of wave reworking increase or sediment input decrease.

•Mouth bar deposits are continue wave reworking into a series of super-imposed coastal barrier bars.

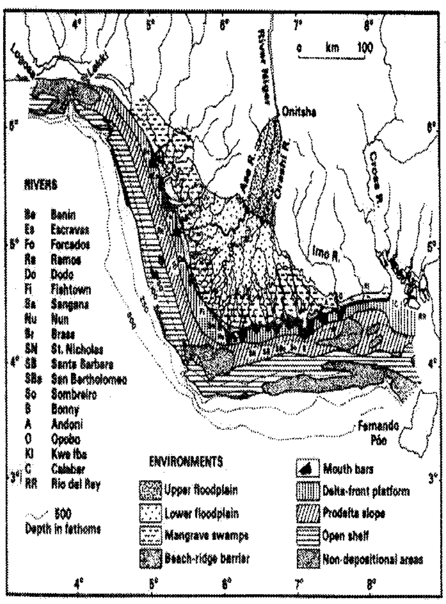


Fig. 5.6-21. Principal sedimentary environments of the Niger delta (from Allen, 1970).

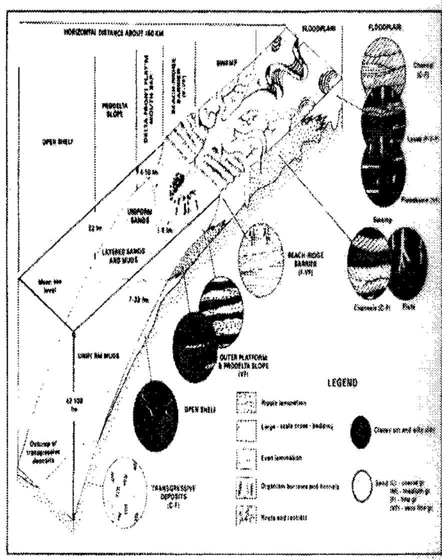
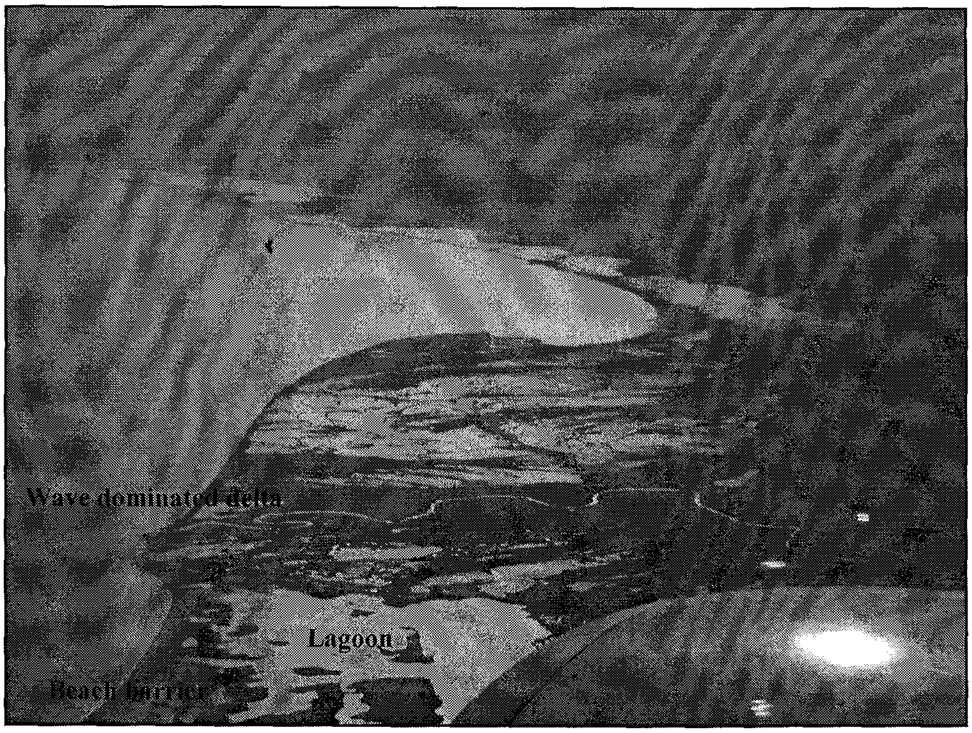
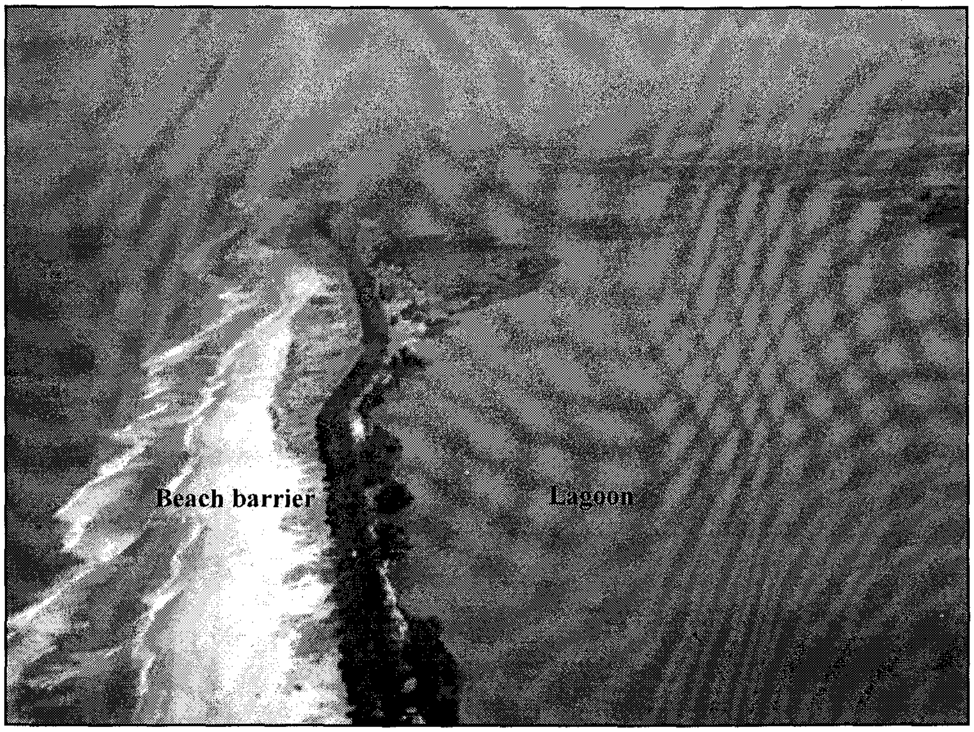


Fig. 5.6-23. Schematic illustration of the properties and relationships of principal sedimentary facies of the modern Niger Delta (from Allen, 1970).


Wave dominated delta
Lagoon
Beach barrier


Beach barrier
Lagoon

•Structure

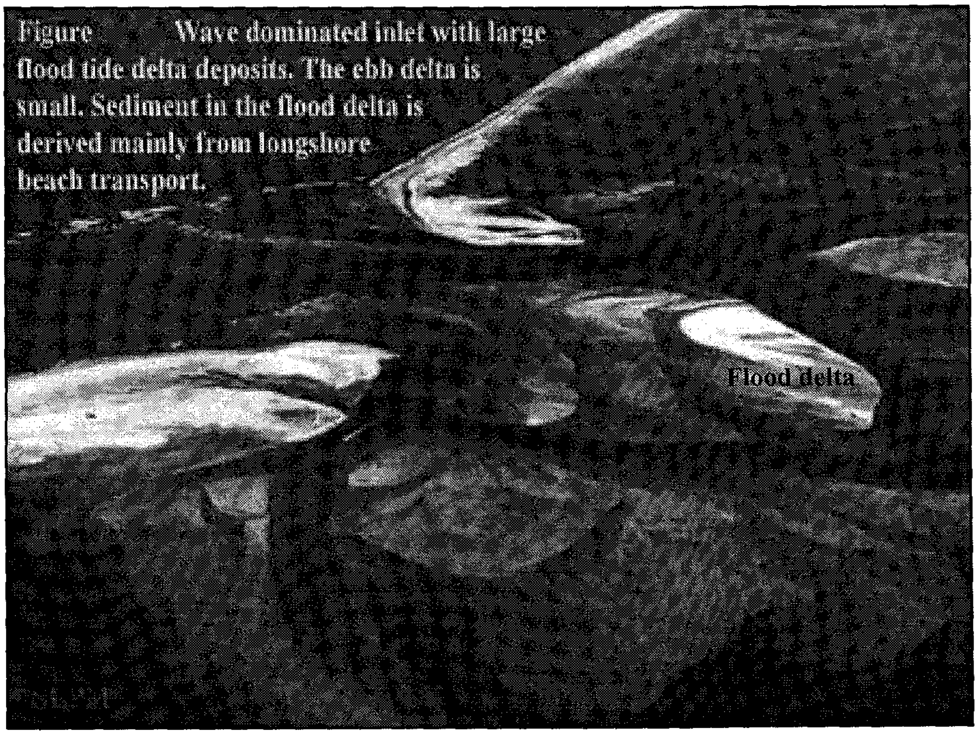
•Lamination to thin-bed, planar bed and cross bed, is the distinctive bedding features.

•Barrier and shore-face sands generally contain low-angle cross bedding, representing wave accretion surface.

•Palaeocurrent distributions are bimodal/random.

•Sands & shales tend to be burrowed & rooted, the last near tops of banks.

•Pro-delta clays are rich in mud pellets.



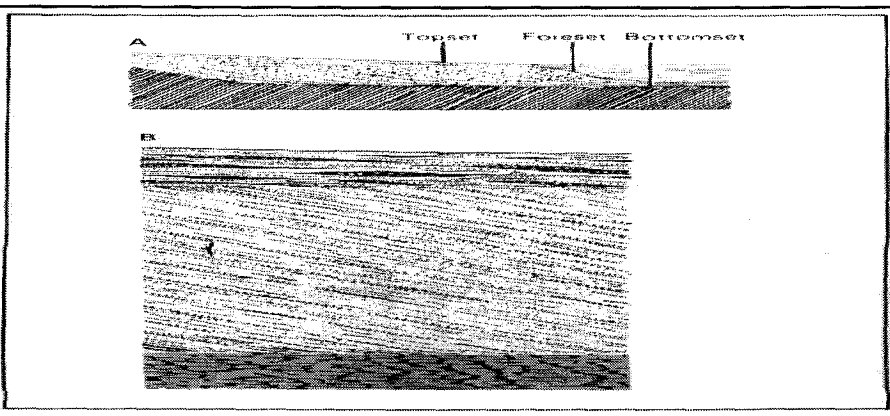


Fig. 5.6-19. Lateral and vertical cross-sections of a delta, showing topset, foreset and bottomset developping as delta grows (from Reineck & Singh, 1975; and from Reading, 1978).

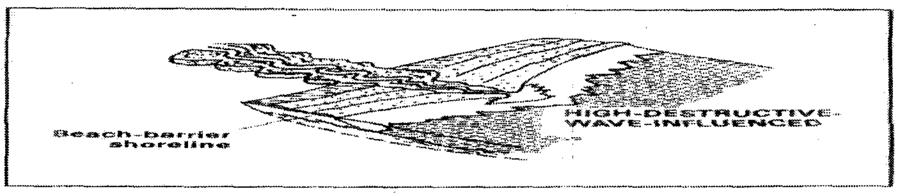


Fig. 5.6-20. Block diagram of wave-dominated deltas (from Fisher et al., 1969).

•Geometry

•Beach-ridge sand form linear body sub-parallel to the basin margin as a convex, arc-cusp or chevron shapes.

•Sand body is dependent on river-wave relationship, giving cuspate to arcuate delta.

•Stringers of sand, shale, coal, evaporites, shell beds and heavy minerals may be present.

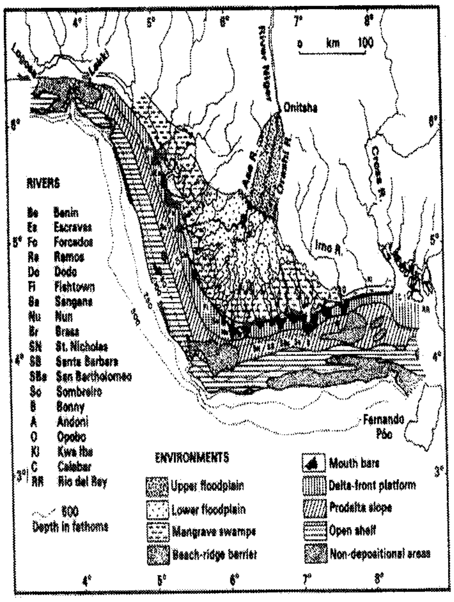


Fig. 5.6-21. Principal sedimentary environments of the Niger delta (from Allen, 1970).

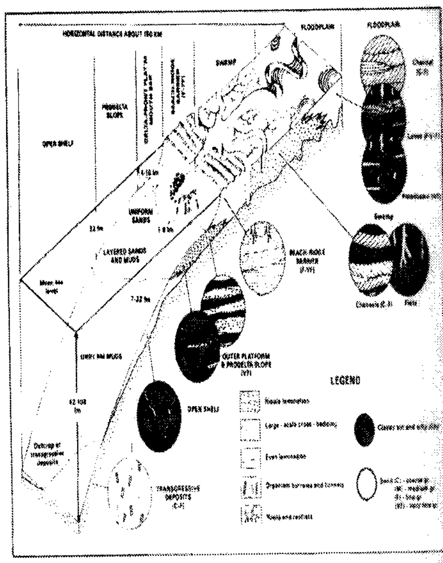


Fig. 5.6-23. Schematic illustration of the properties and relationships of principal sedimentary facies of the modern Niger Delta (from Allen, 1970).

•Associated facies

•Boundaries: parallel boundaries dominate in external as well as internal units. The base of megasequences shows gradation contact. However, distributary channels cut delta marshes showing small scours at the base.

•Sequences: coarsening upward or stacked beach-ridge sequence are well developed. However, beach-ridge sequences are also developed in non-delta, but are commonly backed by lagoon.

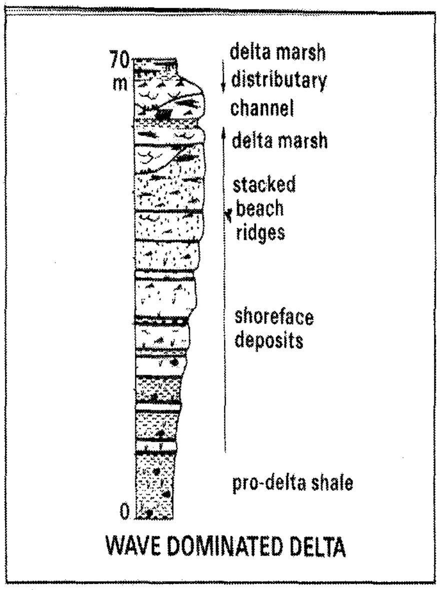


Fig. 5.6-25. Vertical sequence distribution in wave-dominated delta (from Walker, 1979).

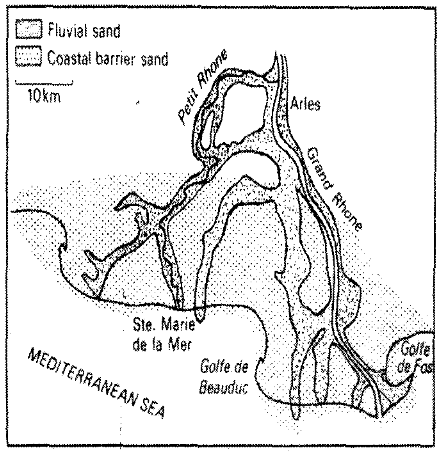


Fig. 5.6-26. Distribution of sand bodies following their origin in the Rhône delta (from Oomkens, 1970).

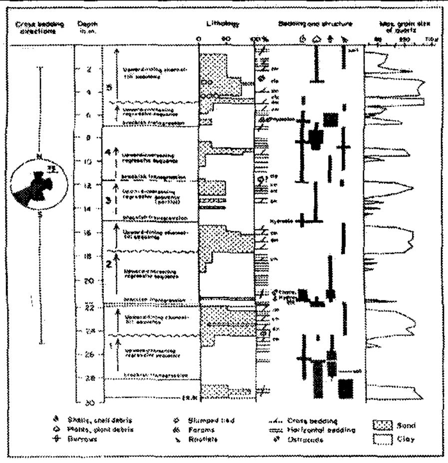


Fig. 5.6-22. - Typical example of deltaic coastal plain sedimentation, Rhône delta. Five upward coarsening sequences, of which three (1, 2 and 5) are overlain by upward fining channel-fill sequence, can be recognized in this core-log (from Oomkens, 1970).

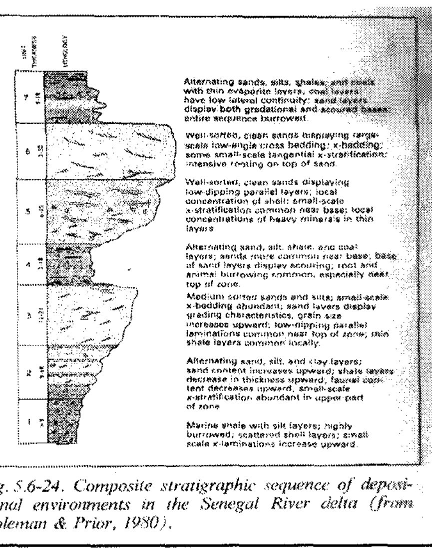


Fig. 5.6-24. Composite stratigraphic sequence of depositional environments in the Senegal River delta (from Coleman & Prior, 1980).

Tidal dominated delta

- The deltas are strongly affected by tides and characterized by a complex tidal sand ridges, shoals and islands separated by fast flow tidal channels, elongated in the same direction of the flow.
- Where the tidal range is low, the overlying may be tidal flat sediment (sub-aerial fine sediment).
- Where the tidal range is high, the fast flow tidal channels during flood and ebb may become the principal source of dispersal sediment into the delta marsh or delta front.

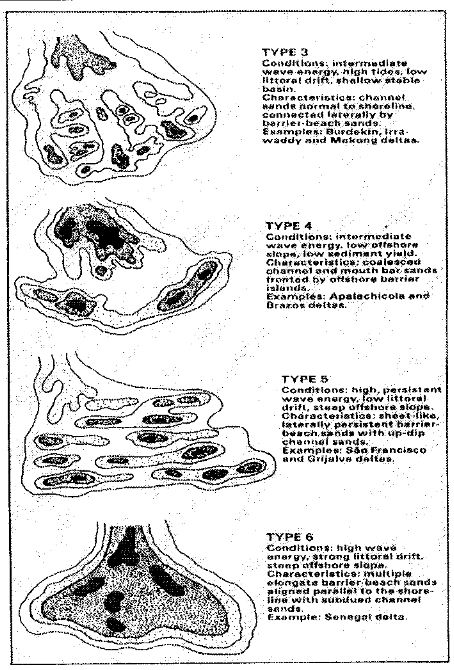


Fig. 5.6-27. Sand bodies in modern wave-dominated deltas (from Coleman & Wright, 1975).

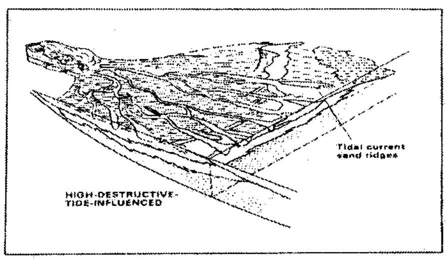


Fig. 5.6-28. Block diagram of a tide-dominated delta (from Fisher et al., 1969).

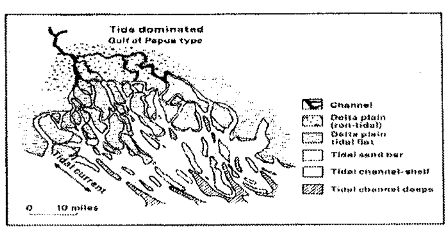
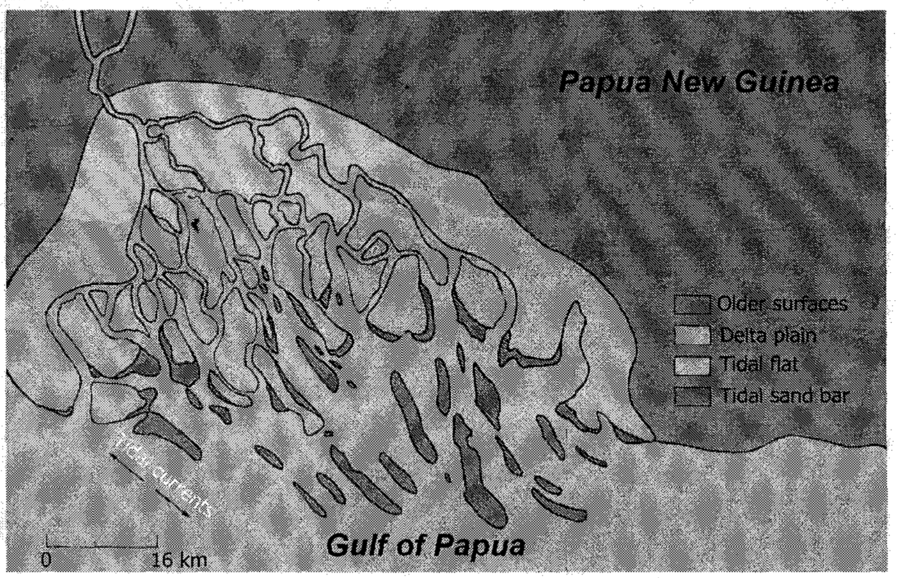
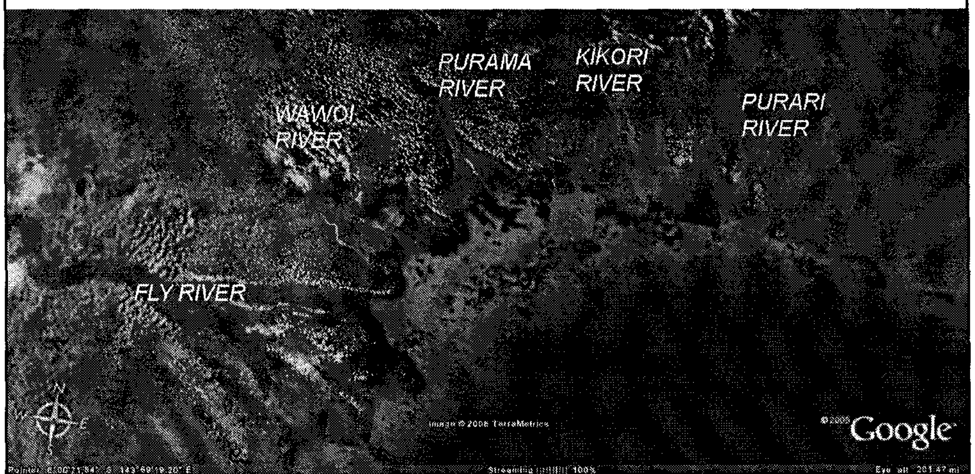


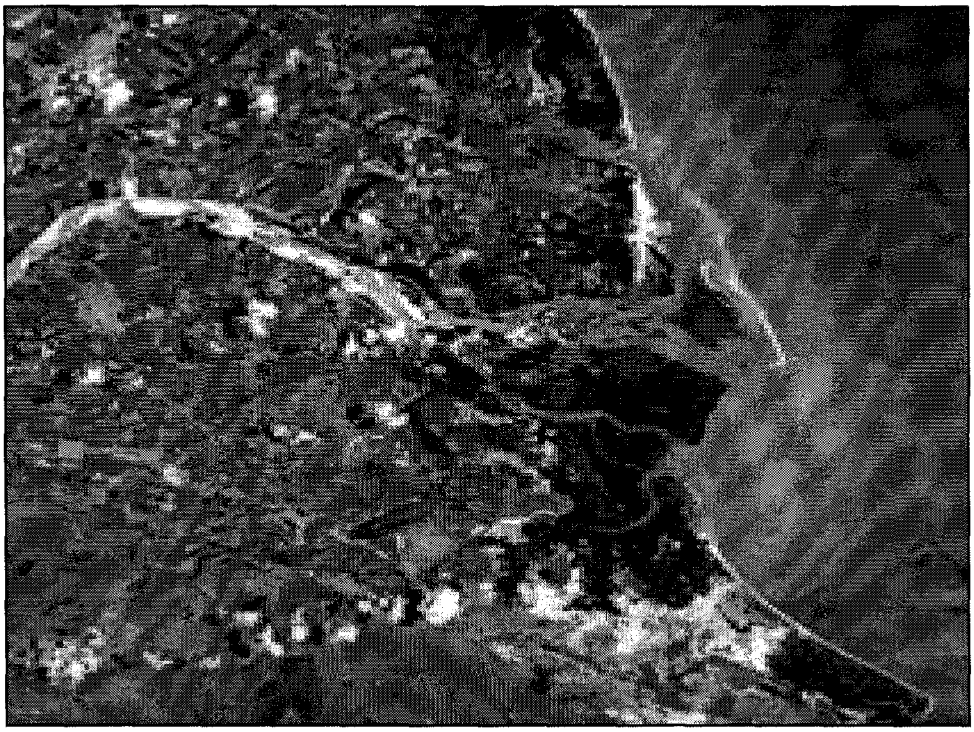
Fig. 5.6-29. Surface distribution of facies and subenvironments in a modern tide-dominated delta: Gulf of Papua (from Fisher et al., 1969).

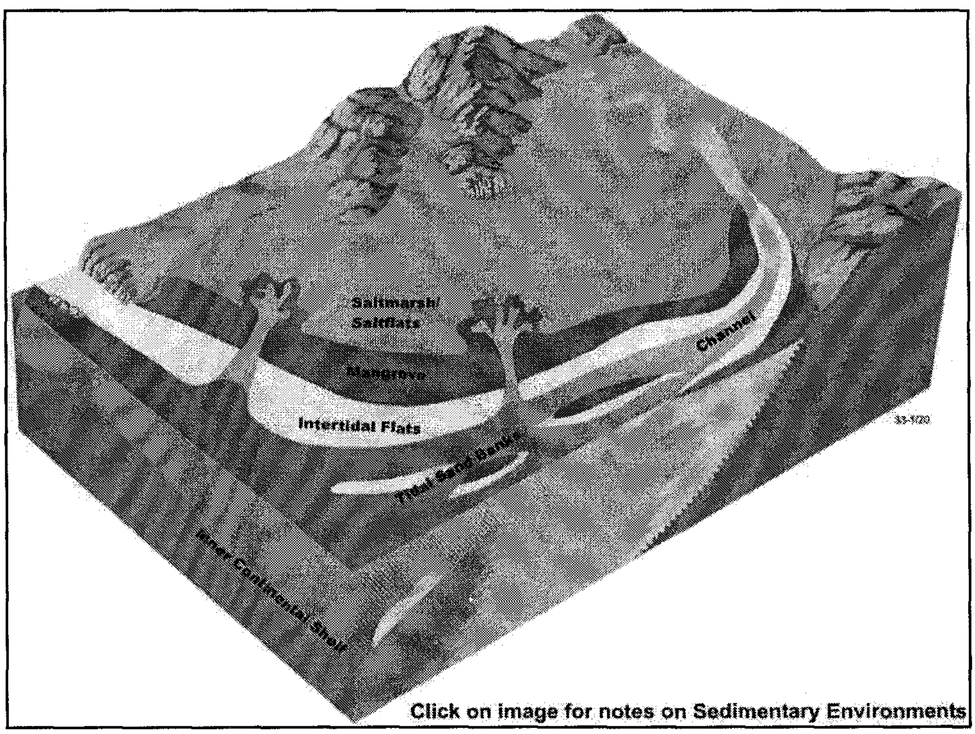


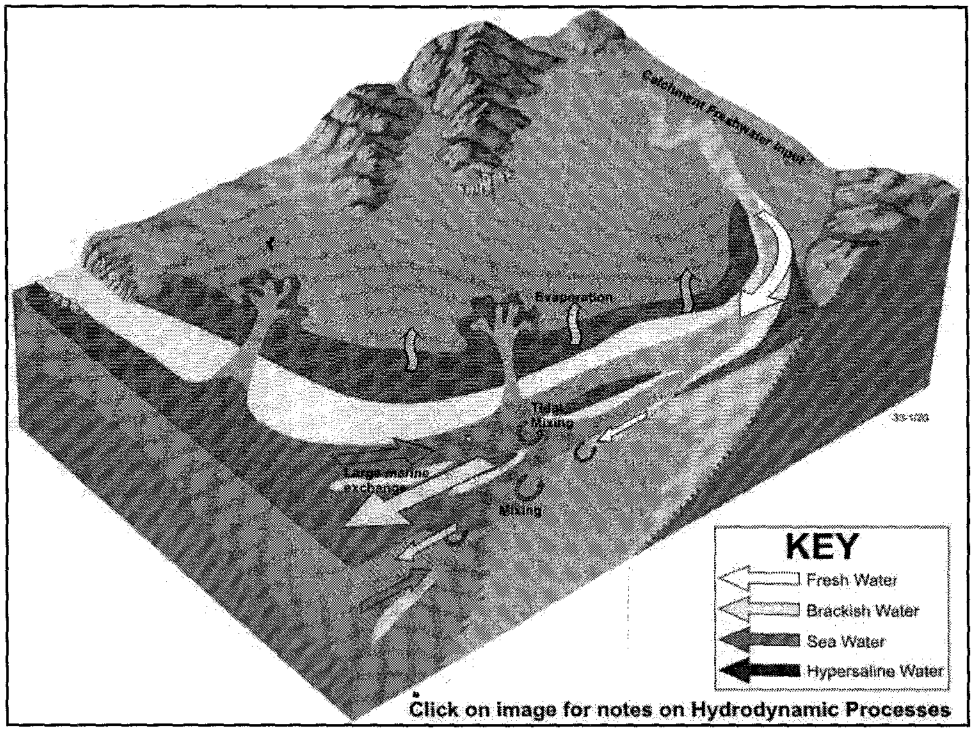
Don Boyd, personal communication, 2007

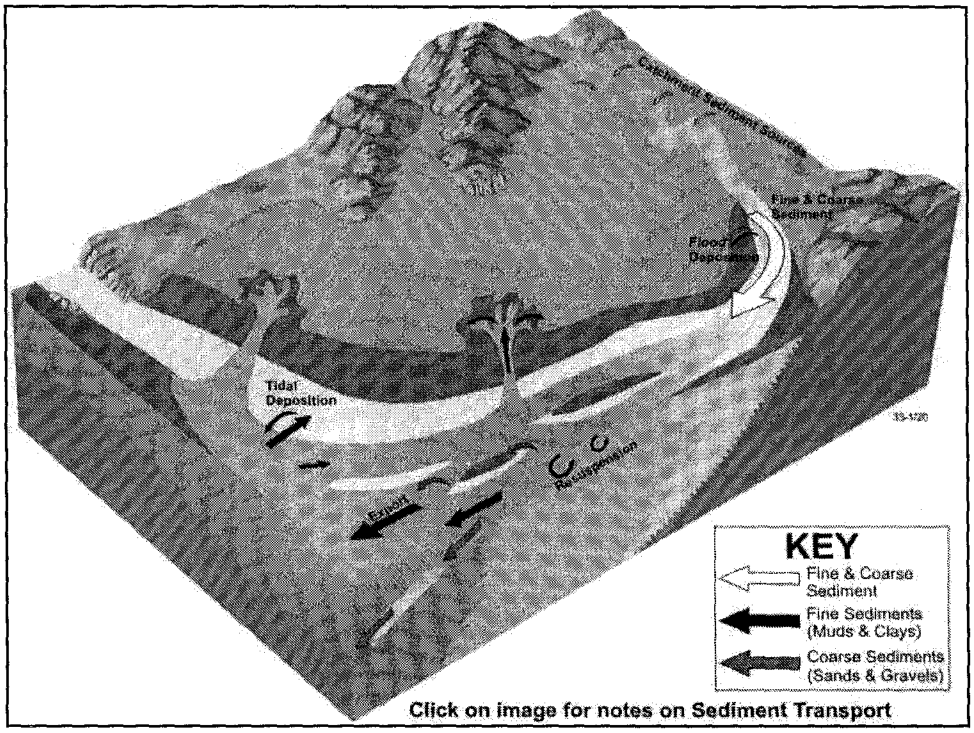


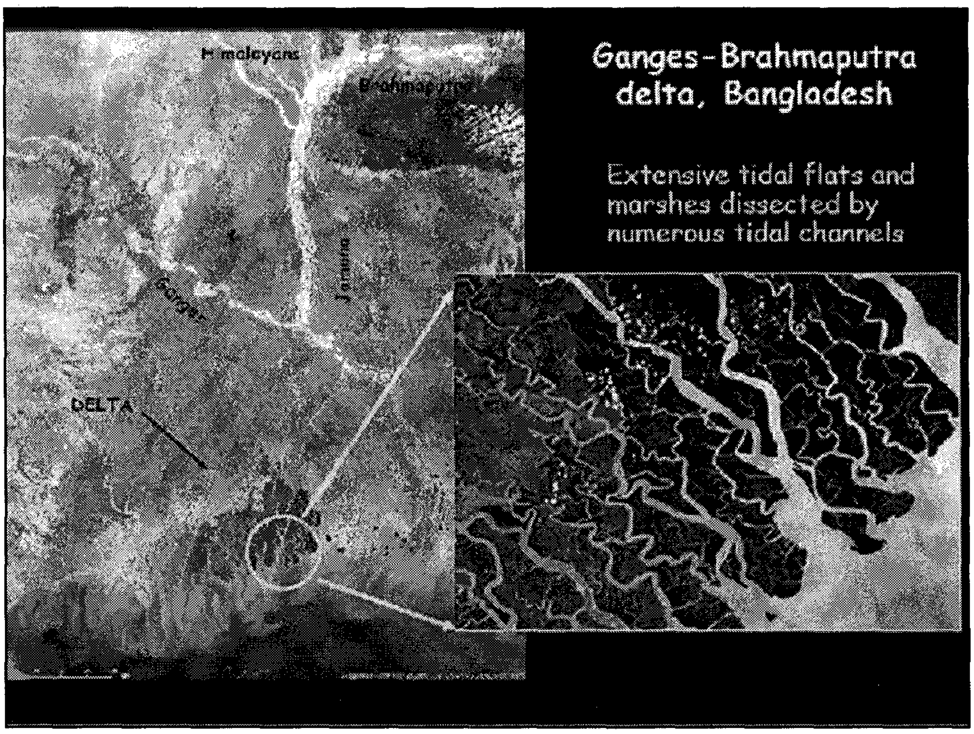
Different tidal deltas are present along the Gulf of Papua, with a fan-like shape or dendritic distributaries




Saltmarsh/
Saltflats
Mangrove
Channel
Intertidal Flats
Tidal Sand Banks
Inner Continental Shelf
Click on image for notes on Sedimentary Environments


Catchment Freshwater Input
Evaporation
Tidal Mixing
Large marine exchange
Mixing
KEY
Fresh Water
Brackish Water
Sea Water
Hypersaline Water
Click on image for notes on Hydrodynamic Processes


Catchment Sediment Sources
Fine & Coarse Sediment
Flood Deposition
Tidal Deposition
Resuspension
Export
KEY
Fine & Coarse Sediment
Fine Sediments (Muds & Clays)
Coarse Sediments (Sands & Gravels)
Click on image for notes on Sediment Transport



•Delta front with bidirectional cross bedded sands (herring bone) may overlain by clay drapes at the top of coarsening up sequences.

•Within mouth bars, the sediments can be reworked into a series of linear ridges parallel to the direction of tidal currents.

•In high littoral drift the linear tidal ridges tend to parallel the shoreline but trend to parallel the direction of tidal currents in low littoral drift.

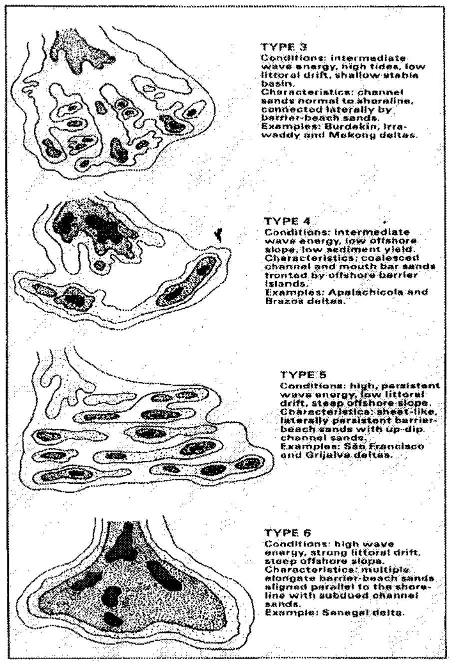


Fig. 5.6-27. Sand bodies in modern wave-dominated deltas (from Coleman & Wright, 1975).

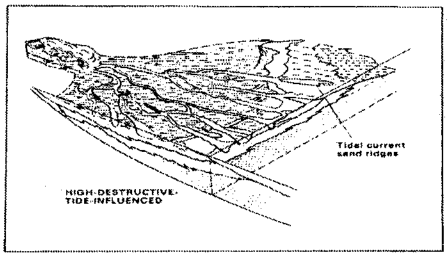


Fig. 5.6-28. Block diagram of a tide-dominated delta (from Fisher et al., 1969).

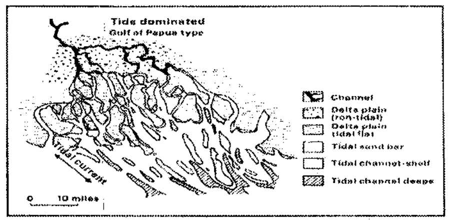


Fig. 5.6-29. Surface distribution of facies and subenvironments in a modern tide-dominated delta: Gulf of Papua (from Fisher et al., 1969).

- **Structure**
- Thin bed with parallel to oblique laminations;
- Bidirectional (herringbone) and unidirectional trough cross bedding;
- Flaser;
- Scour, slump, algal structure, intent bioturbation and mud-crack, are the main features. (fig. 5.6-30)

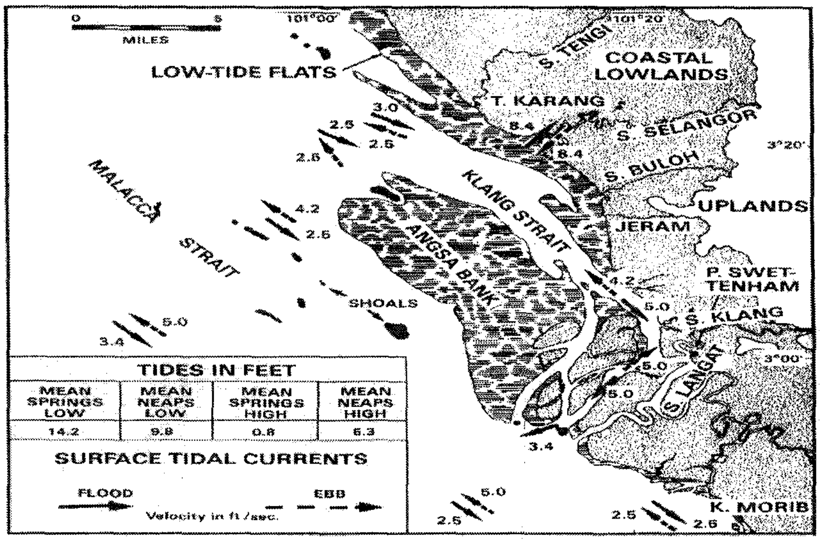


Fig. 5.6-33. Major physiographic areas, tides, and tidal currents of the Klang-Langat Rivers delta. Tides refer to the British Admiralty data for the Malacca Strait (from Coleman et al., 1970).

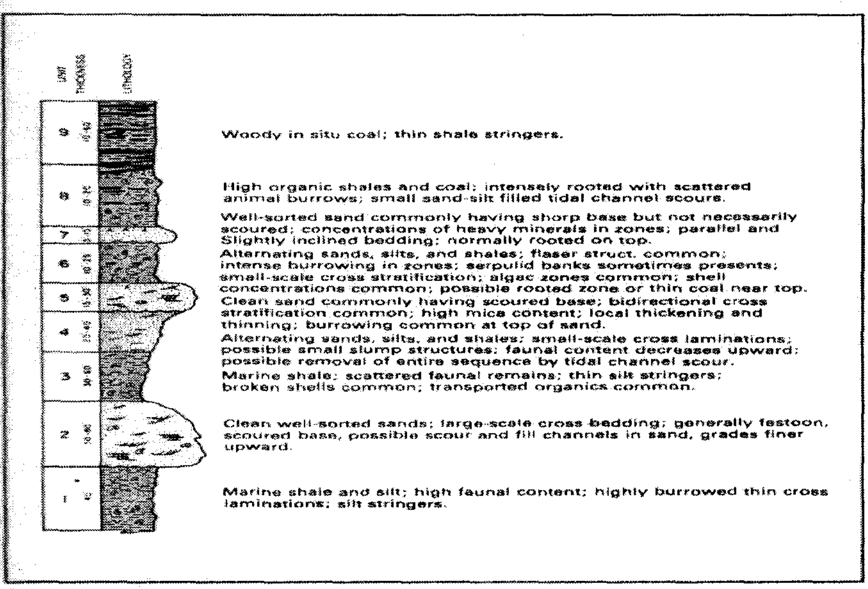


Fig. 5.6-30. Composite stratigraphic sequence of depositional environments in the Klang-Langat Rivers delta (from Coleman & Prior, 1980).

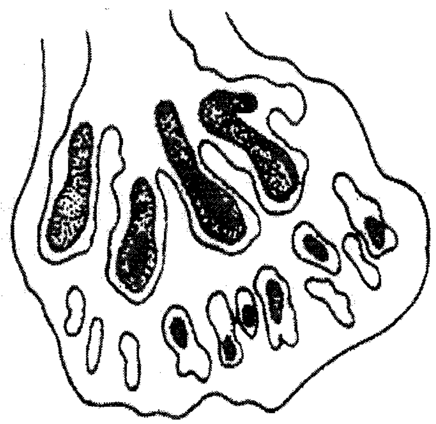
•**Geometry**

•Relative thick, elongated-sand bodies in the direction of the tide, comprising a complex of minor channels and mega-ripple sands.

•**Associated facies**

•Boundaries: Due to permanent bi-direction flow, abrupt planar and scour contacts dominate the sequences.

•Sequences: They tend to show coarsening-upward, followed by fining-upward, without a well-defined boundary.



TYPE 2

Conditions: low wave energy high tidal range, normally low littoral drift, narrow basin.
Characteristics: finger-like channel sands passing off-shore into elongate, tidal current ridge sands.
Example: Ord. Indus. Colorado. Ganges. Brahmaputra deltas.

Fig. 5.6-32. Sand distribution in a tide-dominated delta (from Coleman & Wright, 1975).

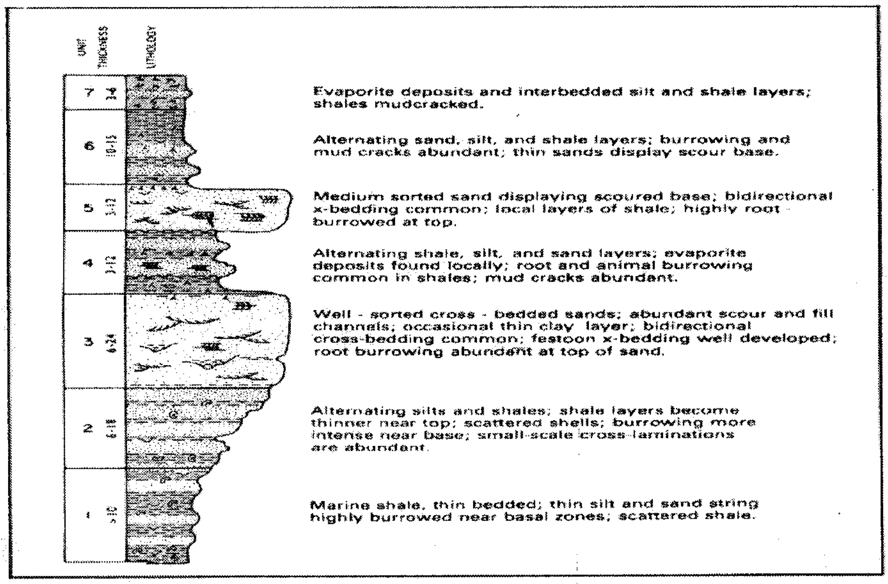


Fig. 5.6-31. Composite stratigraphic sequence of depositional environments in the Ord River delta, Australia (from Coleman & Prior, 1980).

Fan delta

- Fan deltas are alluvial fans that prograde out into a standing body of water from an adjacent highland (Holmes 1965).
- They generally develop on the flanks of basins next to fault bounded.

SHALLOW SEA CARBONATE

- **Definition**
- Environments characterized by carbonate deposits (biochemical processes) in shallow water (<100 m), but sometimes resulting from reworking and redistribution of those sediments by currents.
- **Sellwood, 1978: five zones F1**
- Supra-tidal: sabkha or evaporite
- Inter-tidal (shore zone): algal mat
- Sub-tidal (marine platform)
- Reef belt (back reef, reef core, fore reef)
- Shelf-slope

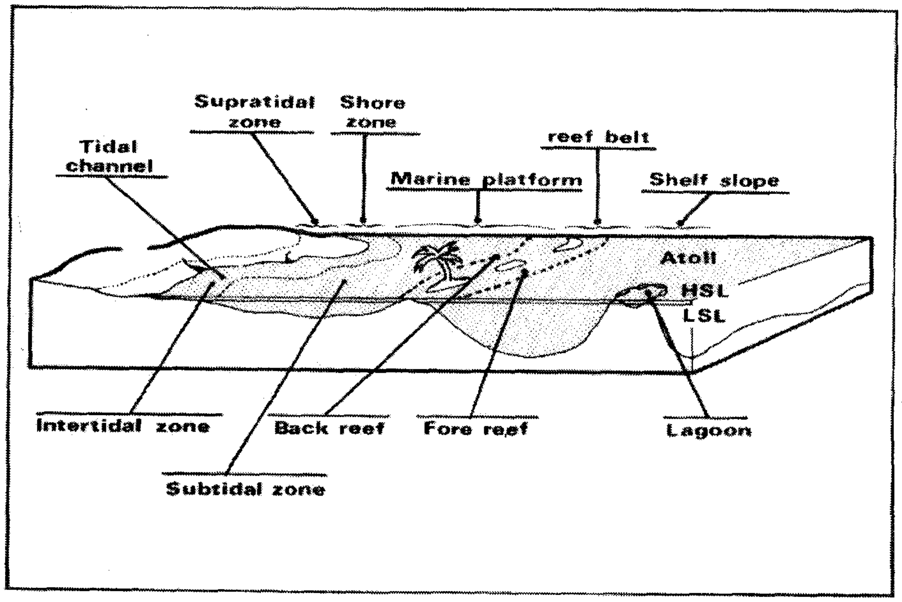


Fig. 5.8-1. Schematic block diagram illustrating the location of shallow water carbonate environments.

- Arid shoreline with low terrigenous input are characterized by carbonates & evaporites.
  - Supra-tidal: sabkha (evaporite)
  - Inter-tidal: algal mat, stromatolite
  - Lagoon: pelletal mud
  - Beach, tidal delta, bar: oolitic-skeleton grain-stone
- Shallow upward sequence: basal high energy, sub-tidal carbonate, inter-tidal stromatolite and top supratidal to terrestrial deposits.

- Inter-tidal:
  - Low energy tidal flat
    - Muddy sequence: tidal flat overlie a sub-tidal bioturbated micrite and thin skeleton lime sand
    - Grainy sequence: tidal flat overlie a sub-tidal cross stratified lime sand
  - High energy beach
    - Beach overlie a sub-tidal bioturbated micrite and thin skeleton lime sand

▪**Porosity**

▪Primary porosity:

▪It is refers to pore space (between particles or cavities within skeleton) that has been preserved since the sedimentary rock was deposited.

▪Secondary porosity:

▪It is refers to pore space (involves solution usually cut across grain) that has been created after deposition by diagenesis or fracturing.

▪**Carbonate deposition models**

▪**Carbonate shelf model:**

▪Coastal (high lying):

▪Fore-shore (beach): C grain, well sorted grain-stone

▪Shore-face (beach front): M grain, less well sorted grain-stone to pack-stone, common trough cross-beds generated by long-shore/ tidal currents

▪Off-shore (beach toe): F grain, less well sorted pack-stone to wacke-stone, common burrow and abundant marine fossils

- Coastal (low lying):
- Supra-tidal: consist of tidal flats/ marshlands in temperate area and sabkhas in arid area
- Inter-tidal: consist of laminated mud in broad ponds between channels, pelleted mud on the gently sloping sides of channels
- Sub-tidal: consist of channel deposits, commonly pellet muds and mollusk shell packstones, that formed as placer/ lag deposit

- Shelf (facies mosaic): evaporite, muddy dolomite
- Muddy shelf sand: widespread of pack-stone and wacke-stone
- Tidal delta: lime mud on the calm side of narrow passageway between barrier islands
- Mud bank: they might be called bioherms or reefs develop as wave resistant
- Patch reef: rapid construction of skeletal/ colonial carbonate debris
- Shelf sand: carbonate sand frequently extending shelf-ward for 10-15 km from the shelf margin
- Shelf basin: deeper depression/ sag develop within a large shelf area filled with marine shale/ carbonate

- Shelf margin: light color, coarser grain

1. Ecologic reef: wave resistant organic buildups
2. Shelf margin sand (carbonate sand shoals):
   - Skeleton debris (washed shelf-ward by current & storm)
   - Oolitic sand (elongate/ belt of sand bars, shelf-ward in high energy or high carbonate precipitation)

- Fore-slope: by-pass type
- Talus and breccia fan: coarse grained carbonate range from sand size to house size
- Pinnacle/ patch reef: back reef and fore reef
- Turbidite: fining up detrital, dark mud with pelagic forams

- Basin: dark color, finer grain
- Carbonate began to dissolve in marine sediments, generally about 4-5 km
- Euxinic basinal muds: dark, organic rich, lamination
- Pelagic oozes: skeleton rich, lamination, mud convert to chalk
- Turbidite sand and debris flow: coarse to fine sand/ mud, thin bedded with slump structures
- Carbonate ramp:
- It is no slope break, tend to be broaden and high energy zone is close to shore.
- It is less common than the carbonate shelf and in fact probably represent the earliest depositional stage in development of a typical carbonate shelf.

- **Classification of carbonate rock**
- Folk classification, 1962
- Lime mud/ micrite: aragonite clay/ skeleton debris silt
- Grains: carbonate silt/ sand/ gravel
- Pore space: filled by clear sparry calcite cement
- Dunham classification, 1962
- Carbonate mud:
- Grains:
- Binding by in situ growth:

▪**Carbonate grain types**

▪Skeleton grain:

▪Un-abraded to abraded shells/ colonial masses

▪Ooids and Pisoliths:

▪Ooids are concentric coating around a detrital nucleus in agitated shallow marine, size 0.3-1.0 mm in diameter. Some ooids may display radial fiber, indicating formation in hypersaline lakes.

▪Pisoliths/ Oncoliths are concentric coating around a detrital nucleus in low energy setting, size 2-10 mm in diameter, The coatings are algal layer in marine/saline lake or caliche layer in shallow soil.

▪Pelletoids:

▪Most pelletoids are originated as fecal pellets from various marine invertebrates. Some may also be altered ooids/ lithoclasts.

▪Modern pelletoids range in size from 0.1-2.0 mm.

▪Pelletoids can produced in all environments, but tend to be destroyed or winnowed out from high energy, and preserved in low energy environments.

▪Aggregates and lumps:

▪They are carbonate grains and fragments joined together by a cryptocrystalline matrix or organic binding or submarine cementation.

▪Illing (1954) called such aggregated particles "lumps" and recognized several types: grapestone/ botryoidal lump, encrusted lumps.

▪Lithoclasts:

▪They are rock fragments resulting from the uplift and erosion of older carbonate rocks.

▪Lithoclastic rocks are called calclithites, usually associated with major fault scarps in arid climates.

▪According to Dunham, depositional environment can be obtained from the present of mud (calm water) or absent of mud (agitated water). He also identified carbonate rock into 3 textures: abundance of mud, abundance of grain, and signs of binding.

▪Mudstone: < 10% grain, mud supported

▪Wackestone: > 10% grain, mud supported

▪Packstone: some mud, grain supported

▪Grainstone: no mud, grain supported

▪Boundstone: bound together during deposition

▪**Lithology**

▪Composition

▪The dominant mineral is calcite, but dolomite, gypsum and anhydrite can be present and abundant in supra-tidal and inter-tidal zone.

▪Terrigenous clastic materials may be interbedded with previous deposits if the platform is connected to a continent or transported by windstorms.

▪Iron-oolites and sideritic ironstones may be present on shoal (swell) areas.

▪Phosphates and glauconite may occur.

▪**Structure**

▪ Sedimentary structures generally define clearly the environment and are listed in F2.

▪**Geometry**

▪Facies related to environments can be distributed as successive belts, parallel to the coastline of as atolls or pinnacles.

▪Associated channel deposits (channel fill, levees) are present in inter-tidal and supra-tidal zones.

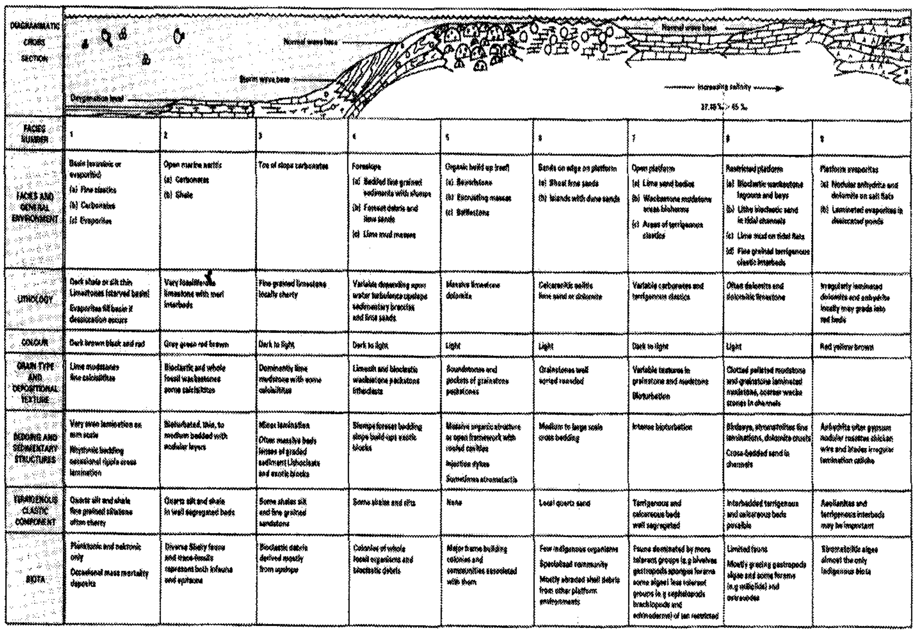


Fig. 5.8-2. The scheme of standard facies belts (adapted from Wilson, 1975).

- **Associated facies**
- Boundaries:
- Due to sequential evolution the boundaries are often not well marked. F19
- Sequences:
- Shallow-up because carbonate accumulations are repeatedly build up to sea level and above. Shallow-up from sub-tidal (B) > inter-tidal (C) > supra-tidal (D) are show in F3 & F4.
- Arid (Persian Gulf) and humid (Florida-Bahamas) are show shallow-up in F5 F6.
- Deepening-up can also exist due to marine transgression (subsidence or eustatic change) F7.

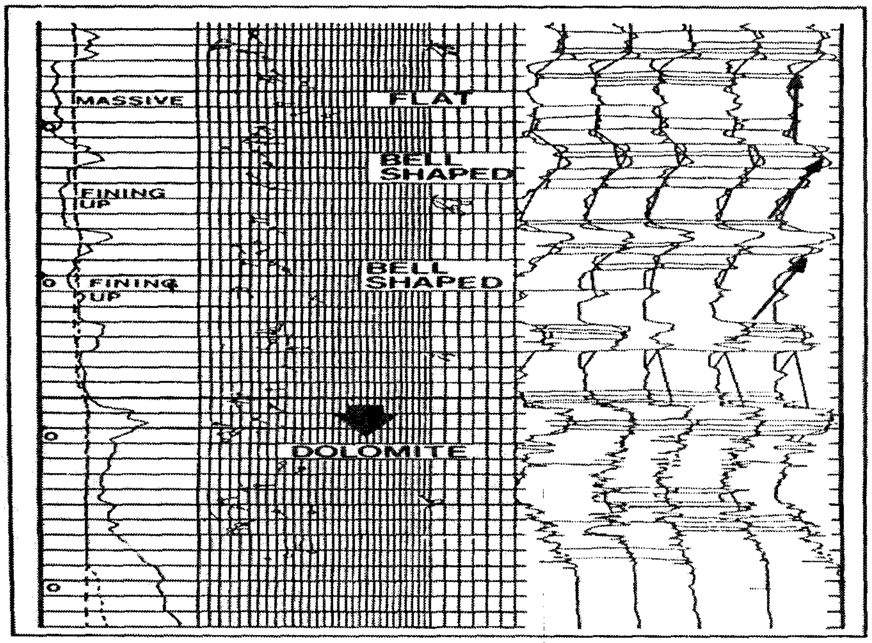


Fig. 5.8-19. Example of resistivity evolution in carbonate formation (from Theys et al., 1983).

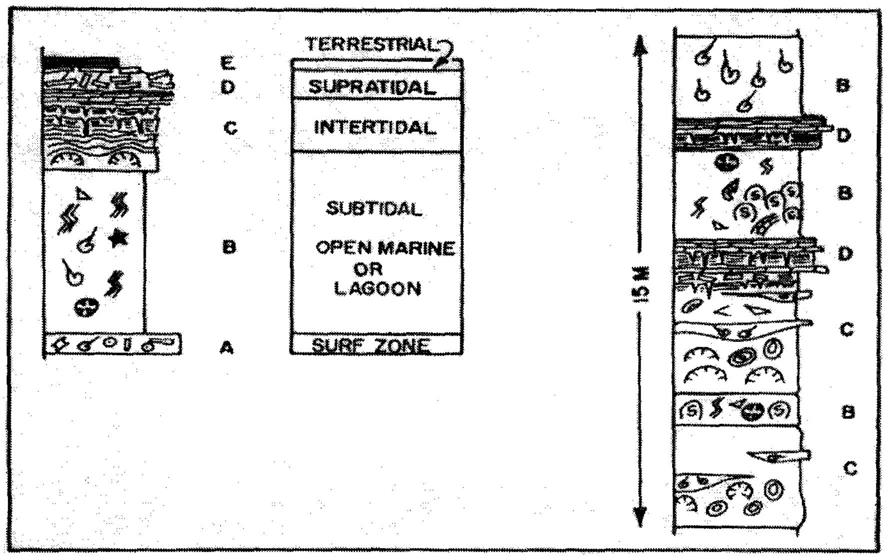


Fig. 5.8-3. The five divisions of the shallowing-upward sequence model for carbonate (from James, in Walker, 1979).

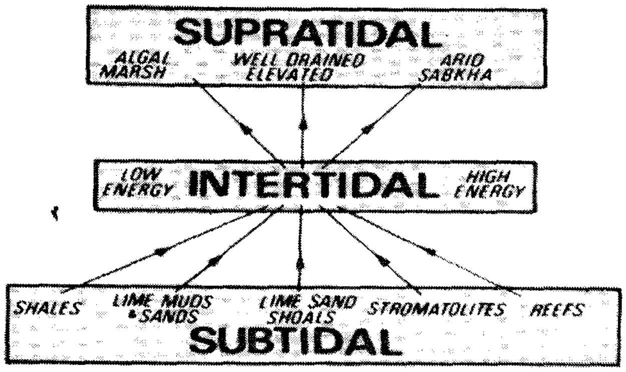


Fig. 5.8-4. A flow diagram indicating the various possible environmental transitions present in a carbonate shallowing-upward sequence (from James, in Walker, 1979).

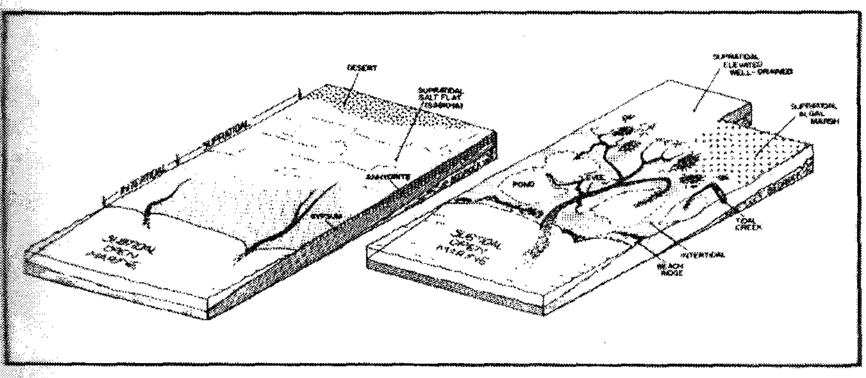
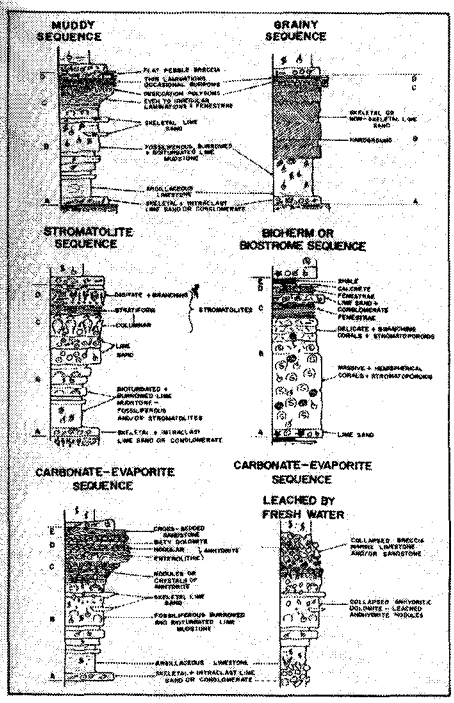


Fig. 5.8-5. Block diagrams showing the major morphological elements of a tidal flat; (a) a hypersaline tidal flat with few tidal channels bordering a very arid desert; (b) a normal marine tidal flat with many tidal channels and ponds bordering an elevated well-drained area of low swamp algal marsh in a humid climate (from James, in Walker, 1979).



◄ *Fig. 5.8-6. Theoretical sequences in different transitions from sub- to supra-tidal subenvironments (from James, in Walker, 1979).*

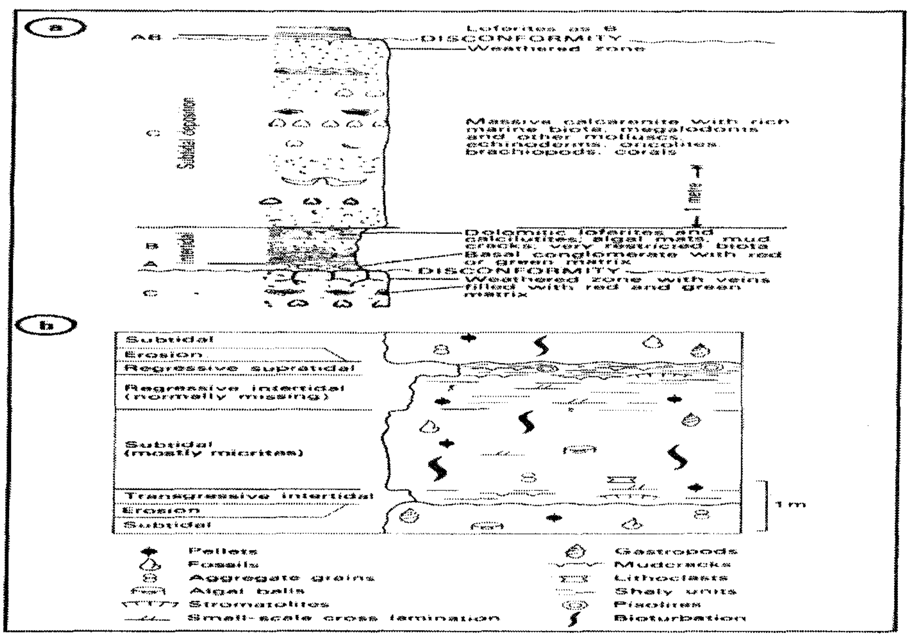


Fig. 5.8-7. Two examples of deepening-upward sequences: (a) an idealized Lofer cyclothem (after Fisher, 1964, 1975); (b) an idealized cycle for the Calcare Massiccio, Italy (after Colacicchi et al., 1975).

- **Wire line log**
- Many logs may not be useful in carbonate rock because of mono-mineral, less argillaceous, tight lime, and do not detect unconnected pores.
- Sonic may be much less detect porosity because grain to grain contact are more cohesive, providing low transit times.
- Density-Neutron cross-plot, points on/below the limestone line.
- Radioactivity in pure limestone is generally low except in shaly limestone, organic limestone or phosphate limestone.

- Dipmeter resistivity shows no event in VH level, which corresponds to tight limestone / dolomite F11.
- Dipmeter resistivity shows no event in M-H level, which corresponds to mudstone / wackestone limestone deposited in back-reef to lagoon F10.
- Dipmeter resistivity shows thin events in L-M activity, which corresponds to grainstone / packstone limestone F12.
- Dipmeter resistivity shows uncorrelated events in M-H activity, which corresponds to wackestone / boundstone limestone. Often conductive if it is vuggy F14 but resistance if it is limestone / dolomite / anhydrite F15.

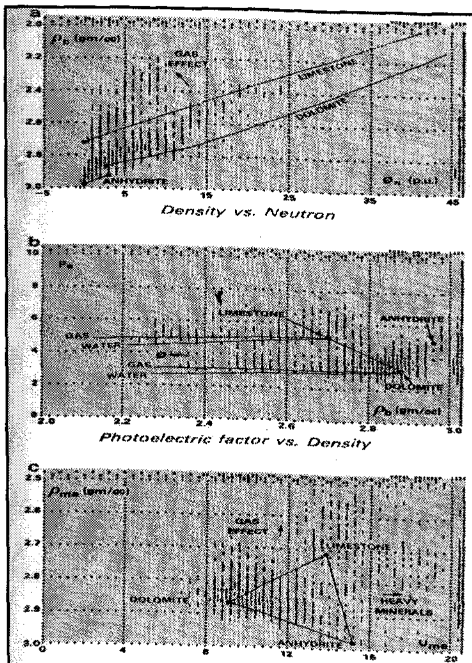


Fig. 5.8-9. Cross-plots (a): density-neutron; (b): photoelectric factor-density; (c): $(\rho_{ma})_a$ - $(U_{ma})_a$ (from WEC Emirates/Qatar, 1981).

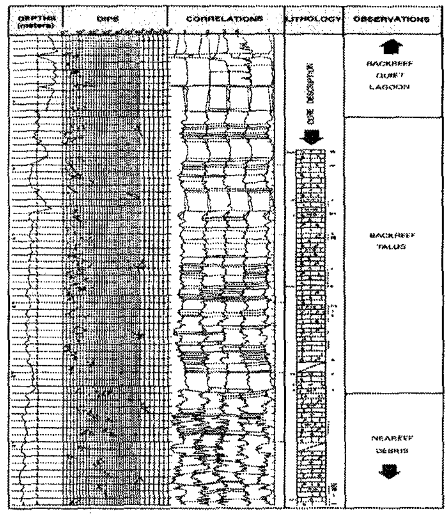
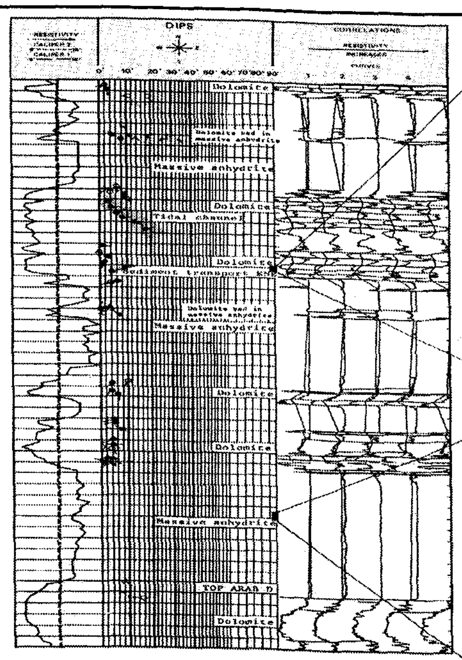


Fig. 5.8-10. Typical GEODIP responses in reef, backreef and lagoon subenvironments (from Theys et al., 1983).



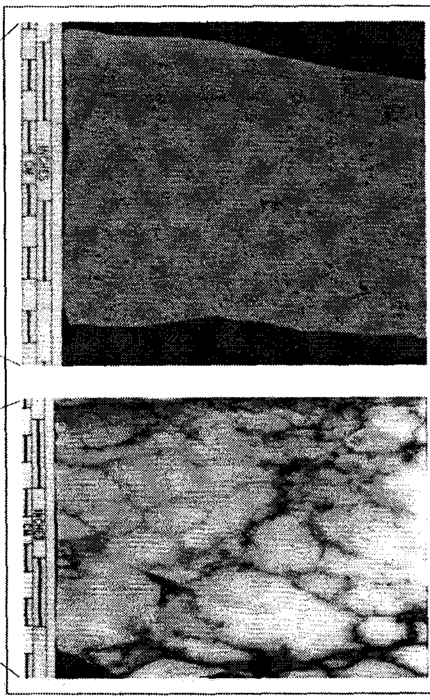
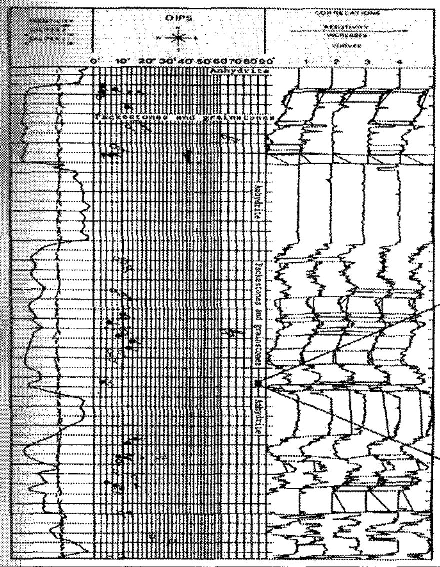


Fig. 5.8-11. Interpretation of GEODIP in terms of facies and subenvironments according to the curve activity and the dip patterns.



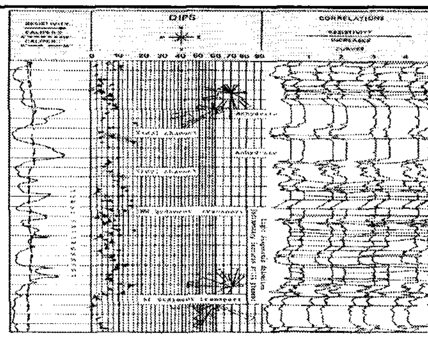
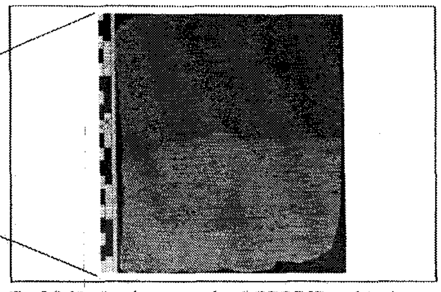


Fig. 5.8-12. Interpretation of LOCDIP display in terms of facies and subenvironments according to the curve activity and the dip patterns.



◄ *Fig. 5.8-13. Another example of GEODIP and its interpretation. The blue patterns indicate a direction of transport toward ESE.*

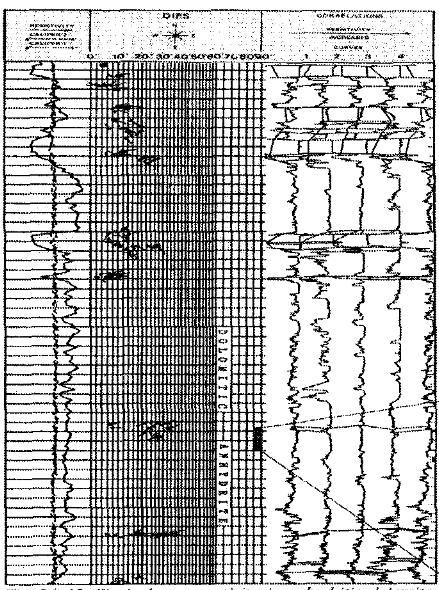


Fig. 5.8-15. Typical curve activity in anhydritic dolomite to dolomitic anhydrite (nodules of anhydrite in dolomite).

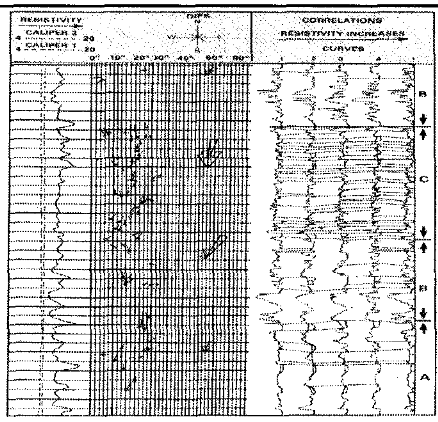
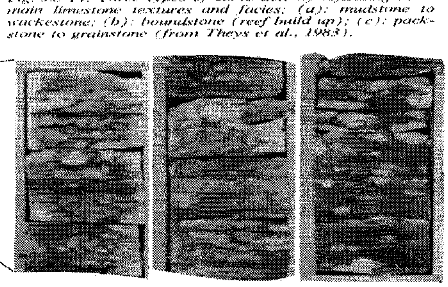


Fig. 5.8-14. Three types of curve activity reflecting three main limestone textures and facies: (a): mudstone to wackestone; (b): boundstone (reef build up); (c): packstone to grainstone (from Theys et al., 1983).



- Blue dip patterns can be interpreted as fore-set of back-reef talus or tidal channel point bars. F11&F12
- Red dip patterns can be interpreted as tidal channel fills. F11&F12
- Green dip patterns can be interpreted as lamination limestone / shaly limestone. F16

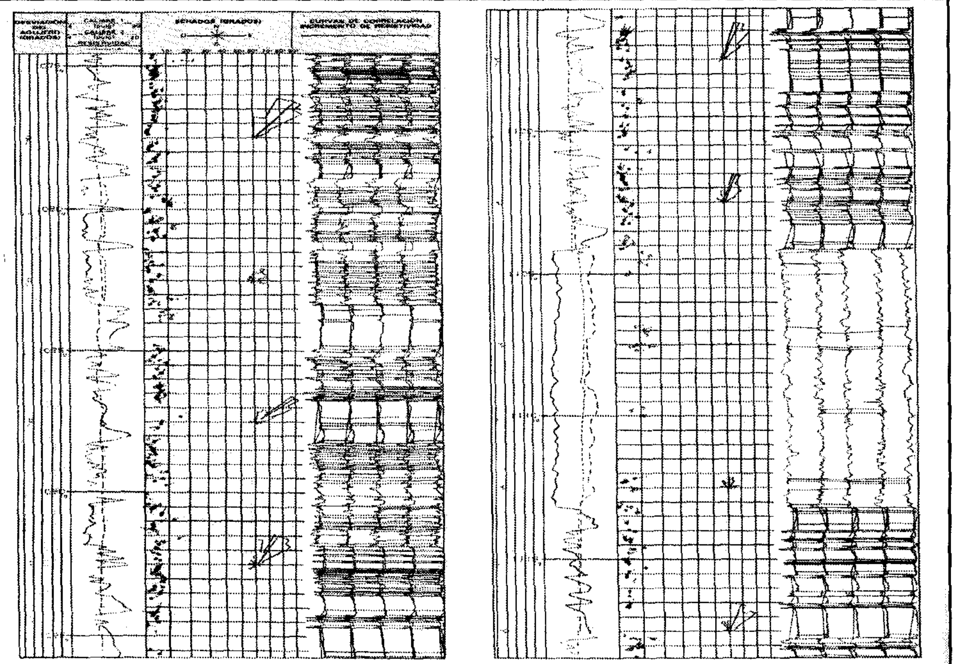
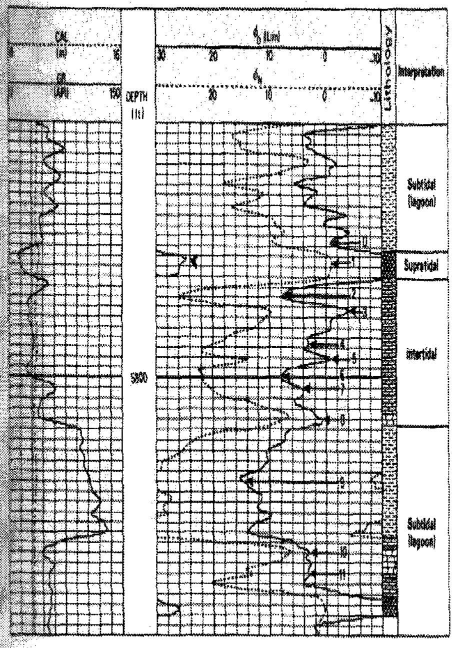


Fig. 5.8-16b. Example of very thin laminations, sometimes shaly, in a limestone-dolomite formation (from Evaluacion de formaciones en Mexico, 1984). GEODIP arrow-plots on a short interval of Fig. 5.8-16a.



◀ *Fig. 5.8-17a. Composite-log of Desert Creek Formation, Paradox Basin.*

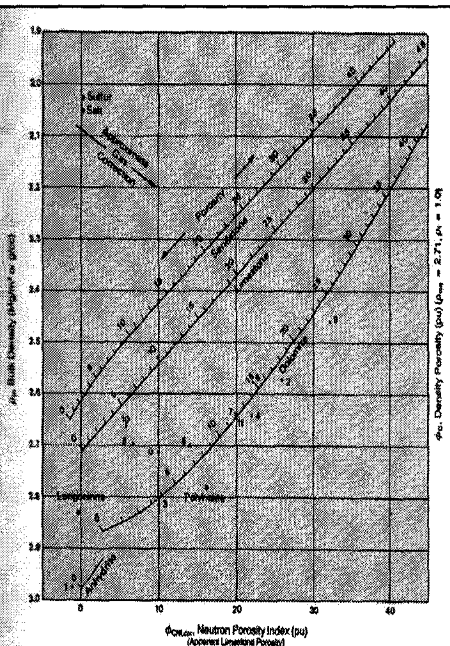


Fig. 5.8-17b. Cross-plot ρ_b or ϕ_N.

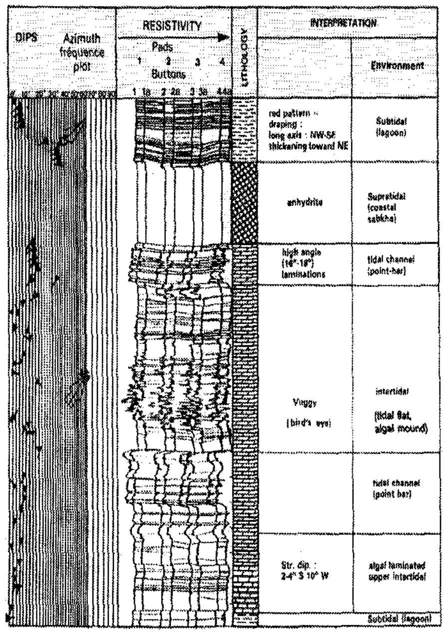


Fig. 5.8-18. LOCDIP display on the same interval and its interpretation.

▪**Seismic**

▪Seismic are generally less susceptible to carbonate facies model. However, topography in shelf margins & pinnacle reefs, large scale accretion bedding, and density contrasts between carbonates and salt/ shale.

▪**Petroleum aspect**

▪Excellent reservoirs can be formed in dolomitized inter-tidal, sub-tidal, and tidal-flat successions which provide widespread zones of fine inter-crystalline porosity.

▪Evaporite layers serve as top seals, seat seals, or lateral seals.