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A Brief Introduction to Turbidite Channel Depositional Systems

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Abstract

This article provides a detailed introduction to the concept, formation process, regional division, and depositional characteristics of deep-water turbidite depositional systems. Turbidity currents are sediment gravity flows characterized by turbulence, which mainly occur in deep water areas below the wave base. The depositional system can be divided into three regions: upstream convergent channels, midstream deep-water channels, and downstream terminal fans. The upstream area is dominated by sand-rich sediments, but lacks effective sealing layers; the midstream area develops a single supply channel complex, forming natural levee deposits; the downstream area has a weakly restricted channel network system, with frequent avulsions forming sand-rich overbank deposits. In addition, the article also discusses the oil and gas reservoir potential of different depositional facies, pointing out that channels filled with high-density turbidite facies have better reservoir properties, while channels filled with debris flow facies have poor reservoir properties. Overall, this article provides a comprehensive analysis and description of deep-water turbidite depositional systems, and has important reference value for research and exploration in related fields.

Keywords

Gravity Flows; Debris Flows; Breach Fans; Branch Channels.

1. Introduction

Debris flows are gravity flows of sediment characterized by turbulent flow. Sediment transport is a combination of suspended and bedload transport. Debris flow deposits are primarily found below the wave base and, therefore, are found on the continental slope or in deep water near the basin margin. Most deep-water sediments are derived from the shelf edge sediment source areas and are transported to the deep water by two main processes: 1) sediments are transported to the shelf edge by rivers and are stored there for a period of time before becoming active due to slope failure, and then are transported downslope by debris flows (Figure 1). The transport process begins as blocky transport, which is laminar in nature. As flow velocities increase, the laminar flow may transition to turbulent, or it may not. If the laminar flow does not transition to turbulent, then the resulting deposit is a blocky transport deposit: mainly slide, slump, and debris flow deposits. If the laminar flow does transition to turbulent, then turbulent debris flows are observed. 2) Sediments are transported to the shelf edge by rivers and, because of the high sediment load during high flow periods in the river, the water carrying the suspended load (freshwater) may be denser than the seawater and a high density bottom current, or density current, will develop and propagate downslope. As the fluid flows downslope, these density currents will transform into true gravity flows.[1-7]

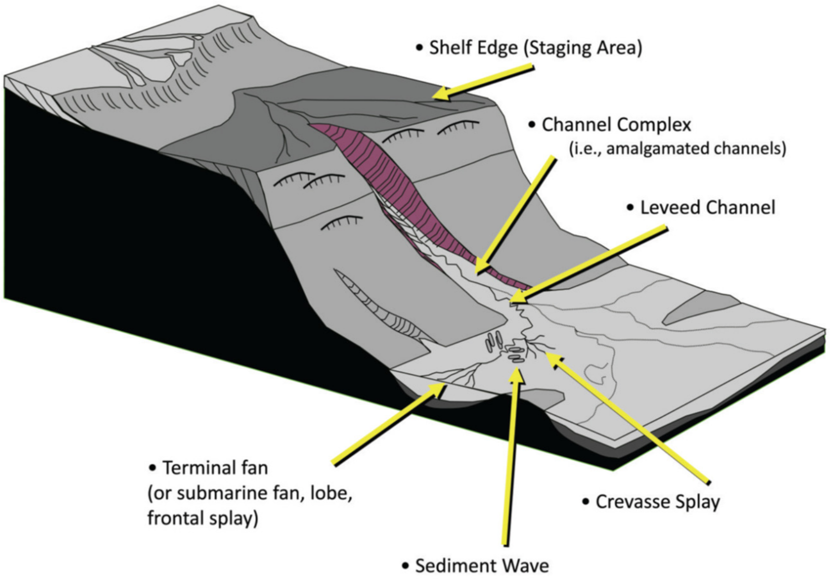

Figure 1. Schematic diagram of morphological units related to deepwater turbidite deposits

The turbidite system can be divided into three zones: 1) the distributary channel zone, which is the most upstream part (nearest to the shelf edge) of the system. 2) The transition zone[8], which is characterized by a single channel complex from the continental slope to the basin floor. 3) When the fluid reaches the basin floor and decelerates, the single channel complex will transform into a fan-shaped channel complex (Figure2)

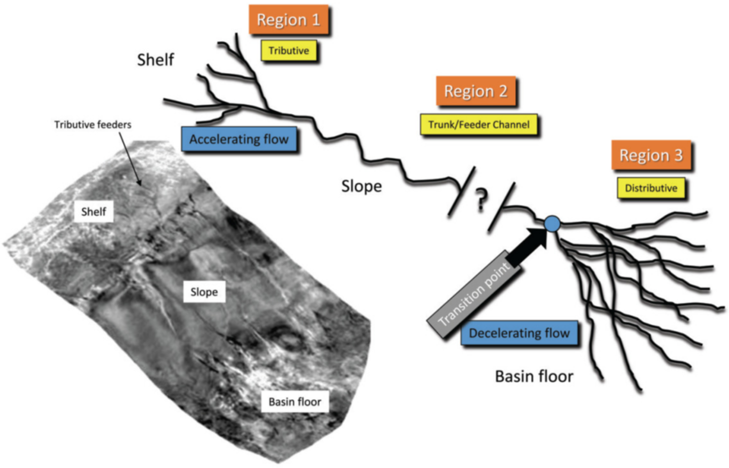

Figure 2. Schematic diagram of turbidite depositional system

1.1. Upstream Converging Waterways

The uppermost region of a turbidite system is typically characterized by convergent ribbon-type channels derived from the continental shelf .The sinuosity of the tributaries is obviously lower than that of the main channels fed by them. A very distinct transition from low to high sinuosity was observed upstream, leading to the conclusion that block transport (i.e., laminar flow) dominated in the upstream part[9], while turbulent flow prevailed further downstream (Figure 3).

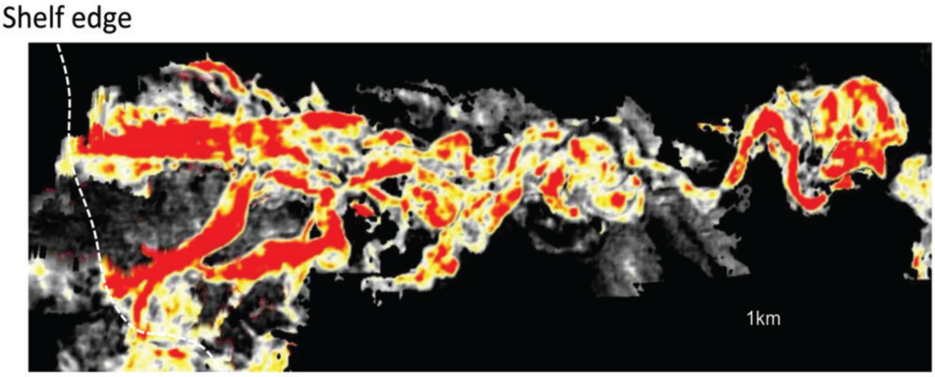

Figure 3. Upstream Amplitude Diagram

Coarse-grained sediments are present in the upper reaches of the submarine canyons but, with respect to hydrocarbon exploration, there is a lack of effective seal strata for turbidite deposits.

2. Deepwater Channels of the Middle Course

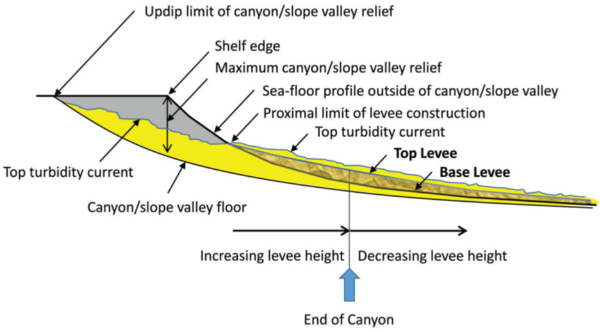

Figure 4. is a schematic cross-section of a canyon extending from the shelf edge to the basin floor.

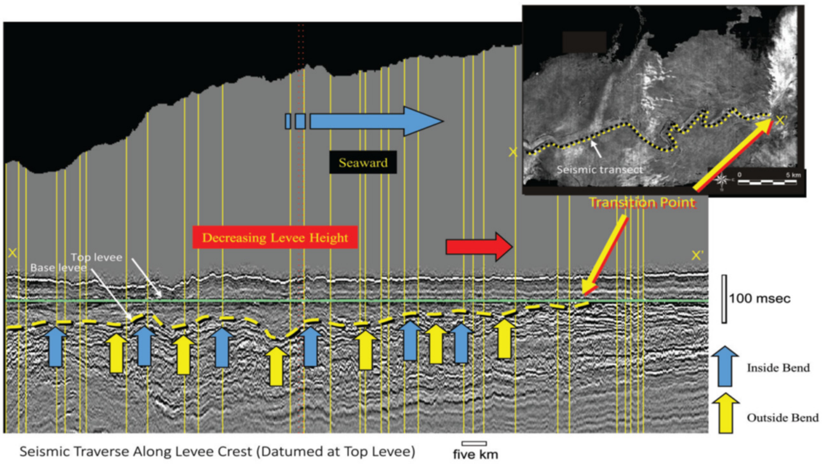

Figure 5. Seismic profile across the top of the natural levee in Makassar Strait, Indonesia

The deep water channel is a single supply channel developed in a valley/slope gorge, consisting of a number of smaller scale channel units. The main channel has some sinuosity and forms a submarine fan or apron at the mouth.As the valley floor drops below the channel floor, bankfull overflow deposits such as natural levees form. Natural levee construction occurs only if the top part of the flow overspills the bank.Beginning at the position of natural levee development upstream, the height of the natural levees increases downstream as the amount of valley incision and erosion decreases (Figure 4). The more gradual slope of the valley floor compared to the adjacent slopes reflects the reduced relief of the erosion. Away from the shelf edge[10], as the distance along the slope increases towards the sea floor, the slopes of the slope and valley eventually converge such that the slope of the sea floor equals the slope of the valley. Here, the height of the natural levees is at its maximum, and the height of the natural levees decreases gradually from this point both upstream and downstream (Figure 4). Figure 5 shows a seismic cross section of the top of a natural levee on the right bank of the turbidity current channel, with the levee height decreasing towards the distal end. Locally, the height of the levees will vary depending on whether they are situated on the concave or convex bank of a sinuous channel. The levees are thicker at the concave bank (outside bend) and thinner at the convex bank (inside bend) and thin gradually towards the distal end (Figure 5).

As the load of sediment in the longshore current gradually decreases, and the gradually decreasing volume of water leads to a gradual decrease in the height of the natural bar[11]. Because the deposit of the natural bar causes the fine particles in the water to be lost, even though the sediment of the water decreases, the overall sand content of the water increases. The water not only loses some sand due to its own deposit on the bed, but also mainly loses the fine particles, because the upper part of the water is mainly composed of fine-grained components. And the reduction of base-level erosion leads to shallower channel depth and gradually lower natural bar height, allowing the more sand-rich part of the water to approach the top of the natural bar. The lower part of the water, not only rich in sand, but also with stronger hydrodynamics, so when this part of the water rich in sand reaches the height of the natural bar, the channel will be cut off and a fan-shaped depression will form. When the rich-sand water continues to overflow, the occurrence of channel cutting and fan-shaped depressions becomes more and more frequent, especially on the outside of meandering channels, where fan-shaped depressions are more common (Figure 6).

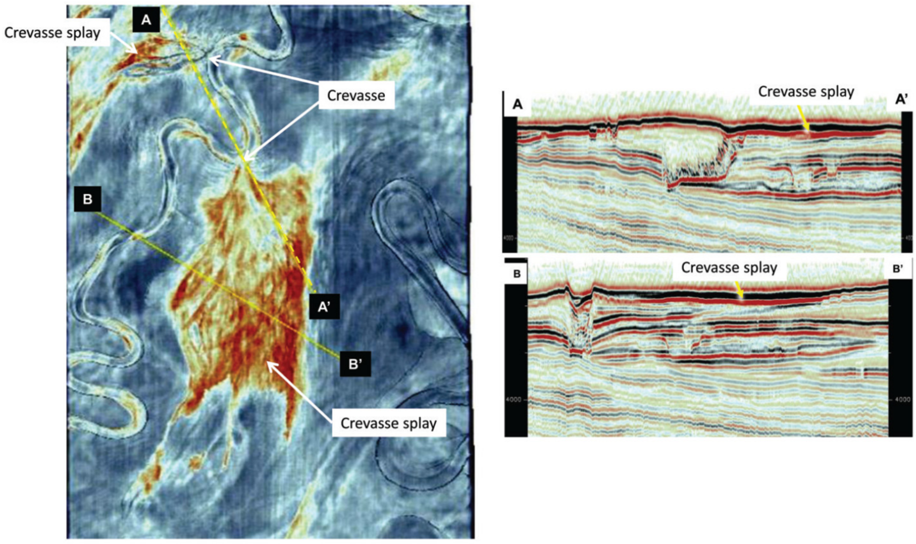

Figure 6. watercourse and breach fan complex

For the deep-water channels, the rock types are diverse, and different scholars have proposed different classification schemes. Five main types of sediments in deep-water channels were recognized by previous workers: turbidites, slumps, mud-rich debris flows, hemi-deep water channelized flows, and prodeltaic deposits.Hemipelagic sediments and mixtures of the foregoing four types; in addition, deep-water gravity flows have been divided into low-density turbidity currents, high-density turbidity currents, and debris flows by some workers[12].

1) Low-density turbidite facies. The low-density turbidite facies often develops cross-bedding, wave-bedding and lens-shaped bedding. The rock types include stratified fine sandstone, stratified mud-rich sandstone, sand-mud conglomerate and blackish-gray mudstone. Except for the cross-bedded sandstone, they all have the feature of high mud content and poor porosity and permeability. The water dynamics at the time of deposit was weak and stable. The coarse-grained sediments with high density, such as gravel and coarse sand, had already been deposited[13]; the fine sand grains and mud began to slowly deposit, forming a thin layer of medium to fine sandstone or interbedded thin layers of sand and mud. The grain size decreases gradually from bottom to top, showing a positive Prosodic features.

2) High-density turbidite facies. The high-density turbidite facies is composed of high-density, poorly to very poorly sorted sandstone sediments.The rock types are medium-fine grained sandstone[14], blocky gravelly-coarse grained sandstone, and blocky mud-cobble gravelly-coarse grained sandstone, which belong to high density turbidite origin. They have the characteristics of low mud content, high porosity and permeability. The depositional environment has relatively strong and stable hydrodynamic conditions, forming medium-coarse sandstone bodies or thick layers, with only a small amount of gravel (cobblestones). The grain size variation is not significant throughout the sandstone layers. Gravel layers with traction structures or drainage structures can be seen at the bottom of some sandstone layers.

3) Debris flow facies. The debris flow facies is mainly composed of high-density, complex, and poorly sorted debris flow sediments. It often contains abundant mud clasts or gravel, with gravel sizes ranging from a few millimeters to a few centimeters. The main lithologies include mudstone interbedded siltstone formed by debris flows, blocky sandstone conglomerate formed by bottom retention deposition, and blocky mudstone siltstone formed by debris flows. These sediments have the characteristics of high mud content and poor porosity and permeability[15]. A large amount of sediments move from the slopes to the deep sea along the continental slope during deposition. The hydrodynamic conditions are strong but unstable. At this time, the debris flow blocks moving as a whole are more likely to be blocked and deposited downward than other dispersed sediment particles, carrying sand-sized or mud-sized particles to form blocky conglomerate.

Based on the porosity-permeability conditions, it can be analyzed that the main rock types of the waterway with high density turbidite filling have less mud content and stronger reservoir properties, which can form good reservoirs; some waterways with low density turbidite filling and pebble-sand mixed filling have more mud in the rock types, which have some effects on the reservoir properties and form general reservoirs; when the rock type of some low density turbidite filled waterway is mainly cross-bedded sandstone, it can serve as a better reservoir type[16]; the rock types of the waterway with isopachous filling and pebble-sand mixed filling are diverse, with more gravel and mud sediments, which are not conducive to the migration and accumulation of oil and gas and form poor reservoirs; the internal rocks of some debris flow filled waterway are mainly bottom retention deposit and mud debris flow deposit with high mud content and many mudstone interlayers, which can act as seepage barriers and play a role in isolating the deep waterway or lobe reservoirs, thus forming different development units. When the rock type of debris flow filled waterway is mainly sandstone debris flow with low mud content, its porosity-permeability conditions are good, and it can serve as a better reservoir.

There are certain rules for the spatial rock types of channels: (1) In the vertical direction, the channel is mainly composed of debris flow sediments;(2) Along the source-to-sink direction, in the channel systems formed by a single turbidity current event, the single channel shows different types of causes with the change of internal flow conditions: the channels filled by debris flows or with higher debris flow proportion are distributed closer to the canyon and continental slope[17], while the channels filled by high-density turbidity flows or with higher high-density turbidity flow lithology are closer to the source area. The channels filled by low-density turbidity flows are further away from the continental slope compared with the channels filled by high-density turbidity flows.

Sinuous channels may be organized in a systematic manner or in a more chaotic manner. Systematic organization results from progressive lateral migration, while a series of sinuous channel elements with both lateral and vertical migration is more chaotic.

In an orderly channel sequence, a series of channels are developed by a series of turbidity current events, but the channels are not completely filled. That is, when one turbidity current event ends, the channel is not completely filled, leaving a channel space for the next turbidity current to reuse. However, due to the fact that the energy of the subsequent turbidity flows is higher than that of the previous flows, an imbalance occurs at the bottom of the channel, leading to partial erosion of the early turbidity flow deposits. This also results in the partial preservation of early turbidity flow deposits and the gradual migration of channels away from the sinuous margin[18]. In an orderly channel pattern, the axis part of the early channel will be preferentially eroded, while the parts deviating from the channel axis and the channel margin will be systemically preserved. Orderly channel sequences are usually characterized by a "downward concave" feature on seismic sections. This may be due to the systematic decrease in fluid energy of deep water turbidity flows[11].

Sinuous channel sequences, formed by individual turbidity currents that completely fill their channels during continuous turbidity events, exhibit a trend of later turbidity flows not immediately re-establishing on the original path. This is exacerbated by differential compaction, with sinuous channel fills assuming an upwarped form that forces subsequent flows into different pathways. Recent studies of turbidite channel fills have shown that within a few thousand years after deposition, differential compaction related to desiccation of the overlying mudstone causes a reversal in the geometry of the fill surface such that the mudstone becomes 'upwarped' and the sandstone 'uparched' due to differential compaction. Typically, channel fills associated with the random channel pattern exhibit a sudden change in channel topography due to adequate fill and abandonment of the channel, in contrast to the fining-upwards fill pattern common in ordered channel sequences.

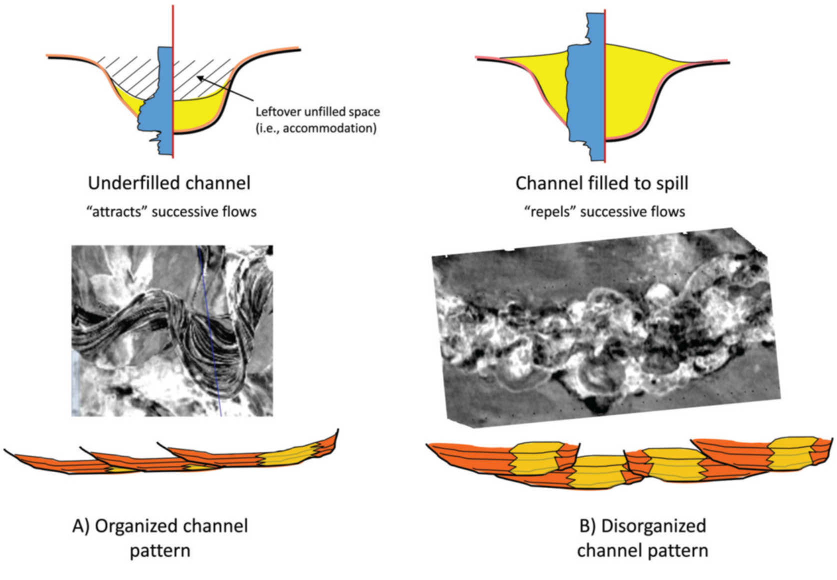

Figure 7. Comparison of stratigraphic, geomorphic, and well log response characteristics between ordered and disordered channel complexes

For the ordered channel unit sequence, the fluid sequence follows a similar path, characterized by systematic offset superposition on the vertical section and wavy and streaky patterns on the plan view. The gradual abandonment of channel units results in a well log response with a sudden change at the bottom, gradually thinning up (bell-shaped) features. For the disordered channel sequence, the subsequent fluids are excluded by the "arched" bottom channels formed by the fillers, resulting in a random migration stacked pattern. At this time, the channels completely filled with sand exhibit a sudden change at both top and bottom (box-shaped) well log response characteristics (Figure 7).

From an oil and gas exploration standpoint, however, the disordered channel pattern is usually the most productive, as the channel axes tend to be better preserved than in the ordered pattern, where the axis deposition is usually continuously eroded.

3. Downstream End Fan

When the middle course river system transitions to a relatively unconfined, broad network of channels, the basin floor or sea floor plain is reached. These weakly confined channels disperse laterally across the sea floor and are controlled by the relief of the sea floor. In the absence of sea floor relief, they are fan shaped. However, where relief is present, the channels preferentially follow the low areas, and the channel coverage is relative to the sea floor relief (Figure 8).

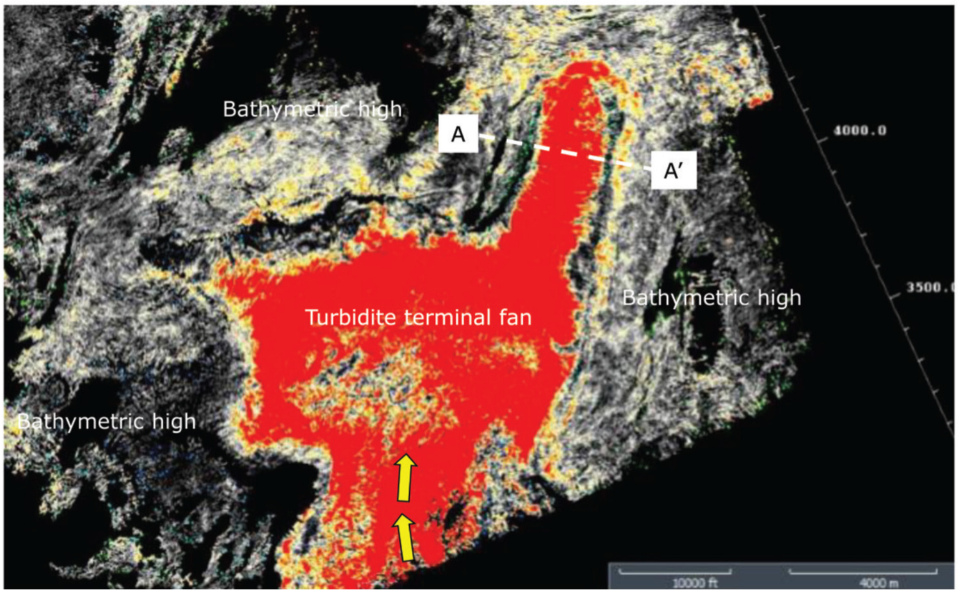

Figure 8. Deep-water fan terminations in regions of basin-floor topography

Downstream, where restrictions are weak, frequent bank failures lead to the development of a widespread network of weakly restricted channels in the adjacent plain. The channels on the terminal fan show a marked decrease in sinuosity compared with the main stem upstream. The frequent bank failures and the development of numerous avulsions on the terminal fan indicate that natural levees are not well developed, and hence the degree of channel confinement is also weak. In addition, because of the weak degree of confinement, it can be inferred that the bankfull deposits on the terminal fan will be more sandy than those in the main stem upstream. Consequently[19], both the channel and bankfull deposits on the terminal fan are dominated by sand.

As the fan margin moves away from the axis, the constriction of the channel weakens gradually, and the flow velocity decreases. Correspondingly, the scale of the channel becomes smaller. Meanwhile, the overbank deposit carrying a large amount of sand continues to develop at the periphery of the channel. As the scale of the channel becomes smaller and smaller and the sand-rich overbank deposit continues to develop, the morphology of the channel gradually approaches that of a sheet, and eventually the distal part of the fan is formed. This transitional geomorphology can be described as a sheetified channelized body, because the channel here is almost unrecognizable, but it is not a true sheet. The characteristics of a sheetified channelized body are that there is still some erosive ability at the bottom, though very weak, while a sheet will not erode the underlying substrate at all. Also, as the fluid velocity at the fan margin decreases, the turbulence will decrease and may even transform into laminar flow on the centimeter scale, resulting in mixed layer and debris flow deposits. The channels at the fan margin become smaller and smaller, and eventually they become too small to be detected by seismic surveys. The gradual change from large channels at the fan apex to small channels at the fan margin is related to the deceleration of sediment gravity flows. At some point, the flow will be slow enough such that little or no erosion occurs, and the fluid will fan out and form sheet deposits. The transition stage from channel to sheet is likely to have small channels, but the deposit is almost sheet-like, showing transitional characteristics, which is called a channelized sheet. The reservoir quality of these distal sediments, in terms of porosity and permeability, is generally poor.

Downstream end fans are generally divided into recharge channels, breach fans, overflow fans, terminal bars, and branch channels.Dao and Shipan dams: 1) The supply water channel is the high-density turbidite deposit with large concentration and coarse grains at the lower part of gravity flow, which may become a type of large and high-quality reservoir; 2) The breach fan is the sheet-like deposit formed by high-energy gravity flow along the breach towards the low-lying area of the levee, which may become a type of large and high-quality reservoir; 3) The overflow fan is the tongue-like deposit formed by low-density turbidite overflow from the channel, which may become a type of reservoir with possible large scale but low quality; 4) The terminal lobe is the sheet-like deposit formed by high-density turbidite experiencing fluid transition from restricted to semi-restricted or semi-restricted to unconfined, which may become a type of large and high-quality reservoir; 5) The branch channel is the ribbon-like deposit formed by gravity flow without bankfull overflow, which is a type of non-quality and non-large reservoir; 6) The point bar is the product of the erosion-deposition of secondary spiral current concave bank and convex bank, which may become a type of possible high-quality and non-large reservoir[20].

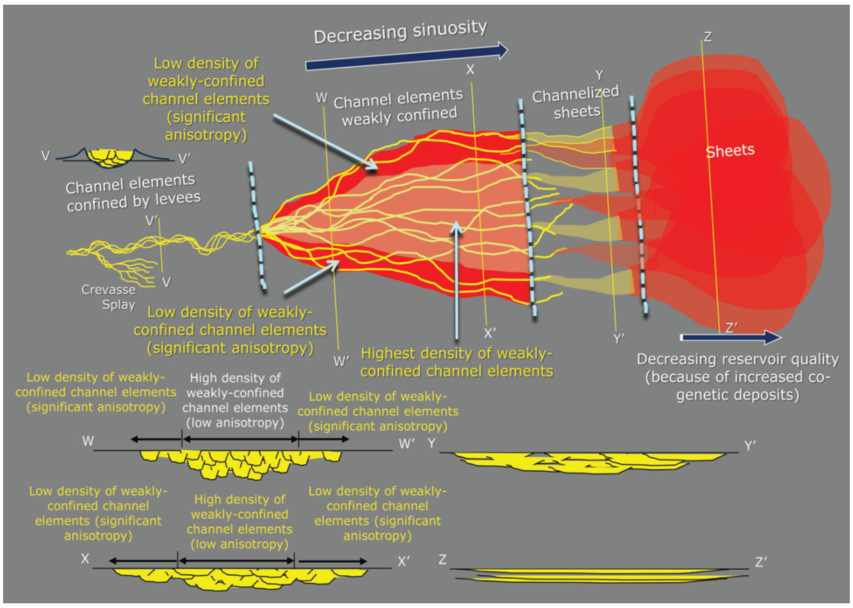

Figure 9. Overall plan and cross-section of the turbidite system

4. Summary

The turbidite depositional system can generally be divided into three areas: the upstream channel is close to the source area and includes the shelf edge and tributary supply canyons. In this area, the gravity flows are completely constrained by the canyon walls. This area is rich in sandstone sediments, but lacks effective seal layers for turbidite deposits. Therefore, it is not suitable for hydrocarbon reservoirs. The middle channel is characterized by the development of a single supply channel complex. The gravity flows are not completely constrained by the channel walls and often form natural levee deposits associated with the channels. The porosity and permeability conditions vary among different gravity flow facies in the supply channels. High-density turbidite deposits are relatively abundant, while the reservoir properties of interbedded sandstone and low-density turbidite fill channels and debris flow fill channels are better. Most reservoir properties of channels with high proportions of low-density turbidite facies are moderate, and those with high proportions of debris flow facies are generally poor. When the supply channel is over.

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