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THREE-DIMENSIONAL NUMERICAL MODELLING TO INVESTIGATE THE INFLUENCE OF SEA LEVEL CHANGE ON DELTA EVOLUTION AND SEDIMENTARY SEQUENCES

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Abstract: An algorithm 'Steepest descent' and a three-dimensional erosion equation were amalgamated to mimic the transportation into a basin under the conditions that; within hundred thousand years and with a constant sediment supply of 5000m^3, four distinct deltas would evolved in response to different sinusoidal sea-level cycles. From the experimental results sedimentary sequences were observed to develop thus: with lower amplitude sea levels, HST (high system tracts) formed when sea level was at its peak. This also matched up with the commencement of the FRST (forced regressive system tracts) that finally got completed as the sea level dropped to its minimum. At sea level low, just before its apparent ascension LST (low system tracts) were formed. TST (transgressive system tracks) got deposited with the obvious landward shift of the shoreline when sea level is rising. For the higher sea amplitudes, lack of sediment accumulation at the onset of highstand was evident, and almost all the systems tracts formed that happened to be sub-aerially exposed got eroded as sea level falls. And because sediments are being produced locally, it led to channel avulsion and delta lobes formation. Nevertheless, when shoreline re-transgressed most of the incised valleys were filled.
Keywords: Basin, Delta, Sea-level, System tracks, Delta lobe.

Introduction

The word delta (Δ) refers to the 4th capital letter of the Greek alphabet and can be defined as a triangular coastal sedimentary deposit at the mouth of a river discharging into standing body of water, in most cases oceans, but sometimes lakes. Typically, deltaic facies coarsen upward (Posamentier *et al,* 1998, Allen and Allen, 1990, Ritchie, *et al* 2004 and Finch 2005), nonetheless, complex interaction of different processes and conditions may results in different depositional patterns depending on the local situations. Coleman and Wright, 1973 and 1975, Orton and Reading, 1993 as well as Angela, 2003, have been studying deltaic depositional facies; they concluded that the morphology and sedimentary sequences of a particular delta depend on varieties of interacting dynamic processes, which

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include sediment load, grain size, relative magnitudes of tides, waves, and fluvial currents in addition to subsidence, eustacy and water depth at the depositional site. A particular classification of delta that was based on distinction in transport pattern on the delta divided it into river, wave and tide–dominated, with Mississippi, Nile and Ganges as corresponding examples (Allaby and Allaby, 2003, Seybold *et al*., 2007).

However, the manner in which sequences are stacked depends mainly on accommodation space and the amount of sediment a basin may receive (Ritchie *et al*, 2004, Finch, 2005). When sea-level drops or there is a tectonic uplift within a basin sediment coming into the basin would be much greater than the space that would accommodate it. This forces facies belt migrates towards the basin centre causing progradational stacking pattern as clinoforms (Hardy *et al*., 1994). Conversely, with sea-level increase, and so also water depth or if tectonic subsidence occurs, accommodation space would exceed sediment supply, facies belt will then tend to migrate towards the coastal area and stacks in a retrogradational fashion. But when sea level remains at a stand-still, sediment supply may tend to keep up with the accommodation space, facies then builds vertically forming an aggradational stacking pattern.

In recent years, there has been rapid development in computer modeling of geological processes (e.g. Lawrence *et al.,* 1990; Kendall *et al.,* 1991; Sinclair *et al.,* 1991; Hardy *et al* 1994; Bitzer and Salas, 2002; Overeem, *et al*., 2005). Even so, published works on delta have been mainly on specific case studies. It is therefore important that deltas are modeled considering the fact that they have large spatial and temporal dimension with complex sedimentary records (Angela, 2003). Numerical modeling is therefore an essential tool that can aid in understanding how different factors control the development of the morphological and architectural features and sequence variability in sedimentary environments we observe in the field. Overeem *et al.,* (2005) described deltaic systems as ‘’bypass zones’’, and only a portion of sediments produced by the drainage system can actually be held at that zone, most of the sediment accumulated is as a result of erosion of the topographically higher surfaces and re-deposition into low laying surfaces by fluvial incisions as they are likely to be sub aerially exposed.

In this work, a three-dimensional numerical modeling approach is employed to examine how sea level changes and sediment influx can produce different delta morphologies.

Significant changes on delta evolution will be modeled over a hundred thousand years with an initial specific volume of sediment contribution that will come from the catchments to the basin per time step at different sinusoidal sea-level amplitudes.

Problem definition

Formation of delta entails complex interactions between different geological processes such as sediment influx, sea-level fluctuations, wave actions, tectonics, etc. Each exerting certain degree in controlling the morphological and architectural features as well as sequence variability we observe within delta packages. Modeling is therefore an essential tool that can aid in understanding and recognition of the variable impact each parameter may have had as delta evolve. Common developed features such as delta lobes, bypass zones, and channel avulsion that are associated with deltaic depositional environments have large spatial and temporal dimensions. Hence, their investigations and proper perception requires a three-dimensional approach.

Database and methodology

Steepest descent model using FOTRAN coded language was used. It is a three-dimensional numerical modeling approach modified from (Ritchie *et. al*, 2004). It is designed to investigate the influence of sea level change, erosion and sediment flux on the evolution of deltas. Albeit the work has been build on the general outcome of their work, on the other hand, it did not attempt to investigate asymmetric sea level cycles, nor assumed a sub horizontal topographic surface as it were in Ritchie's method. Preferably it considered symmetric sinusoidal sea level amplitudes of 12.5m, 25.0m, 50.0m and 75.0m (with either rising or falling initiation, Figure 3) over a hundred thousand years sea level cycle. Sea level is altered within the program in order to understand the influence of various sea-level changes at constant sediment input of $5000m^3$ through time, with more sediment being added to the volume as channels get incised and heights get eroded.

The modeling consists of a 10km x 16km drainage basin corresponding to grids of cells size of 40m x 40m that represent a steeply inclined surface of the earth dipping basin-ward carrying down sediments (Figure 1) through an input point located at a central distance of 8km (Figure 2). Erosion, transport and accumulation of sediments from the catchments to a depositional basin is the perception behind this model base on the given erosion equation $dG = KA^m S^n$ (see model parameters for details).

The modeling approach is basically intended to model deltaic depositional system; however it can as well be relevant to any progradational sedimentary sequence.

It is acknowledged that other factors such as coastal energy and tectonics that are not considered in this work exert certain degree of control on delta morphology. Nevertheless, in view of the fact that stratigraphic sequential units and bounding surfaces are recognized to have being essentially influenced by relative sea level alterations and sediment in-flux ([16] Leeder 1982, Allen and Allen 1990, Ritchie *et al*. 2004, Finch, 2005), rationalizes the chosen methodology.

Model parameters used in this research

Dynamic model equation: $dG=KA^m S^n$

Where:

A—total upstream contributing area

S— is the local gradient along drainage direction

m and n—constants given by the values m=0.6 n=1.0, (m/n ratio 0.35-0.6)

K—erodibility

Cell size — 40m

Hillslope diffusion on land angle of repose— 10º

Spatial extent of model dimension— 16km x10km

Modelling period— 0-100,000 years (tmax = 100,000 years) at dt=25 years

Sea level amplitudes— +/- 12.5m, 25.0m, 50.0m and 75m

Values of erosion coefficients of 0.000015 and 0.00015

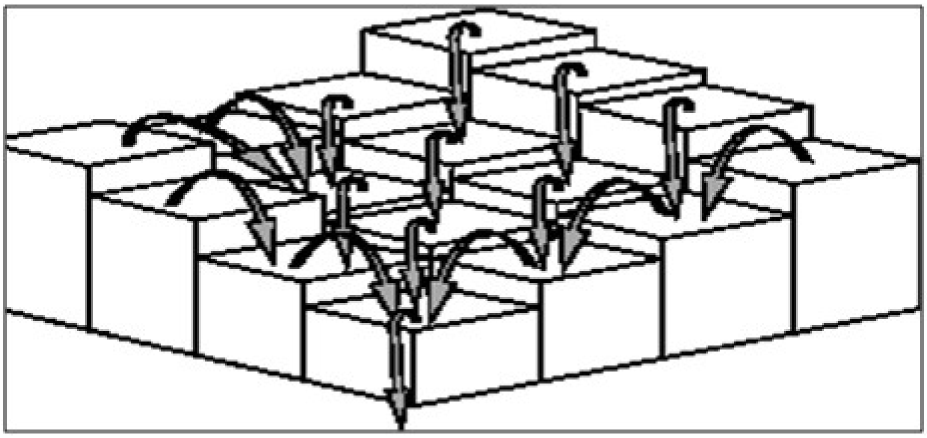


Figure 1: A 'steepest descent' cell grids of 40m x 40m dimension. (After Finch, 2005)

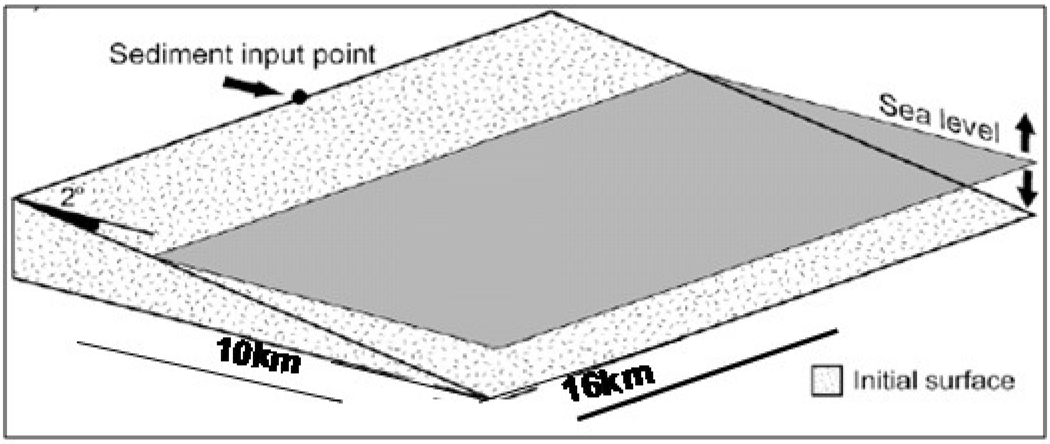


Figure 2: Illustration of sea level, and sediment input point
(Modified from Ritchie *et al* 2004).

Work flow

The data provided, is designed in such a way that a user has control over some vital parameters such as the total time in years, sea level amplitude, erosional coefficient, among others. Parameters are altered according to the attribute a user needs to consider in the final model. For the purpose of this research, sea level amplitude is varied thereafter the program is set to run. A single run will normally take a minimum of 10 hours to be completed, but the process is repeated until the desired quantity of data needed to be analyzed was obtained. The resultant data is then exported into Petrel program for surfaces to be created. Creation of stratigraphic sequences and dip cross-sections were done using Adobe Illustrator, while interaction between sea level and sediment flux is design using spreadsheet application. The model is constructed in such a way that deltas are produced every 25,000 years while surfaces developed after every 12,500 years.

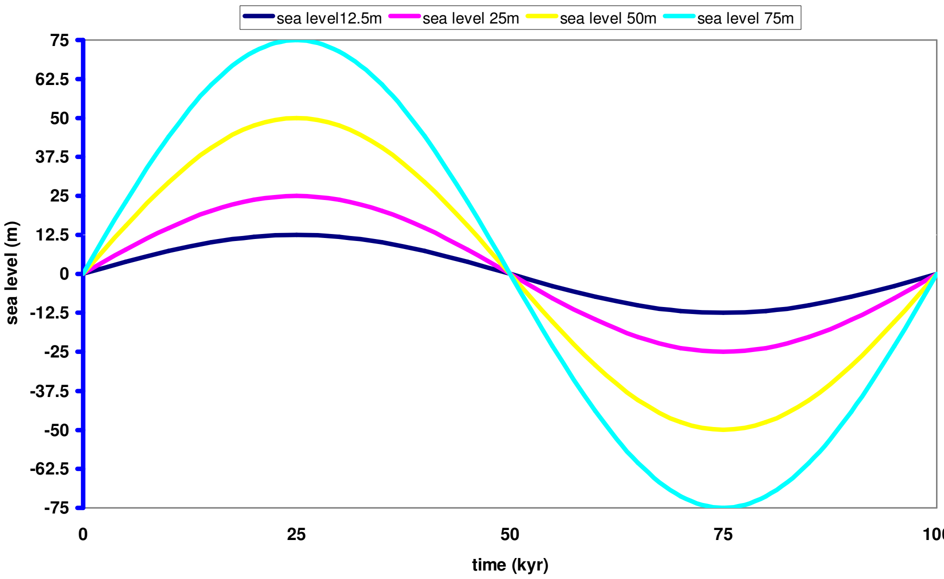


Figure 3: Sinusoidal sea-level amplitudes used for this modeling.

Results, observations and discussion

The stratigraphic response to a sinusoidal sea-level change of 12.5m and constant sediment supply of 5000m^3 per year:

In this model the stratigraphy develops within 100kyr in responds to sinusoidal sea-level cycle of 12.5m starting from a rising stage. Four distinct deltas evolved within the time frame, with the highest sea level rise dominating the deposition within the first 25kyr. The delta formed is broad with a smooth delta front (Figure 4a). 50kyr marked the end of force regression (Figure 4b) and the beginning of lowstand, at this time, the delta gets narrower as well as sea level falling back to 0.0157m. 75kyr (Figure 4c) is the period of maximum progradation of the shoreline. The delta is particularly lobate in appearance with clear deviation of the depositional pathway from the centrally situated sediment input point. Severe erosion at the landward part of the shoreline is apparent. The delta front of the previous delta is now inactive, eroding into the new delta.

At some points along the new shoreline, large volumes of sediment are captured and smaller deltas build out on the flank of the main delta system. The main delta is by this time very large approximately 3km wide and 5km deep in to the basin. The two deltas are separated by a sector starved of sediment, whilst the shoreline starts to transgress landward at the last episode of the sea level cycle from lowstand at -12.5m back to 0.0157m.

How created surface maps (figure 4) relate to the shoreline, delta fronts, position of the sea-level, lobes formation and transporting channels are presented below.

Shore line is horizontal and retrograding at this time of highest sea level rise (Figure 4a), while the delta front shows a smoother outline without any trace of delta lobes or switching. The hinterland is gradually eroding and depositing sediments into the basin with the majority of the sediments coming in through the sediment input point located 8000m along the extent of the basin. Other minor channels are depositing sediment all the way along the shoreline.

At 50kyr, the earlier formed delta has being abandoned and becomes a component of the delta plain, its being eroding into the newly formed delta and emptying sediment into the basin (Figure 4b). The shoreline has moved basin ward; the delta gets narrower with an uneven delta front. This period also witnesses the initiation of new delta lobes with more sediments moving into the basin as well as channels becoming wider. The time of maximum progradation of the shoreline is at 75kyr (figure 4c) where delta front is very irregular. The delta plain suffers from intense erosion and re-deposition into the active delta. Channels are wide and deeply incised with new delta lobes being established. Shoreline is retrograding landward because sea level is abruptly rising from -12.5m to 0.0157m (Figure 4d). Two distinct deltas are present with the larger to the left of the input point receiving most of the sediment supply coming from a single channel that is widening. Infilling of the incised valleys is one of the obvious features that cannot be missed out at this period of transgression.

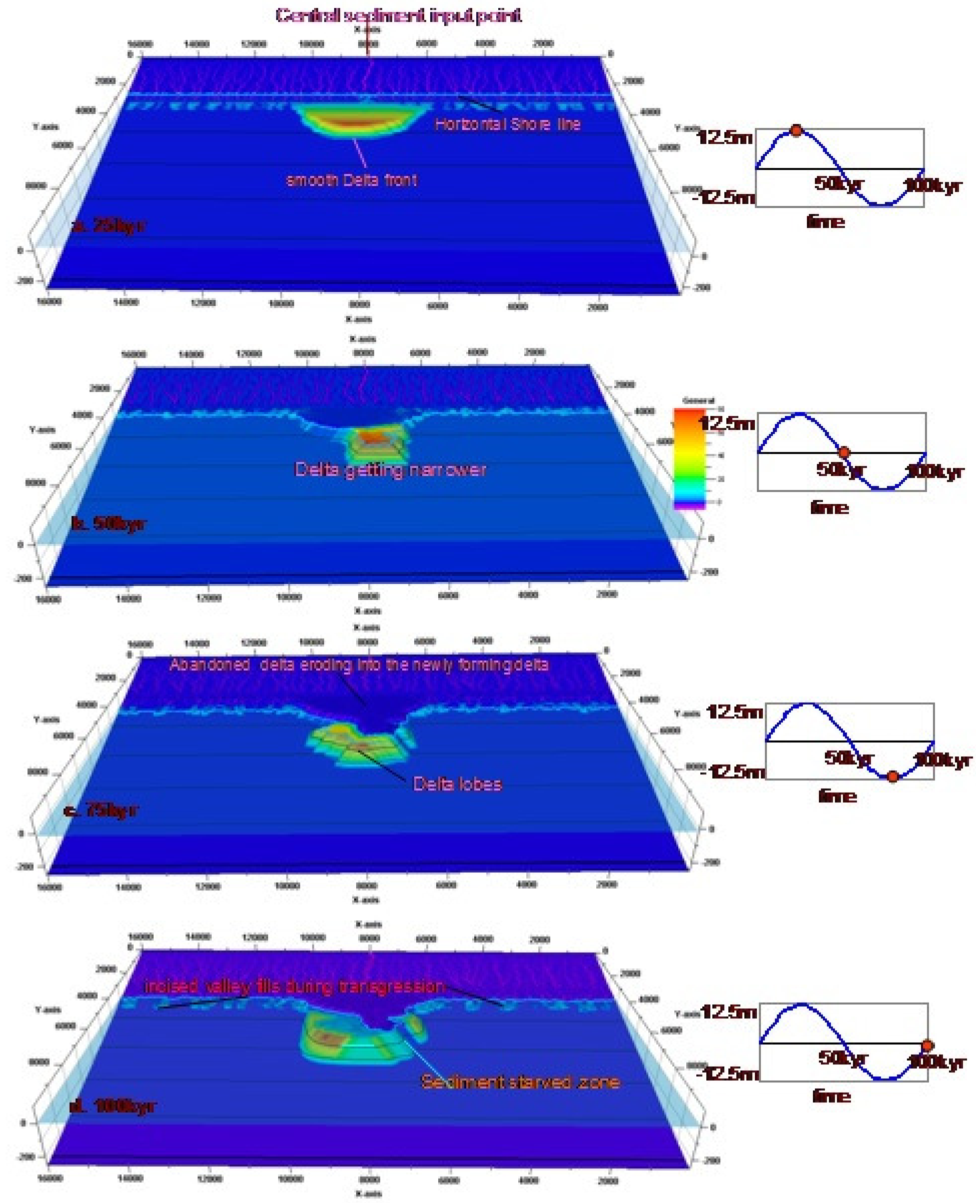
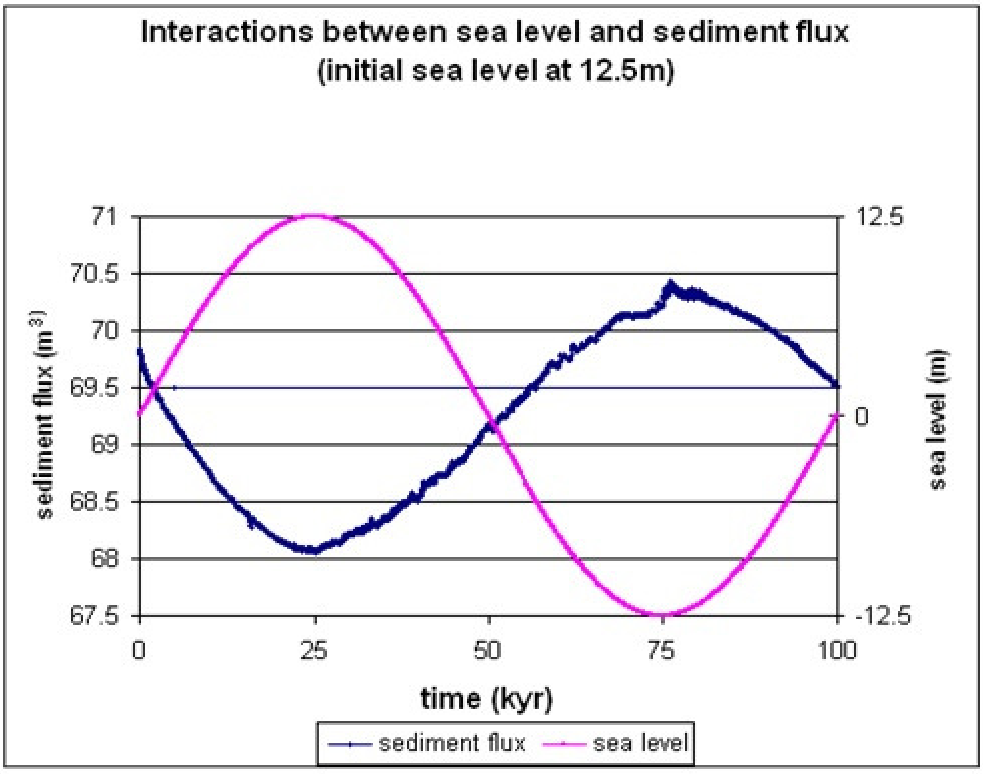


Figure 4: Surface maps of the experiment with a sea-level amplitude of 12.5m and annual sediment supply of 5000m^3 at (a) 25kyr, (b) 50kyr (c) 75kyr, and (d) 100kyr). The color bar indicates the material that has been eroded (purple) or deposited (red) in the previous 25kyr. The light blue color shows the present shoreline.



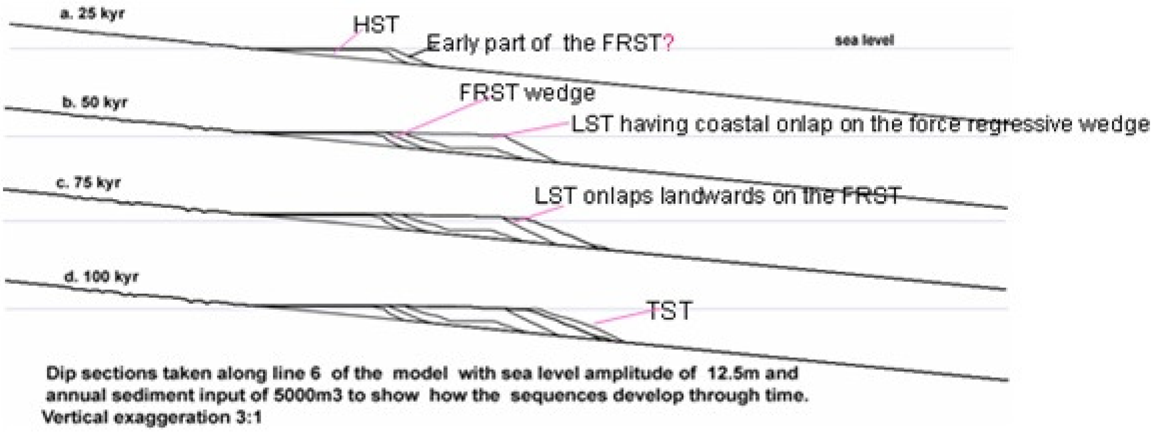


Figure 5i Graph showing the total amount of sediment the basin received in relation to sea-level change.
Figure 5ii: Stratigraphic dip section taken at 7,600m along the length of the basin showing the sequential evolution of the model in figure 4.

The largest volume of sediment received by the basin is at 75kyr when the sea level is at its minimum (figure 5i). The least amount of sediment fed into the basin is at the time of high sea level rise.

From the stratigraphic dip section of the model (Figure 5ii), it is observed that during the highest rise of sea-level, deposition of HST was concluded and probably part of the FRST The completion of the forced regressive wedge could be attributed to the time when sea level was at zero after 50kyr, as well as the beginning of LST which almost certainly its deposition was completed just at the beginning of the rising sea level. The last part of the depositional cycle, 75kyr-100kyr ended with the TST been deposited.

The stratigraphic response to a sinusoidal sea-level change of 25m and constant sediment input of 5000m^3 per annum:

In this model the stratigraphy develops within 100kyr in responds to sinusoidal sea level cycle of 25m starting from a rising stage, four distinct deltas evolved within the time frame. Deposition started when the sea level is high, the delta formed is broad with smooth delta front (Figure 6a). As sea level falls to zero, the delta gets narrower, the maximum regression period was reached after 75kyr of the sea-level cycle. At this time, the delta organizes itself into a series of lobes. A clear deviation from a centrally located depositional axis to one that is off towards one of the flanks of the delta is observed (Figure 6c).

Severe erosion on the landward part of the shoreline is also apparent, more especially the delta front of the previous delta that is now inactive but topographically higher. At some point within the model, sediments have being trapped as sea level rises and the shoreline moves landward. By the 100th kyr two distinct delta lobes had formed as a result of avulsion of the main delta (Figure 6d). The largest volume of sediment received by the basin is at 75kyr (Figure 7i) when the sea-level is at its minimum. The least amount of sediment fed into the basin is at the time of high sea level rise (25kyr).

Figure 7ii, is the stratigraphic dip section of the model where it is observed that during the highest rise of sea-level, deposition of HST was effected which it shows features both of aggradation and progradation. A forced regressive wedge, which is somewhat progradational is developed at the time when the sea level is at zero in the 50th thousand year. Progradational to aggradational LST and obvious incision of the previously formed systems tracks is at the maximum regression of the shoreline. When the sea level rises once more, the shore line begins to migrate landward, TST is deposited.

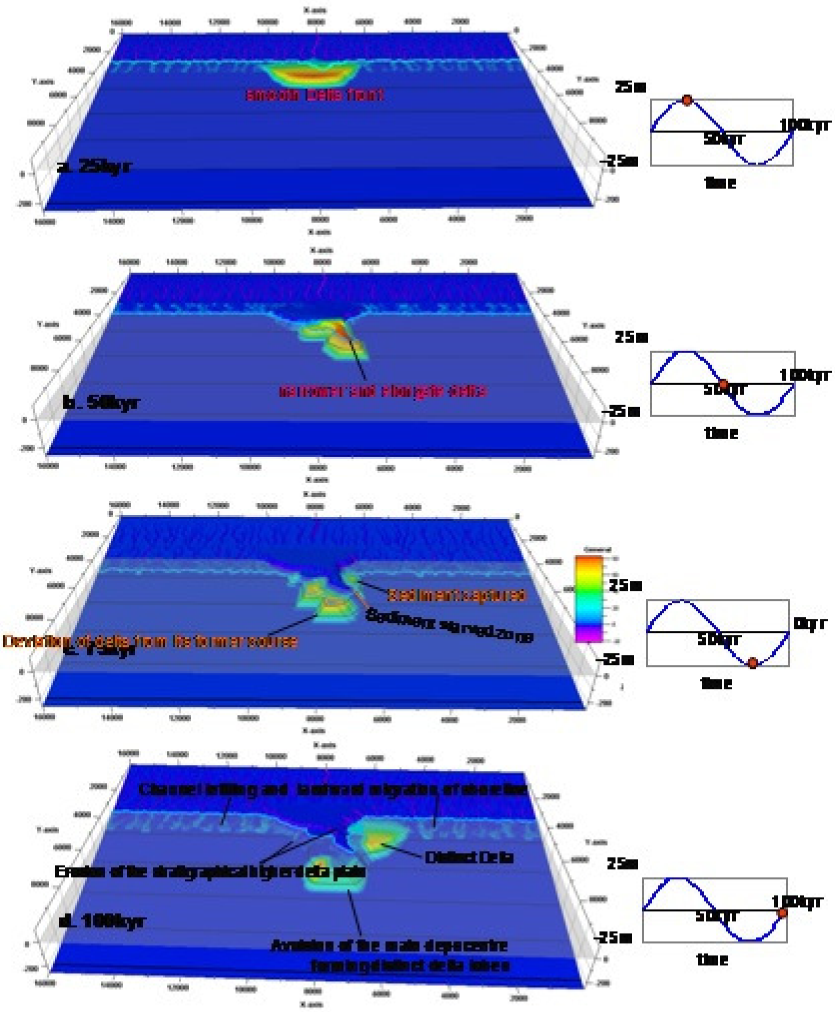
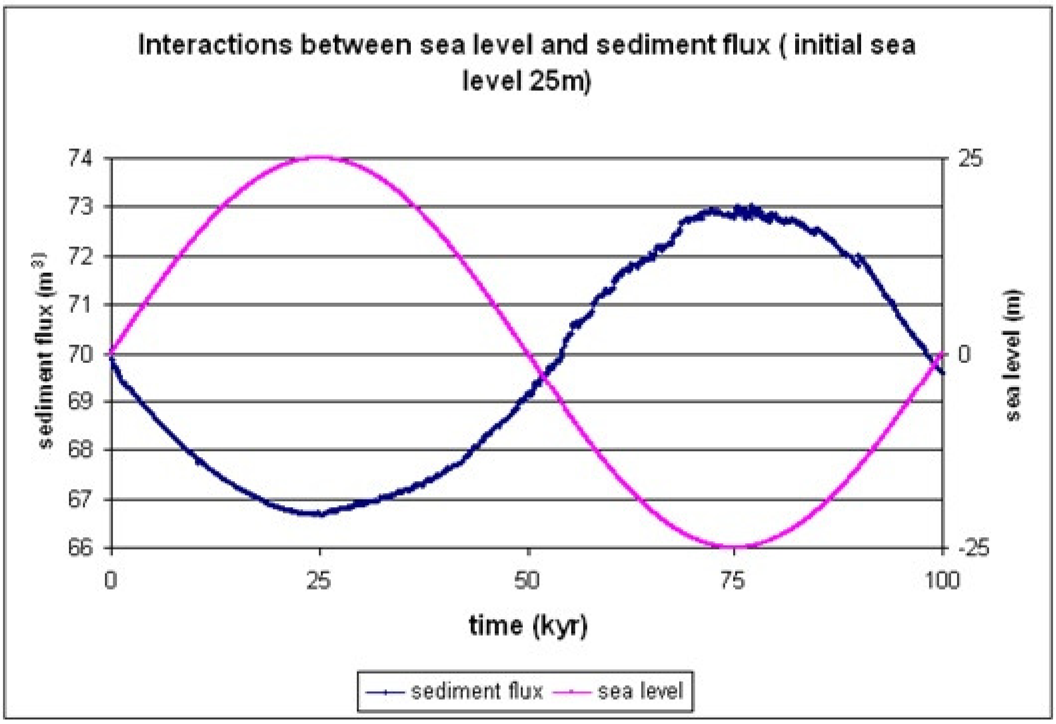


Figure 6: Surface maps of the experiment with a sea-level amplitude of 25m and annual sediment supply of $5000m^3$ at (a) 25kyr, (b) 50kyr, (c) 75kyr, and (d) 100kyr). The colour bar indicates the material that has been eroded (purple) or deposited (red) in the previous 25kyr. The light blue colour shows the present shoreline.



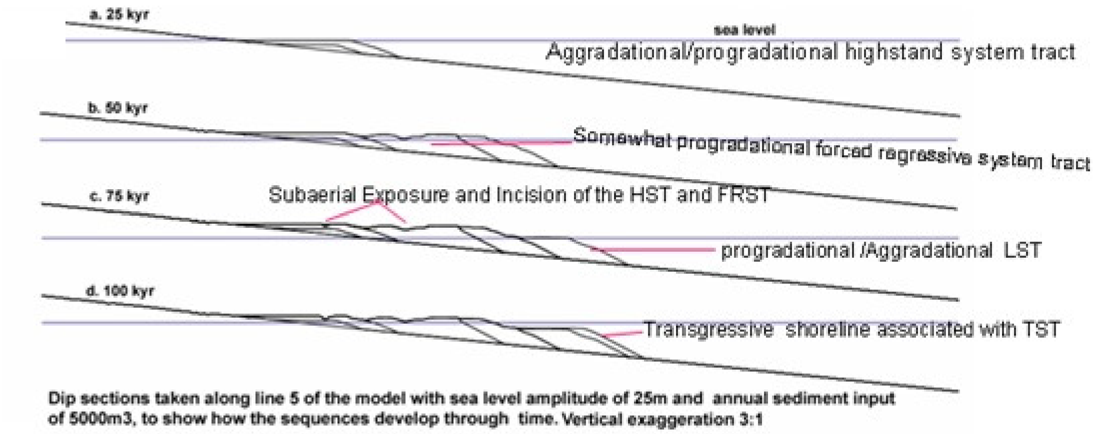


Figure 7i: Graph showing the total amount of sediment the basin received in relation to sea-level change.
Figure 7ii: Stratigraphic dip section taken at 7,200m along the length of the basin showing the sequential evolution of the model in Figure 6.

The stratigraphic response to a sinusoidal sea-level change of 50m and constant sediment input of 5000m^3 per annum:

In this model the stratigraphy develops within 100kyr in response to a sinusoidal sea level cycle of 50m, starting from a rising stage of the sea level. Four distinct deltas evolved within this time frame. Deposition started when the sea level is high, as with the other models.

The Shore line is horizontal and retrograding; at this time of highest sea level rise (25kyr).The Delta front shows a smoother outline without any trace of delta lobes or switching. The hinterland is gradually eroding and depositing sediments into the basin with the majority of the sediments coming in through the sediment input point. Other minor channels are depositing sediment all the way along the shoreline (Figure 8a).

At 50kyr, the delta produced has an uneven delta front., at this time the sea-level is almost at zero (0.0628m). Sediment by the shore line is eroding and incision of the exposed surfaces is observed (Figure 8b), here the delta started to form lobes earlier as compared to the models with sea-level amplitudes of 12.5m and 25m.

The maximum progradation of the shoreline is at 75kyr. Here deposition has moved laterally to the right side of the input point. Channels are wider and more incised. For in the last model figure 8d which its development was at the end of this sea level cycle, the delta is large to some extent, approximately 2.5km long and 2km wide. It has moved almost 2.5km away from the central depositional point of 8000m. It is also at this time that the land ward shift of the shoreline, flooding and infilling of incised channels occurred.

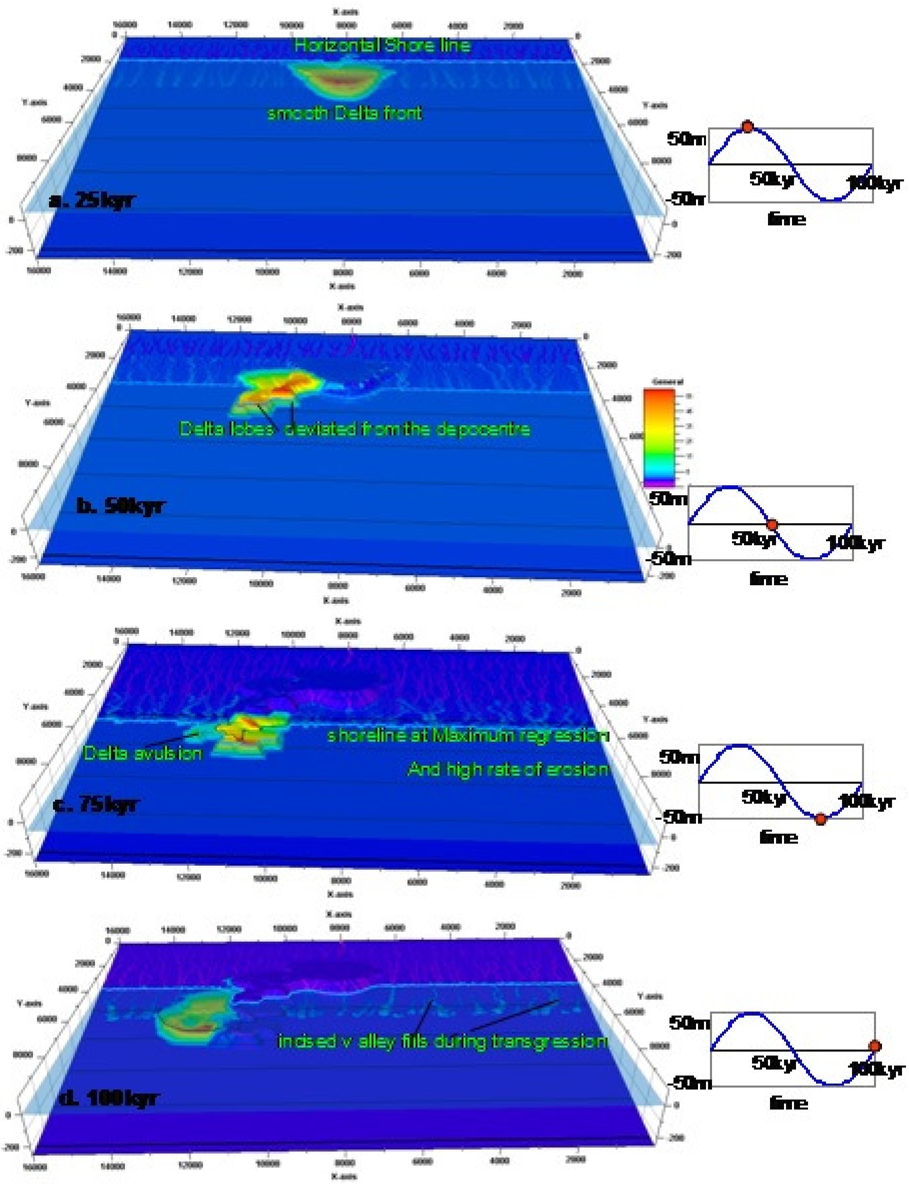
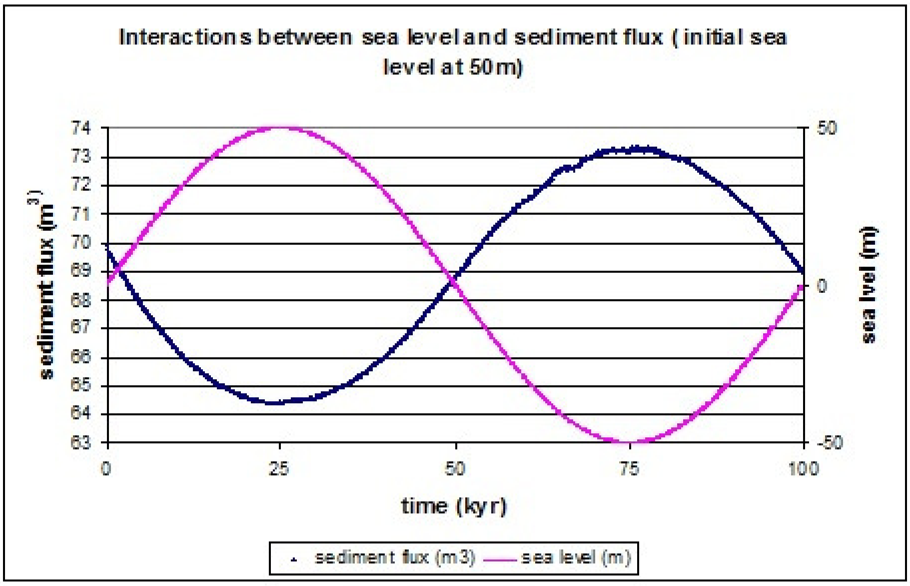


Figure 8: Surface maps of the experiment with sea-level amplitude of 50m and annual sediment supply of 5000m^3 at (a) 25kyr, (b50kyr (c) 75kyr, and (d) 100kyr). The colour bar indicates the material that has been eroded (purple) or deposited (red) in the previous 25kyr. The light blue colour shows the present shoreline.



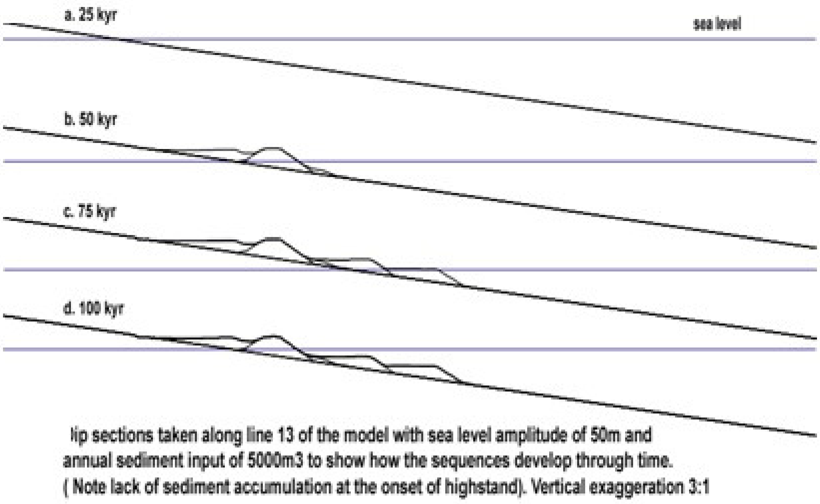


Figure 9i: Graph showing the total amount of sediment the basin received in relation to sea-level change.
Figure 9ii: Stratigraphic dip section taken at 10,400m along the length of the basin showing the sequential evolution of the model in figure 8

The largest volume of sediment received by the basin is at 75kyr when the sea level is at its minimum (Figure 9i). The least amount of sediment fed into the basin is at the time of high sea level rise.

From the stratigraphic dip section of the model, (Figure 9ii), taken far off the sediment input point show no sediment deposition during the last 25kyr.

The stratigraphic response to a sinusoidal sea-level change of 75m and constant sediment input of 5000m^3 per annum:

In this model the stratigraphy develops within 100kyr in response to sinusoidal sea level cycle of 75m, starting from a rising stage of the sea level. Four distinct deltas evolved within the time frame. Deposition started when the sea level is high, as with the other models. At 25kyr, the delta that developed is elongated with a shape like that of lunate bar approximately 4km long (Figure 10a).

At normal regression of the sea-level (50kyr), erosion and several incised channels are observed with delta lobes already well developed (Figure 10b); just as in the model with sea-level amplitude of 50m. It is important to note that obvious delta lobes development in the models with 12.5m and 25m sinusoidal sea level occurred during the lowstand i.e. 75kyr. For some reasons, at 75kyr in this model, the delta is channel-like in appearance (Figure 10c). By the end of the cycle infilling and drowning of channels had occurred as the sea-level rises shifting the shoreline in a landward direction. A sediment starved zone separated the delta into 2 different lobes (Figure 10d).

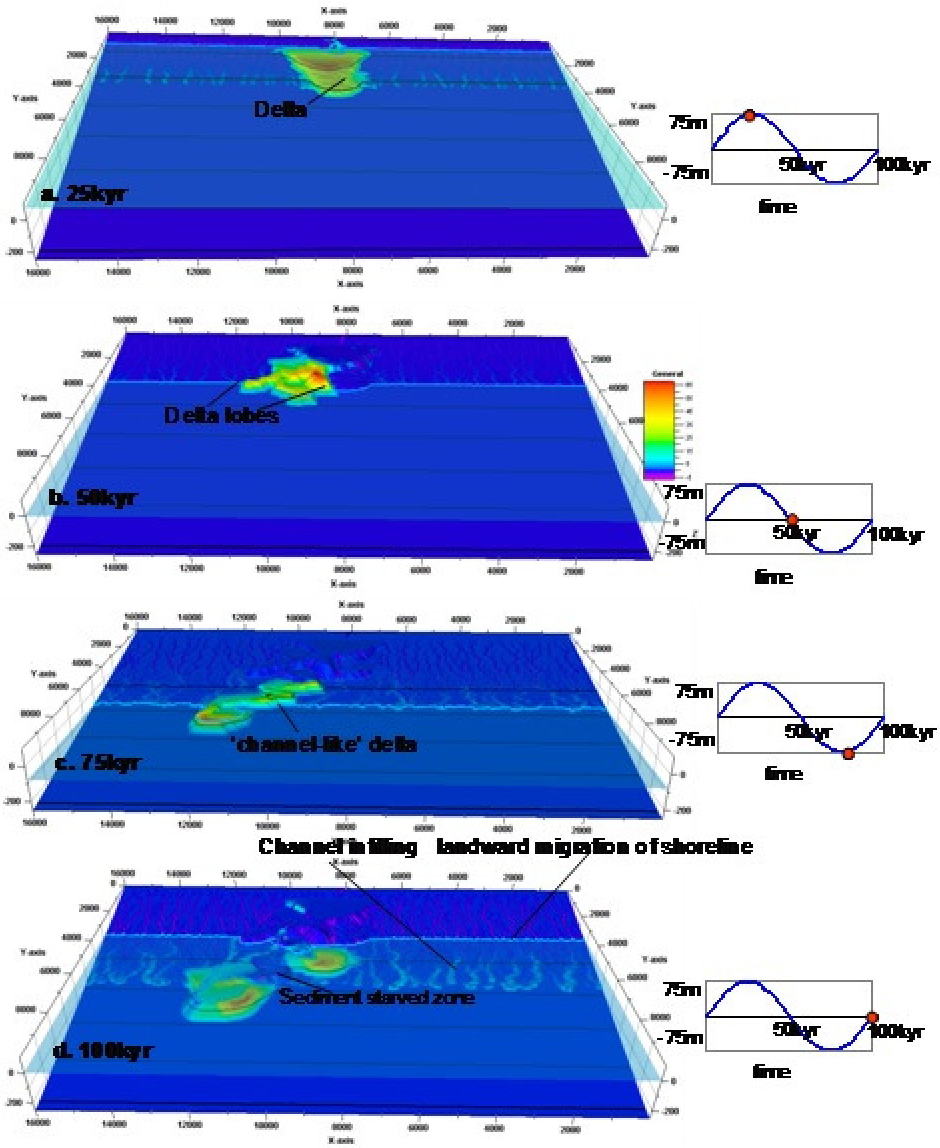
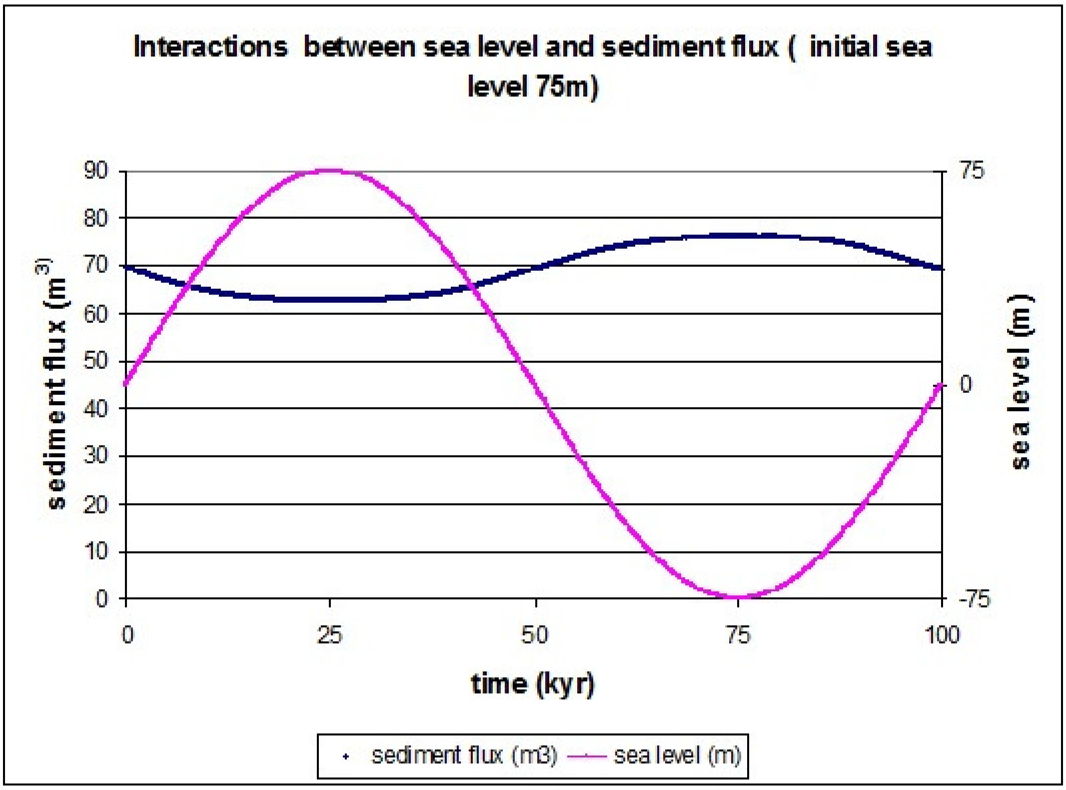


Figure 10: Surface maps of the experiment with a sea-level amplitude of 75m and annual sediment supply of $5000m^3$ at (a) 25kyr, (b) 50kyr, (c) 75kyr, and (d) 100kyr). The colour bar indicates the material that has been eroded (purple) or deposited (red) in the previous 25kyr. The light blue colour shows the present shoreline.



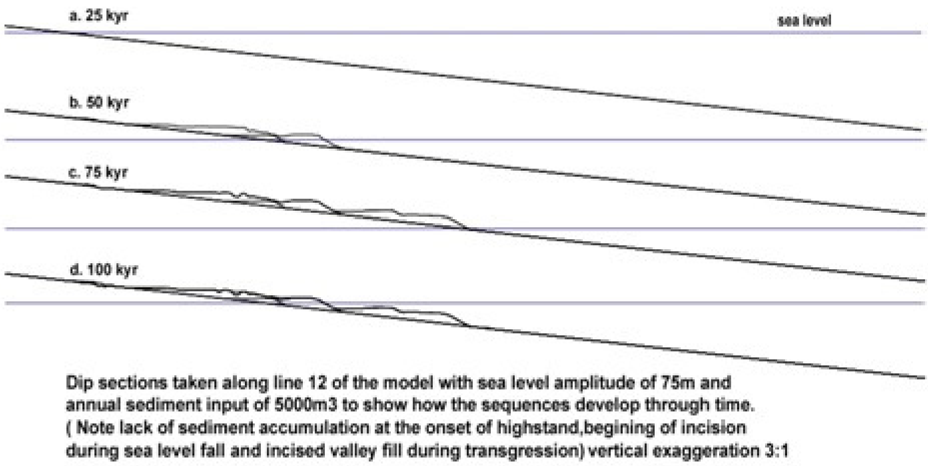


Figure 11i: Graph showing the total amount of sediment the basin received in relation to sea-level change.
Figure 11ii: Stratigraphic dip section taken at 7,200m along the length of the basin showing the sequential evolution of the model in Figure 10.

Sediment deposition at the time of sea- level fall is just slightly above, the deposition during sea-level rise (Figure 11i). Even so, the dip cross section of the model taken 200m away from the central input point indicates no deposition at all during the rise in sea level (Figure 11ii). At 75kyr all the systems tracts seem to be sub-aerially exposed and deep incisions are observed, there is probably just insignificant deposition during the last 100kyr, if at all.

Conclusion

During sea level high stand, the shoreline is horizontal and retrograding; deltas form are broad with smoother delta fronts that are arcuate in nature and show no trace of switching away from the depocentre. And development of deposits with aggradational/progradational stacking pattern resulted. At the time of maximum progradation of the shoreline, deltas produced have irregular delta fronts with bird's foot or channel-like pattern. This is more especially with those models of higher sinusoidal sea level curves. While the delta plain suffers from intense erosion, channel incisions and re-deposition of sediments into the active delta resulted in the establishment of new delta lobes.

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