Sequence Stratigraphy of the Pliocene-Pleistocene strata and shelf-margin delta of the eastern Niger Delta, Nigeria

By

Oluwaseyi A. Fatoke

Proposal
Presented to the Department of Geosciences University of Houston
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Geology

Thesis Committee
Dr. J. Bhattacharya (Advisor UH)
Dr. W. Dupre (UH)
Dr. P. Copeland (UH)
Dr. C. Winker (Shell International)

Table of Contents

1.0 Abstract

Recently, deltas have been classified into inner, mid, shelf-margin and bayhead deltas. This thesis focuses on shelf-margin delta in unstable progradational margins; current models have only documented the role of eustatic sea level changes on shelf-margin delta development and evolution. Constraints imposed by neo-tectonics and sediment supply have not been well documented. Additionally, current models have tended to link shelf-margin delta cannibalization to time equivalent deepwater lowstand deposits. This study aims to test the shelf-margin concepts in an unstable progradational passive margin with active down-to-basin and counter regional growth faults by examining the role of locally created accommodation on shelf-margin delta development and evolution especially along depositional strike and the link between fluvial feeder systems on the shelf and deepwater sediments. In addition, the study intends to document the sequence stratigraphy model of an unstable progradational margin with active down-to-basin and counter regional faults. Present sequence stratigraphic models of unstable progradation margin are based on Gulf of Mexico systems that lacks active counter regional faults. This research will utilize 70,000km2 of high quality 2D seismic data and 14,000km2 of 3D seismic data as well as wireline logs, biostratigraphy data, sidewall and ditch cuttings description from over 146 wells from the eastern part of the Niger Delta. The Niger Delta was selected because it is a classical unstable progradation margin with active down-to-basin and counter regional faults that complicates depositional patterns and stratigraphy. The Niger Delta is a large hydrocarbon province and understanding of the role of internal versus external forcing factors in sequence architectures is critical to future exploration activities in the delta.

2.0 Research Focus

Early sequence stratigraphic models of deltas generally tend to be dip oriented and largely focus on control by eustatic sea level changes (Vail et al. 1977; Posamentier et al. 1988; Van Wagoner et al. 1990). In addition early sequence stratigraphic models were developed on structurally stable passive margin. Because most early models were dip-oriented, along depositional strike variability in sequence stratigraphic signatures are less well known. The standard sequence stratigraphic model predicts that delta progradation to the shelf-margin is controlled by relative sea level fall and is associated with an incised valley on the shelf and significant cannibalization of the shelf-margin delta if sea level falls below the shelf-break (Suter and Berryhill 1985; Suter et al. 1987; Porebski and Steel 2003; 2006; Fig. 1 and Fig. 2).

Steel et al. (2000; 2003) defined four types of shelf-margin delta that succeeds one another spatially during a fall to rise in sea level and when extensively incised by fluvial feeder systems (during a sea level fall) forms a linked system with slope channels and basin floor fans (Fig. 3 and Fig. 4). The authors also argued that the shelf-margin deltas enunciated above and its sea level interpretation as well as linked shelf-margin delta – down dip lowstand deposits are valid for shelf-margins that build into water depths between 200 -800 meters. Steel et al. (2002); Diebert et al. (2003) and Johannessen and Steel (2005) furthermore, described four shelf-margin delta clinoform types from the Eocene of Spitsbergen and linked the preservation of clinofom topsets, trajectories, height and geometries to presence of sands at the slope and basin floor (Fig. 4b).

Steel et al. (2000; 2003), Steel et al. (2002) and Diebert et al. (2003) concepts of shelf-margin delta and clinoform development were based on studies of the structurally simple Eocene shelf-margin foreland basin on Spitsbergen and the Miocene shelf-margin of the Carpathian foredeep basin. In addition, the basic controlling parameter on the development of the shelf-margin deltas as opined by Steel et al. (2003) is relative sea level fall, except where the shelf is narrow or where sediment supply is extraordinarily high (like continental scale Mississippi river, that can build deltas near the shelf-margin without sea level falling). Furthermore, the architecture of shelf-margin deltas is postulated to be primarily controlled by relative sea level changes. Shelf-margin deltas formed during sea level fall are attributed to be forced regressive packages with a stepped fall progradation stacking patterns (Hunt and Tucker 1992; 1995; Posamentier et al. 1992; Kolla et al. 2000). Shelf-margin deltas that form during a rise in sea level are stacked aggradational packages. However, these concepts and models were developed in relatively stable foreland and foredeep basins and may not be analogous to shelf-margin deltas in other depositional setting. There is therefore a need to test these models in other basins especially basins that are structurally complex such as unstable progradational margin. Also the roles of sediment supply and large basin forming growth faults in modifying the architecture and type of shelf-margin delta formed have not been well documented.

Fault-controlled subsidence, sediment supply and basin physiography have been recognized as important factors influencing the morphology, strata geometry, facies stacking patterns and along strike variability of depositional systems in deltas (Schlager

1991; Posamentier and Allen 1993; Gawthorpe et al. 1994). Such influences are even more pronounced in growth faulted shelf-margin deltas where the presence of growth faults complicates the sequence stratigraphic interpretation of deltaic successions (Van Heijst et al. 2002).

Numerical modeling on deltas and analog flume experiment on growth faulted shelf-margin deltas show that the effect of these local controls can overwhelm the effect of eustatic sea level change creating depositional sequences that are significantly different from those predicted by eustatically derived sequence stratigrahic models (Van Heijst et al. 2002; Ritchie et al. 2004a; Ritchie et al. 2004b). Also, sequence stratigraphic studies on tectonically active margin have also shown that neo-tectonics imposes constraints on the depositional patterns of the deposits and its sequence stratigraphic expression both along dip and strike (Gawthorpe et al.1994; Ercilla and Alonso 1996; Goodbred and Kuehl 2000; Hodgetts et al. 2001; Hiscott 2001; Zecchin et al. 2003). Ritchie et al. (2004a; 2004b) indicated from theoretical considerations that sediment supply and local tectonic controls, such as fault controlled subsidence, can lead to poorly developed incised valleys during sea level fall. The authors further suggested that these local controls could cause variations in relative sea level change along a basin margin resulting in shelf-margin deltas that lack incised valleys and forced regressive delta lobes.

These local factors have the potential to influence the shelf-margin delta concepts as postulated by Steel et al. (2000; 2003) and cause a variation in the evolutionary shelf-margin delta sequence or prevent the development of specific shelf-margin delta types, even during a eustatic fall-to-rise sea level cycle. Local basin factors like sediment supply can also influence the formation of a linked shelf-margin delta – downdip lowstand deposits. Anderson et al. (2003) Showed from the East Texas – Western Louisiana margin, that rivers with high sediment yield continue to grow during sea level fall, reach the outer shelf/shelf margin before maximum lowstand and form shelf-margin deltas that are not linked to slope and basin floor deposits because the rivers usually avulse before maximum eustatic lowstand. Rivers with low sediment yield also progrades to the shelf-margin during sea level fall but form shelf-margin deltas with linked lowstand deposits because the rivers are usually fixed on the shelf, resulting in incision and re-incision caused by higher order sea level fluctuations into the sandy shelf-margin delta and bypass of sediments downdip into lowstand slope and basin floor fans. According to Anderson et al. (2003) local tectonic factors can also prevent rivers on the outer shelf from avulsing.

In addition, the sequence stratigraphic model of deltas along unstable progradational margin is different from that in stable progradational margin (Fig. 5, Pacht 1990). Unstable progradational margin are characterized by shale/salt diapirs and major gravity driven down-to-basin and counter regional growth faults (Winker 1982; Nemec et al. 1988; Brown et al. 2004). In this setting the shelf-slope break may be sometimes abrupt and developed along scarps created by growth faults. The existing sequence stratigraphic models for unstable progradational margins have only documented the role and influence of down-to-basin growth faults. The role of counter regional faults has not been well recognized in most models (Pacht 1990; Van Heijst et al. 2002; Brown et al. 2004). In addition, the interplay between down-to-basin growth faults and counter regional faults in terms of timing and extent of fault created subsidence along depositional strike and how this affects the resultant sequence stratigraphic model have not been recognized.

The aims of this study are:

1) Test the shelf-margin concepts of Steel et al. (2000; 2003) in an unstable progradational margin using seismic and well data by examining the impact of locally created accommodation along depositional strike on shelf-margin delta types, clinoforms, geometry, evolution and development.

2) Test the preservation of eustatic signals within systems tracts in an unstable progradational margin with along strike variation in fault generated accommodation

3) Test the Steel et al. (2000); Steel et al. (2002); Diebert et al. (2003) and Johannessen and Steel (2005) model that link the presence of fluvially cannibalized shelf-margin delta and top truncated clinoforms to presence of slope channels, slope and basin floor fans. This study hypothesizes that significant fluvial incision and top truncated clinoforms at the shelf-margin is not always necessary for slope channels, slope fans and basin floor fans to develop (Fig. 3, Fig. 4 and Fig. 4b).

4) At present in many deltaic settings it is unclear whether deepwater sediments were fed by lowstand shelf-margin deltas or incised valleys that crossed the shelf to feed slope canyons directly (Saller et al. 2003, Fig. 7). Current models however, suggest that slope and basin floor fans are fed by fluvial feeder systems mainly incised valley that crossed the shelf to discharge sediments into slope canyons. This study intends to examine the current linked shelf-deepwater model and hypothesizes that depending on local basin factors like fault controlled subsidence and varying sediment supply, deepwater sediments can be fed directly by shelf-margin deltas.

5) Examine the role of counter regional faults and the interplay between down-to-basin faults and counter regional faults in modifying the current sequence stratigraphic models developed for unstable progradational margin. Present models are based on the Gulf of Mexico, which lacks active counter regional faults and are mainly focused on the accommodation created by down-to-basin faults. However, there are other unstable progradational margins with active counter regional faults and the interplay between these two faults has the potential to create sequences and systems tracts that are significantly different from the present model.

This study focuses on shelf-margin delta in unstable progradational margin because of its importance as petroleum systems. Specifically the study will focus on the Pliocene – Pleistocene growth faulted margin and shelf-margin delta in the eastern Niger Delta, Nigeria. The Niger Delta is a large hydrocarbon province and typifies the classical unstable progradational margin. The Niger Delta located on the southern coast of Nigeria has been steadily prograding since the Tertiary into the Gulf of Guinea and is stratigraphy and depositional patterns is complicated by shale cored collapse structures (large active down-to-basin and counter regional faults) (Allen 1964 and 1965; Short and Stauble 1967; Evamy et al. 1978; Doust and Omatsola 1990).

Most sequence stratigraphy models of the Niger Delta are based on Gulf of Mexico type down-to-basin growth faults and constraints imposed by counter regional faults on depositional patterns have not been well documented. Understanding constraints imposed by internal (neo-tectonics, sediment supply) and external forcing factors (eustasy) in an area of economic interest such as the Niger Delta is critical to future exploration activities in the basin (Pacht 1990; Van Heijst et al. 2002; Owoyemi and Willis 2006 and Magbagbeola and Willis 2007). Moreover, Sediment supply to the Niger Delta is from different drainage basins by rivers with varying discharge levels (Fig. 8, Allen 1964).

This study intends to evaluate and document the variations in depositional systems from shelf to upper slope and along depositional strike resulting from the controls imposed by varying sediment supply and local tectonics in a shale cored, growth-faulted shelf-margin delta in the eastern part of the Niger Delta.

2.1 Regional Setting

The Niger Delta in southern Nigeria is located in the Gulf of Guinea at the triple RRR junction that led to the separation of South America from Africa (Short and Stauble 1967;

Burke 1971; Whiteman 1982, Fig. 9). It is one of the largest deltaic systems in the world, covering an area of approximately 1 million km2 with 12km thick of clastics regressive wedge at the center (Evamy et al. 1978; Doust and Omatsola 1990). Damuth (1994) recognized three structural provinces in the modern Niger Delta. An upper zone of extensional faults (listric growth) beneath the outer shelf, a middle translational zone dominated by mud diapirs and shale ridges beneath the upper slope and a lower slope/rise dominated by imbricate thrust structures (toe thrusts).

The delta builds out in a series of regressive offlap cycles and has been subdivided into three diachronous lithologic units- the massive, of the Akata shales, grading upward into the interbedded shales and shallow marine-fluvial sands of the Agbada Formation and the alluvial sands Benin Formation.

The Niger Delta has been divided into a series of megastructures or depobelts that are bounded by large scale (hundreds of kilometers long) growth faults (Evamy et al. 1978; Knox and Omatsola 1989; Doust and Omatsola 1990). In comparison to other deltas the depobelts can be viewed as transient basinal areas (intraslope sub-basins) that succeeds one another in space and time as the delta progrades seawards (Brown et al. 2004). Six depobelts have been identified and have been interpreted to have formed over a 25 my period from Miocene to present day. They are from north to south named: Greater Ughelli, Central I, Central II, Coastal Swamp I, Coastal Swamp II and Offshore.

The Niger Delta according to Evamy et al. (1978) evolved as a prograding (regressive) delta with well developed growth faults regarded as gravity sliding/slump feature initiated when the sandy delta progrades over undercompacted clays with low shear strength. The authors postulated that the amount of growth fault created accommodation is insufficient to contain the prograding delta and this led to the creation of new fault-controlled depocenters seaward. Shale ridges that were displaced basinward during differential loading formed counter regional faults.

Knox and Omatsola (1989) proposed an "escalator regression" model to explain the deposition and the stepwise building of the Niger Delta. Rapid progradation of the delta led to the loading and burial of offshore marine shales. This resulted in overpressuring, followed by basinward and vertical movement of the shales. Shale mobilization led to the structural collapse of the slope and the formation of seaward dipping growth faults. The growth faulting was exacerbated by rapid accumulation of sandy deposits in the footwall block of the fault. This led to accelerated loading of the underlying shales, which in turn accelerated their mobilization and created more extension on the faults. Prodelta shales that were deformed by the rising shale ridge and landward dipping normal faults characterize the distal part of the depocenters. Continuous sediment supply and depletion of the mobile underlying shales led to rapid filling of the newly created accommodation by the prograding delta and the shifting of deposition basinward, to load a new area. The Knox and Omatsola (1989) model predicts that the Agbada Formation did not form by progradation but aggradation of delta plain and shallow marine delta front sediments as the delta became stalled on the rapid subsiding depocenter.

3.0 Data

The data for this study consist of 70,000km2 high quality 2D seismic data and 14,000km2 3D seismic data of various vintages (acquired between 1989 – 1999) covering the coastal to the offshore depobelt in the eastern part of the Niger Delta (Fig. 10 and Fig. 11). The data is from 0 – 5000 milliseconds and also include data from 146 wells. The well data include wireline logs (Gamma Ray and/or spontaneous potential logs as well as Resistivity, Density, Sonic and Neutron logs), floral and fauna diversity and abundance data, shell Nigeria biostratigraphic derived age data, sidewall sample and ditch cutting sample descriptions from all wells.

4.0 Methodology

The study will cover the Pliocene – Recent strata in the coastal –offshore depobelt of the eastern part of the Niger delta (0 – 3s). For this study, the seismic data will be used to interpret major growth faults and counter regional faults within the study area. Maximum flooding surfaces identified (5.0Ma, 3.9Ma, 2.8Ma, 2.0Ma, 1.3Ma) from the wells, will be tied to the seismic data and use to identify age-constrained horizons that will then be interpreted and mapped (Fig. 12). These horizons will provide a 3rd order chronostratigraphic framework for interpreting the depositional systems. The age constrained horizons will be tied to the Pliocene – Pleistocene eustatic sea level chart (Haq et al 1987) and allows the identified shelf-margin delta to be placed within eustatic sea level context (Fig. 13). The interpreted horizons coupled with the growth faults interpretation will be used to interpret fault throws and aid in establishing the magnitude of along depositional strike, fault generated accommodation.

Conventional seismic stratigraphic procedures, which involve recognition of regionally mappable seismic discontinuities and units and the description of seismic facies within each defined time bounded unit, will be carried out (Mitchum et al. 1977; Krassay and Totterdell, 2001; Lobo et al., 2005). This will be integrated with facies interpretation from well data, sidewall and ditch cutting samples to identify and map depositional systems and elements. Seismic stratigraphic methods will also be used to describe the external and internal stratal geometries of the depositional systems and elements in order to define stratigraphic architectures and stacking patterns within depositional systems (Vail et al. 1977). The stacking patterns and stratal surfaces identified from seismic and well data as well as biostratigraphic data will be used to identified sequences and system tracts and to develop a sequence stratigraphic framework for the study area. Seismic stratigraphic architectures and stratal stacking patterns will be compared to externally forced, predicted stacking patterns using the eustatic sea level curve. This will allow for the effect of locally generated fault controlled accommodation to be compared with global eustatic sea level changes and allows for the tests number one and two to be achieved.

Shelf-margin delta types, clinoform types, trajectories and geometry will be interpreted and evaluated along depositional strike using the 2D and 3D seismic data and allows for the role of neo-tectonics in shelf-margin delta development and evolution to be assessed.

Seismic stratigraphic methods that allows for the internal and external description of seismic facies will be combined with 3D seismic horizon slices, seismic volume visualization, spectral decomposition, amplitude analysis and gated amplitude extraction within age confined units to support the identification of depositional systems and elements from the shelf-to–deepwater. This will aid in the construction of paleogeographic maps for each age defined units thereby permitting the linkage and relationship between the shelf-to-deepwater depositional systems along depositional dip and strike to be examined. This will also allow the model that link fluvially cannibalized shelf-margin delta and top truncated clinoforms to submarine canyons, slope channels, slope and basin floor fans to be tested.

Bathymetric maps will be constructed for the present day Niger Delta as an aid in understanding the location of shelf-edge break, location of continental slopes, water depths and location of submarine canyons. This information will aid in the understanding of the Pliocene-Pleistocene depositional systems. Isochron and thickness maps will be constructed within the identified key time interval. The displacement of isochrones across major faults as well as the thickness variations across faults will help to understand the rate of fault movement which can be directly linked to fault created accommodation as well as the timing of such fault activity. The thickness variation between the maximum flooding surfaces and any identified sequence boundary will indicate the depth of incision.

Seismic stratigraphy will be used to extend interpretation and depositional systems to areas without borehole information along depositional dip and strike in the study area.

5.0 References

Adeogba, A. A., T.R. McHargue and S.A., Graham, 2005, Transient fan architecture and depositional controls from near-surface 3-D seismic data, Niger Delta continental slope: AAPG Bulletin, v. 89, no. 5, p.627-643.

Anderson, J.B., K. Abdulah, J. Wellner and S. Sarzalejo, 2003, Late Quaternary shelf-margin delta and slope-fan complexes of the east Texas-western Louisiana margin: variable response to eustasy and sediment supply, in H.H., Roberts, R.H., Fillon, and J.B., Anderson, eds., Shelf Margin deltas and linked down slope petroleum systems: Global significance and future exploration potential: Gulf Coast Section SEPM 23rd Bob F. Perkins Annual GCSSEPM Foundation Research Conference, p. 67-78.

Allen, J.R.L., 1964, The Nigerian continental margin: bottom sediments, submarine morphology, and geological evolution, Marine Geology, v. 1, p. 289-332.

Allen, J.R.L., 1965, Late Quaternary Niger Delta, and adjacent areas: sedimentary environments and lithofacies: AAPG Bulletin v. 49, p. 547-600.

Armentrout, J.M., K.A. Kanschat, K.E. Meisling, J.J. Tsakma, L. Antrim, D.R. McConnell, 2000, Neogene Turbidite systems of the Gulf of Guinea continental margin slope, offshore Nigeria, in A.H. Bouma and C.G. Stone eds., Fine-gained turbidite systems: AAPG Memoir 72/SEPM Special Publication 68, p. 93-108.

Bhattacharya J.P. and R.K. Davies, 2001, Growth faults at the prodelta to delta –front transition, Cretaceous Ferron sandstone, Utah: Marine and Petroleum Geology, v. 18, p. 525-534.

Brown Jr., L.F., G. Loucks, H. Trevino, and U. Hammes, 2004, Understanding growth faulted, intraslope subbasins by applying sequence stratigraphic principles: Examples from the south Texas Oligocene Frio Formation: AAPG Bulletin, v. 88, no. 11, p.1501-1522.

Burke. K.C., 1972, Longshore drift, submarine canyons, and submarine fans: AAPG Bulletin, v. 56, p. 1975-1983.

Cummings D.I., R.W.C. Arnott, 2005, Growth-faulted shelf-margin deltas: a new (but old) play type, offshore Nova Scotia: Bulletin of Canadian Petroleum Geology, v. 53, p. 211-236.

Damuth, J.E., 1994, Neogene gravity tectonics and depositional processes on the deep Niger Delta continental margin: Marine and Petroleum Geology, v. 11, no. 3, p. 320-346.

Deibert J.E., T. Benda, T. Loseth, M. Schellpeper, and R.J. Steel, 2003, Eocene clinoform growth in front of a storm-wave-dominated shelf, central basin, Spitsbergen: no significant sand delivery to deepwater areas: Journal of Sedimentary Research, v. 73, p. 546-558.

Deptuck, M.E., G.S. Steffans, M. Barton, and C. Pirmez, 2003, Architecture and evolution of upper fan channel-belts on the Niger Delta slope and in the Arabian Sea: Marine and Petroleum Geology, v. 20, p. 649-676.

Doust, H., and E. Omatsola, 1990, Niger Delta, in J.D. Edwards and P.A. Santagrossi, eds., Divergent/passive margin basins: AAPG Memoir 45, p. 201-238.

Ercilla, G., B. Alonso, 1996, Quaternary siliciclastic sequence stratigraphy of western Mediterranean passive and tectonically active margins: the role of global versus local controlling factors, in M. De Baptist and P. Jacobs eds., Geology of Siliciclstic Shelf Seas: Geological Society London, Special Publications, v. 117, p. 125-137.

Evamy, B.D., J. Haremboure, P. Kamerling, W. Knaap, F.A. Molloy, and P.H. Rowlands, 1978, Hydrocarbon habitat of Tertiary Niger Delta: AAPG Bulletin, v. 62, no.1 p. 1-39.

Galloway, W.E., 1975, Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems, in M.L. Broussard eds., Deltas: Models for exploration: Houston Geological Society, p. 87-89.

Galloway, W.E., 1986, Growth faults and fault-related structures of prograding terrigenous clastic continental margin: Transactions Gulf Coast Association of Geological Societies, v. XXXVI, p. 121 - 128.

Galloway, W.E., 1989a, Genetic depositional sequences in basin analysis I: Architecture and genesis of flooding surface-bounded depositional units: AAPG Bulletin, v. 73, p. 125 - 142.

Galloway, W.E., 1989b, Genetic depositional sequences in basin analysis II: Application to northwest Gulf of Mexico Cenozoic basin: AAPG Bulletin, v. 73, p. 153 - 154.

Gawthorpe, R. L., A. J., Fraser, R.E.LI., Collier, 1994, Sequence stratigraphy in active extensional basins: implications for the interpretation of ancient basin fills: Marine and Petroleum Geology, v. 11, p. 642-658.

Goodbred, Jr., S.L., and S.A. Kuel, 2000, The significance of large sediment supply, active tectonism, and eustacy on margin sequence development: Late Quartenary stratigraphy and evolution of the Ganges-Brahmaputra delta: Sedimentary Geology, v. 133, p. 227-248.

Hart, B.S., D.A. Sibley and P.B. Fleming, 1997, Seismic stratigraphy, facies architecture and reservoir character of a Pleistocene shelf-margin delta complex, Eugene Island block 330 field, offshore Louisiana: AAPG Bulletin, v. 81, p. 380-397.

Hiscott, R.N., 2001, Depositional sequences controlled by high rates of sediment supply, sea-level variations, and growth faulting: the Quartenary Baram Delta of northwestern Borneo: Marine Geology, v. 175, p. 67-102.

Hodgetts, D., J. Imber, C. Childs, S. Flint, J. Howell, J. Kavanagh, P. Nell and J. Walsh, 2001, Sequence stratigraphic responses to shoreline-perpendicular growth faulting in shallow marine reservoirs of the Champion field, offshore Brunei Darussalam, South China Sea: AAPG Bulletin, v. 85, p. 433-457.

Johannessen, E.P., R.J. Steel, 2005, Shelf-margin clinoforms and prediction of deepwater sands: Basin Research, v. 17, p. 521-550.

Knox, G.J. and E.M. Omatsola, 1989, Development of the Cenozoic Niger Delta in terms of the escalator regression model and impact on hydrocarbon distribution, in W.J.M. van der Linden, S.A.P.L. Cloetingh, J.P.K. Kaasschieter, W.J.E. van der Graff, J. Vandenberghe and JA.M. van der Gun, eds., KNGMG Symposium on Coastal Lowland Geology and Geotechnology, Proceedings: Dordrecht, The Netherlands, Kluwer Academic Publishers, p. 181-202.

Krassay, A.A., and J. M., Totterdell, 2003, Seismic stratigraphy of a large, Cretaceous shelf-margin delta complex, offshore southern Australia: AAPG Bulletin, v. 87, p. 935-963.

Lobo, F.J., J.M.A. Dias, F.J. Hernandez-Molina, R. Gonzalez, L.M. Fernandez-Salas and V. Diaz del Rio, 2005, Late Quartenary shelf-margin wedges and upper slope progradation in the Gulf of Cadiz margin (SW Iberian Peninsula), in D.M. Hodgson and S.S. Flint, eds., Submarine slope systems: Processes and products: Geological Society London, Special Publications, v. 244, p. 7-25.

Mayall, M.J., C.A. Yielding, J.D. Oldroyd, A.J. Pulham and S. Sakurai, 1992, Facies in a shelf-edge delta-an example from the subsurface of the Gulf of Mexico, Middle Pliocene, Mississippi canyon, block 109, AAPG Bulletin, v. 76, p. 435-448.

McMurray, L.S., R.L. Gawthorpe, 2000, Along strike variability of forced regressive deposits: Late Quaternary, northern Peloponnesos, Greece, in D. Hunt and R.L. Gawthorpe, eds., Sedimentary responses to forced regressions: Geological Society London, Special Publications, v. 172, p. 363-377.

Meckel, L.D., 2003, Shelf margin deltas: the key to big reserves, in H.H. Roberts, R.H. Fillon, and J.B. Anderson, eds., Shelf Margin deltas and linked down slope petroleum systems: Global significance and future exploration potential: Gulf Coast Section SEPM 23rd Bob F. Perkins Annual GCSSEPM Foundation Research Conference, p. 231-266.

Mellere, D., A. Breda and R.J. Steel, 2000, Fluvially-incised shelf-edge deltas and linkage to upper-slope channels (central Tertiary basin, Spitsbergen), in H.H. Roberts, R.H. Fillon, and J.B. Anderson, eds., Shelf Margin deltas and linked down slope petroleum systems: Global significance and future exploration potential: Gulf Coast Section SEPM 23rd Bob F. Perkins Annual GCSSEPM Foundation Research Conference, p. 231-266.

Morton, R.A., and J.R. Sutter, 1996, Sequence stratigraphy and composition of Late Quaternary shelf-margin deltas, northern Gulf of Mexico: AAPG Bulletin, v. 80, no. 4, p. 505-530.

Muto, T., and R.J. Steel, 1997, Principles of regression and transgression: the nature of the interplay between accommodation and sediment supply: Journal of Sedimentary Research, v. 67, p. 994-1000.

Nemec, W., R.J. Steel, J. Gjelberg, J.D. Collinson, E. Prestholm and I.E. Oxnevad, 1988, Anatomy of collapsed and re-established delta front in Lower Cretaceous of Eastern Spitsbergen: Gravitational sliding and sedimentation processes: AAPG Bulletin, v. 72, p. 454-476.

Orton, R.J., and Reading, H.G., 1993, Variability of deltaic processes in terms of sediment supply, with particular emphasis on grain size: Sedimentology, v. 40, p. 475-512.

Owoyemi, A.O., and B.J. Willis, 2006, Depositional Patterns across syndepositional normal faults, Niger Delta, Nigeria: Journal of Sedimentary Research, v. 67, p. 994-1000.

Pacht, J.A., B.E., Bowen, J.H., Beard and B.L., Shaffer, 1990, Sequence- stratigraphy of Plio-Pleistocene depositional facies in the offshore Louisiana South Additions: Transactions Gulf Coast Association of Geological Societies, v. XL, p. 643-659.

Porebski, J.S. and R.J. Steel, 2003, Shelf-margin deltas: their stratigraphic significance and relation to deepwater sands: Earth Science Reviews, 62, p. 283-326.

Porebski, J.S. and R.J. Steel, 2006, Deltas and sea-level change: Journal of Sedimentary Research, v. 76, p. 390-403.

Posamentier, H.W., 2003, A linked shelf-edge delta and slope-channel turbidite system: 3D seismic case study from the Eastern Gulf of Mexico, in H.H., Roberts, R.H. Fillon, and J.B. Anderson, eds., Shelf Margin deltas and linked down slope petroleum systems: Global significance and future exploration potential: Gulf Coast Section SEPM 23rd Bob F. Perkins Annual GCSSEPM Foundation Research Conference, p. 205-230.

Posamentier, H.W. and G.P. Allen, 1993, Variability of the sequence stratigraphic model: effects of local basin factors: Sedimentary Geology, v. 86, p. 91-109.

Posamentier, H.W., M.T., Jervey and P.R., Vail, 1988, Eustatic control on clastic deposition I-Conceptual framework, in C.K. Wilgus, B.S. Hastings, C.G.St.C., Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner, eds., Sea-level changes: An integrated approach, SEPM, Special publication 42, p. 109-124

Ritchie, B.D., R.L. Gawthorpe and S. Hardy, 2004, Three dimensional numerical modeling of deltaic depositional sequences 1: influence of the rate and magnitude of sea-level change: Journal of Sedimentary Research, v. 74, p. 203-220.

Ritchie, B.D., R.L. Gawthorpe and S. Hardy, 2004, Three dimensional numerical modeling of deltaic depositional sequences 2: influence of local controls: Journal of Sedimentary Research, v. 74, p. 221-238.

Saller, A.H, J.T. Noah, A.P. Ruzuar and S. Schneider, 2003, Linked lowstand delta to basin floor fan deposition, offshore Indonesia: An analog for deep-water reservoir systems: AAPG Bulletin, v. 88, p. 21-46.

Short, K.C., and A.J. Stauble, 1967, Outline of the geology of Niger Delta: AAPG Bulletin, v. 52, p. 761-799.

Steel, R.J., J. Crabaugh, M. Schellpeper, D. Mellere, P. Plink-Bjorklund, J. Deibert, and T. Loeseth 2000, Deltas vs. Rivers on the shelf edge: their relative contributions to the growth of shelf-margins and basin floor fans (Barremian and Eocene, Spitsbergen), in P. Weimer, R.M. Slatt, J. Coleman, N.C. Rosen, H. Nielson, A.H. Bouma, M.J. Styzen, and D.T. Lawrence, eds., Deep-water reservoirs of the world: Gulf Coast Section SEPM 20th Annual Research Conference, p. 981-1009.

Steel, R.J., S.J. Porebski, D. Mellere, M. Schellpeper, and P. Plink-Bjorklund, 2003, Shelf-edge delta types and their sequence stratigraphic relationships, in H.H., Roberts, R.H. Fillon, and J.B. Anderson, eds., Shelf Margin deltas and linked down slope petroleum systems: Global significance and future exploration potential: Gulf Coast Section SEPM 23rd Bob F. Perkins Annual GCSSEPM Foundation Research Conference, p. 205-230.

Steel, R.J., and T. Olsen, 2002, Clinoforms, clinoform trajectories and deepwater sands: CD-ROM, GCS-SEPM Foundation, 21st Annual Research Conference: Sequence Stratigraphy, p. 367-380.

Suter, J.R. and H.L. Berryhill , JR., 1985, Late Quaternary shelf-margin deltas, Northwest Gulf of Mexico, AAPG Bulletin, v. 69, p. 77-91.

Sydow J., and H.H. Roberts, 1994, Stratigraphic framework of a Late Pleistocene shelf-edge delta, northeast Gulf of Mexico: AAPG Bulletin, v. 78, p. 1276-1312.

Torres, J., B. Savoye, and P. Cochonat, 1995, The effects of Late Quaternary sea level changes on the Rhone Slope sedimentation (Northwestern Mediterranean), as indicated by seismic stratigraphy: Journal of Sedimentary Research, v. B65, P.368-387.

Van Heijst, M.W.I.M., G. Postma, W.P. Van Kesteren, and R.G. de Jongh, 2002, Control of syndepositional faulting on systems tract evolution across growth-faulted shelf-margins: An analog experimental model of the Miocene Imo River field, Nigeria: AAPG Bulletin, v. 86, p. 1335-1366.

Van Wagoner, J.C., R.M. Mitchum, K.M. Campion, and V.D. Rahmanian, 1990, Siliciclastic sequence stratigraphy in well logs, cores and outcrops: Concepts for high-resolution correlation, of time and facies: AAPG, Methods in Exploration Series 7, 55p.

Weber, K.J., and E.M. Daukoru, 1975, Petroleum geology of the Niger Delta: Proceedings of the Ninth World Petroleum Congress, v. 2, p. 209-221.

Winker, C.D., 1982, Cenozoic shelf margins, northwestern Gulf of Mexico, in M.A., Morad, J.E. Kilgore, D.K. Cameron Jr., (eds), Trans. Gulf Coast Association Geological Societies, 32nd Annual Meeting, v. 32, p. 427-448.

Winker, C. and R.C. Craig, 2003, Sequence boundary ambiguities in shelf-margin deltas and shelf-slope transition: illustration from the Pleistocene of the Gulf of Mexico, in

H.H., Roberts, R.H. Fillon, and J.B. Anderson, eds., Shelf Margin deltas and linked down slope petroleum systems: Global significance and future exploration potential: Gulf Coast Section SEPM 23rd Bob F. Perkins Annual GCSSEPM Foundation Research Conference, p. 205-230.

Winn, R.D., H.H. Roberts, B. Kohl, R.H. Fillon, J.A. Crux, A.H. Bouma and H.W. Spero, 1998, Upper Quaternary strata of the upper continental slope, Northeast Gulf of Mexico: sequence stratigraphic model for a terrigenous shelf edge, Journal of Sedimentary Research, v. 68, p. 579-595.

Zecchin, M., F. Massari, D. Mellere and G. Prosser, 2003, Architectural styles of prograding wedges in a tectonically active setting, Crotone Basin, Southern Italy: Journal of the Geological Society London, v. 160, p. 863-880.

Vail, P.R., R.M., Mitchum, and S. Thompson, 1977, Seismic stratigraphy and global changes in sea level, part 3: Relative changes of sea level from coastal onlap, in C.E. Payton, ed., Seismic stratigraphy-Application to hydrocarbon exploration: AAPG, Memoir 26, p. 63-81.

6.0 Figures

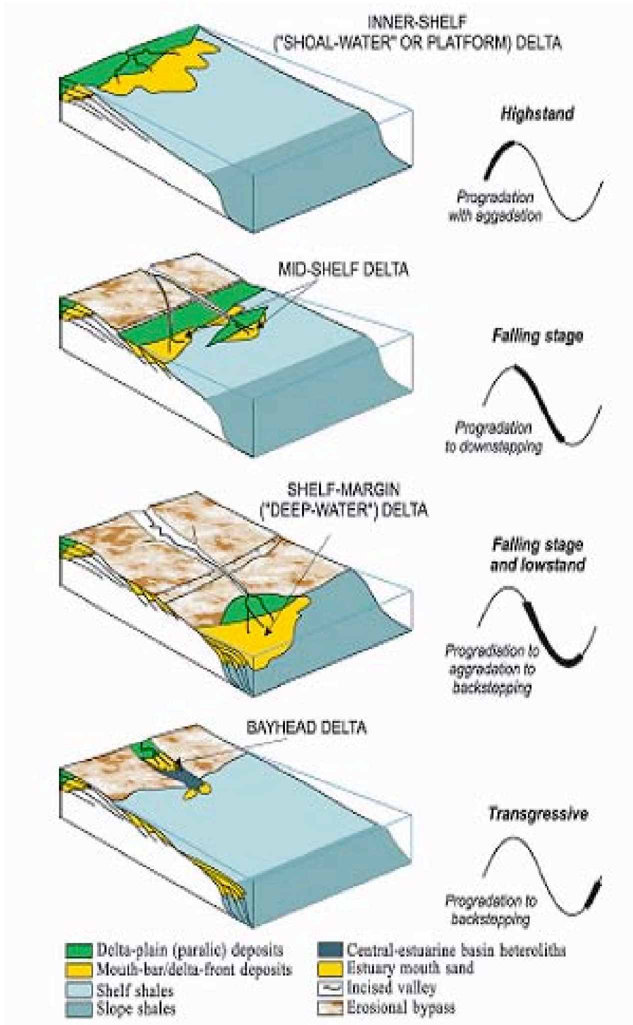


Fig. 1: Delta classification based on relative sea level and position on the shelf (from Porebski and steel 2003)

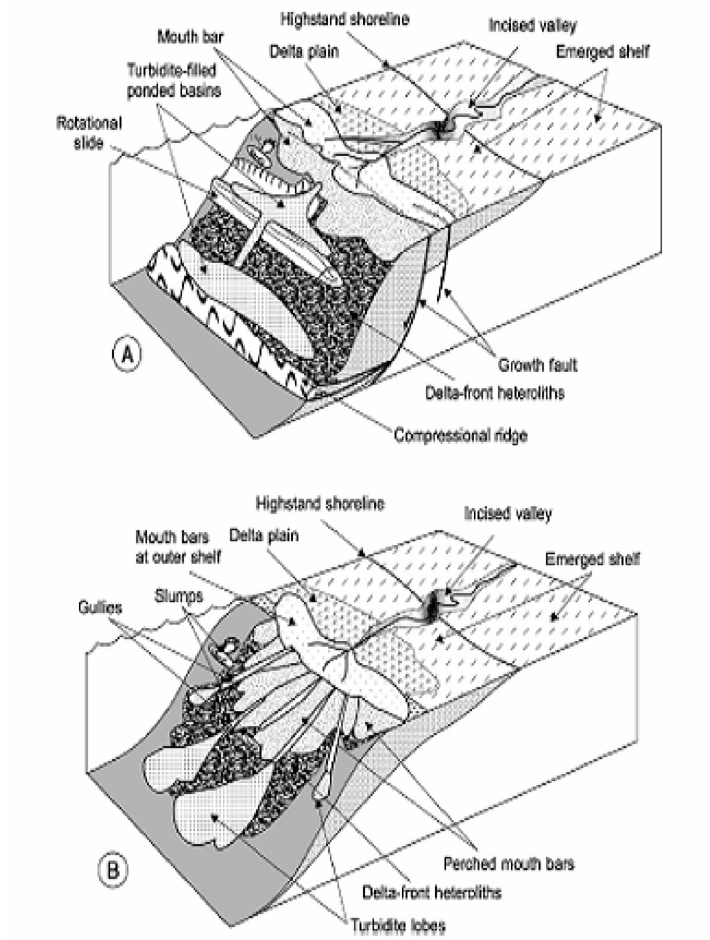


Fig. 2: Schematic diagram of (A) unstable shelf-margin and (B) stable shelf-margin (from Porebski and Steel, 2003)

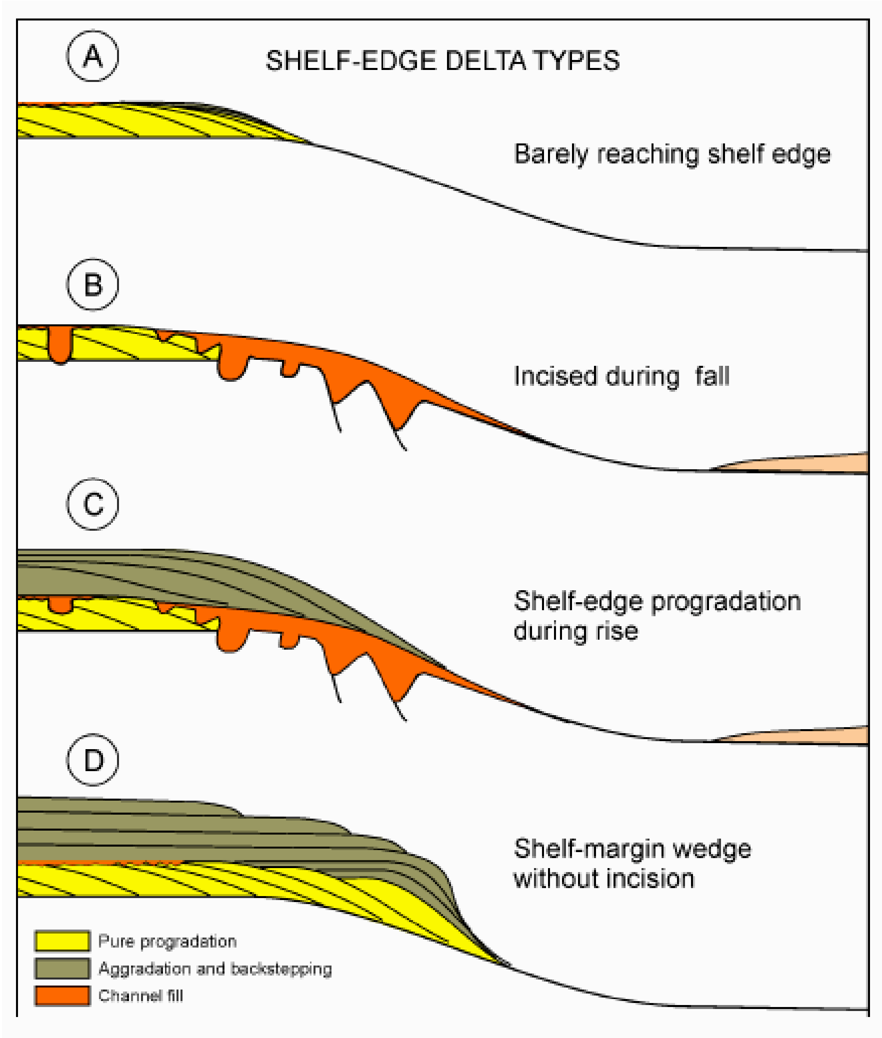


Fig. 3: Shelf –margin delta types (from Steel et al. 2003)

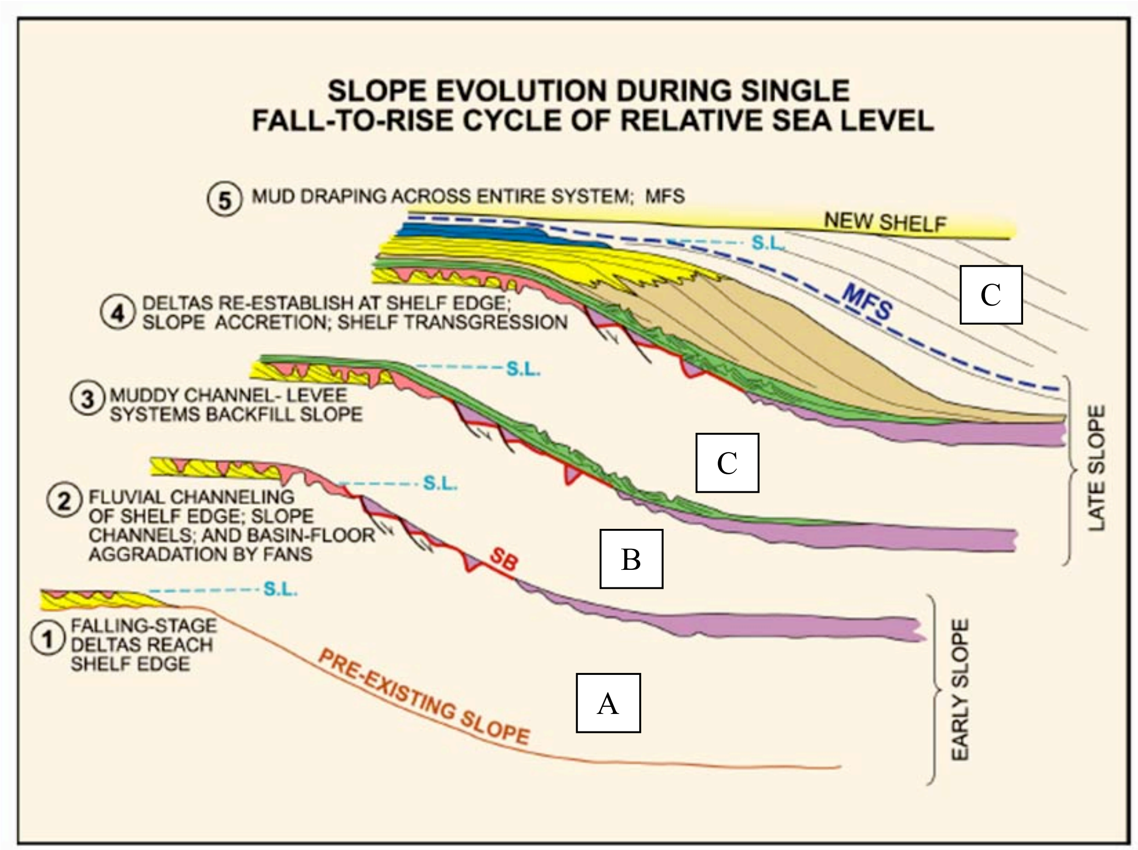


Fig. 4: Evolutionary series of shelf-margin deltas (Type A through C forms during a fourth order sea level fall-to-rise. From Steel et al. 2003)

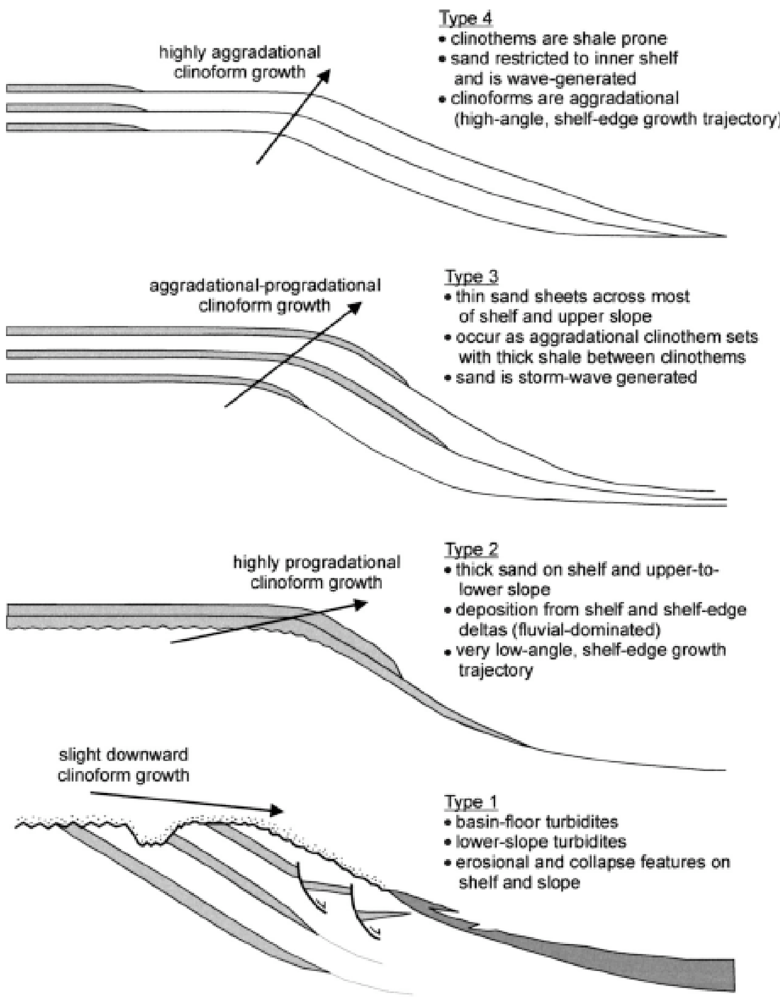


Fig. 4b: Clinoform types and linkage with slope and basin floor fans (From Deibert et al. 2003)

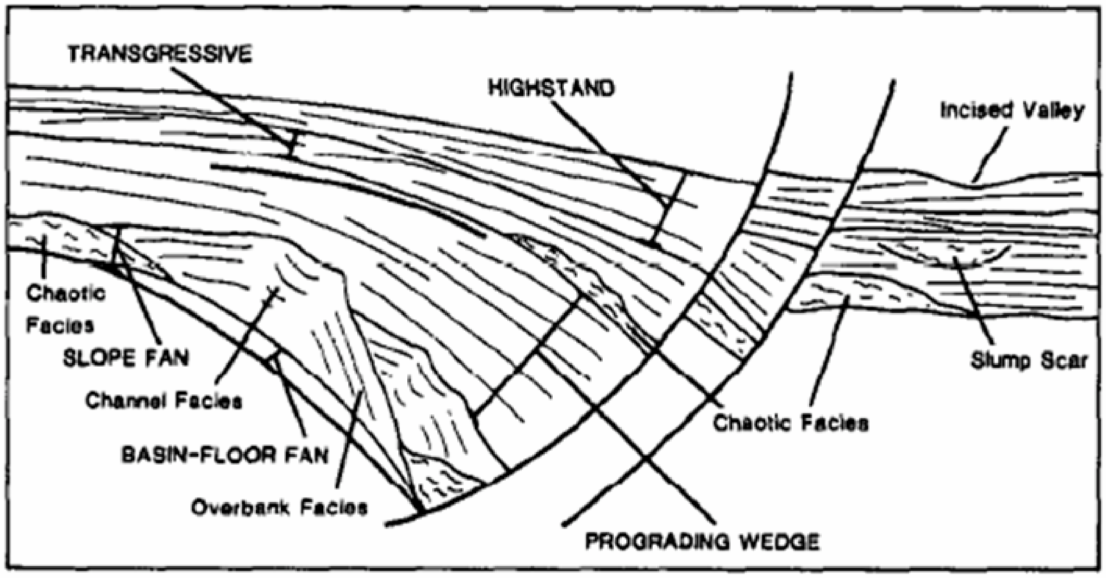


Fig. 5: Sequence, systems tract and seismic facies developed along unstable progradational passive margin Pacht et al. 1990)

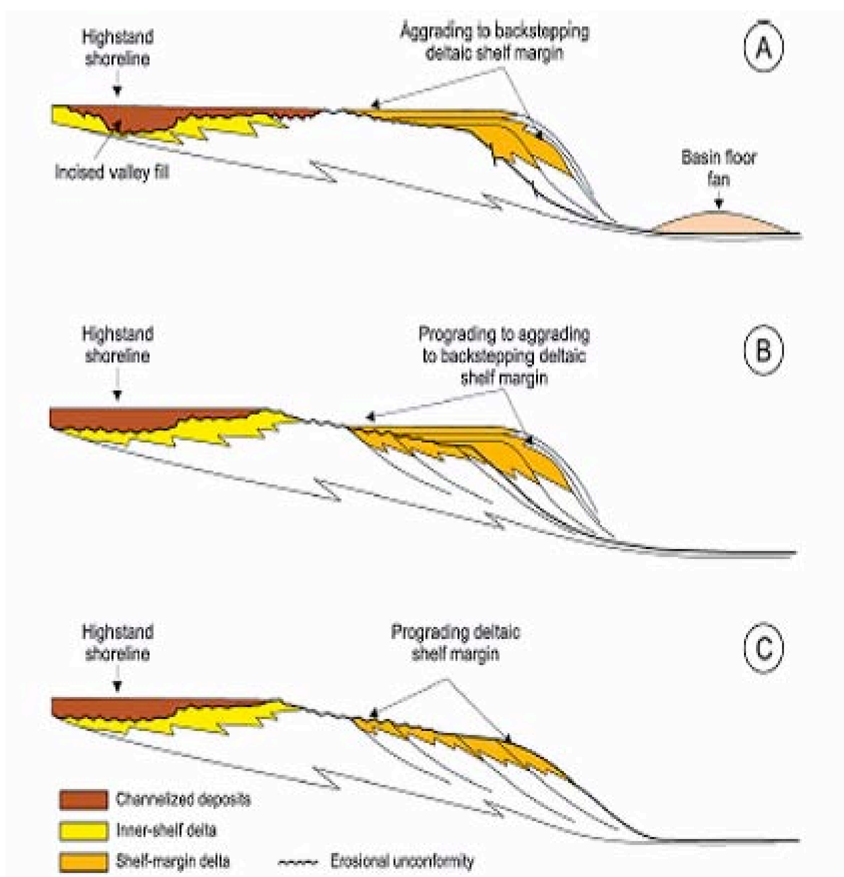


Fig. 6: Shelf-margin delta as a predictor of deep water sedimentation (from Porebski and Steel, 2003)

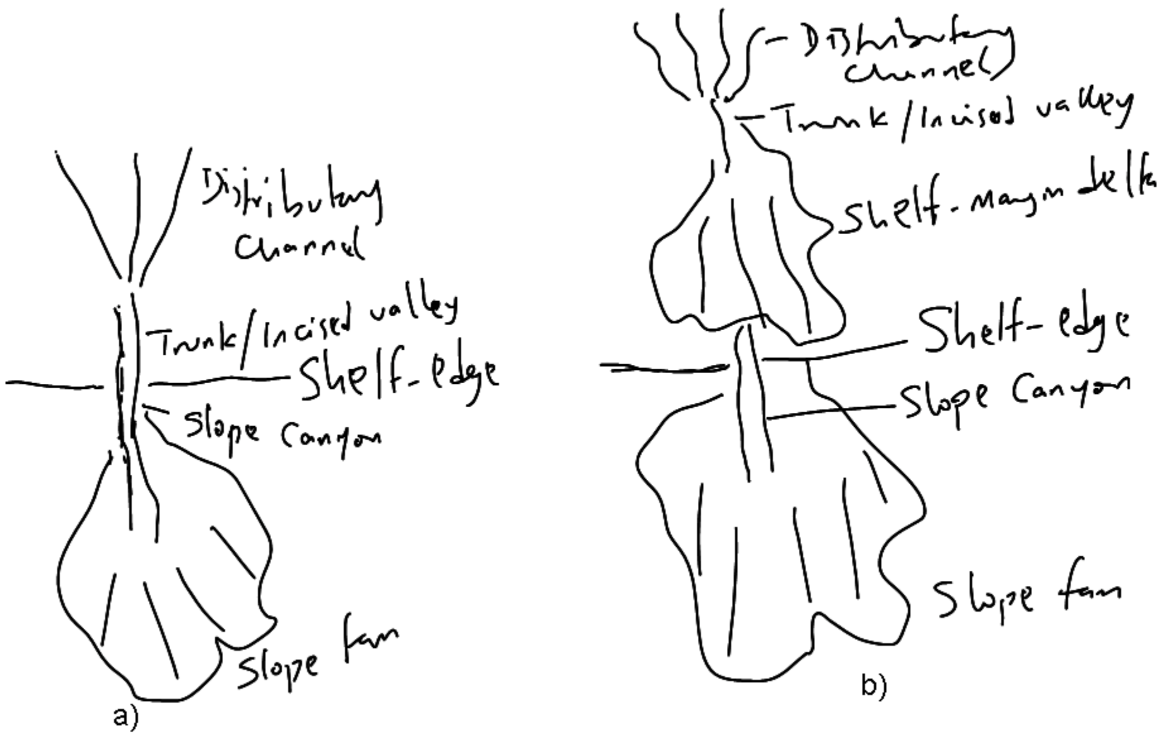


Fig. 7: Linked slope fan, canyon and shelf feeder systems model
a) Present sequence stratigraphic model
b) Variation imposed by local basin factors

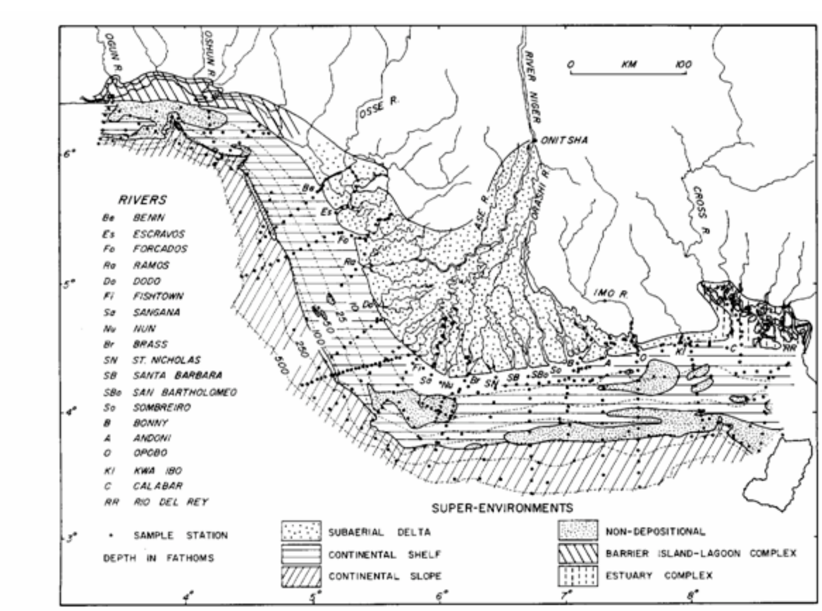


Figure 8: Map of Niger Delta showing the major feeder systems (from Allen 1965)

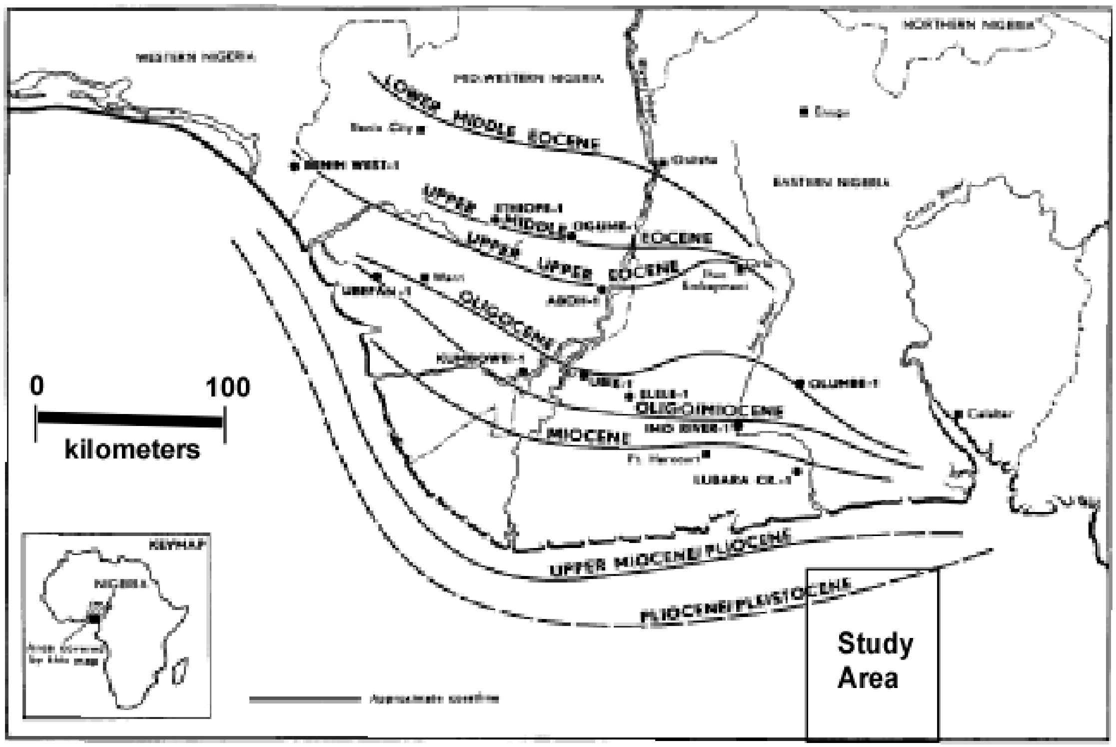


Fig. 9: Study Area (from Short and Stauble, 1967)

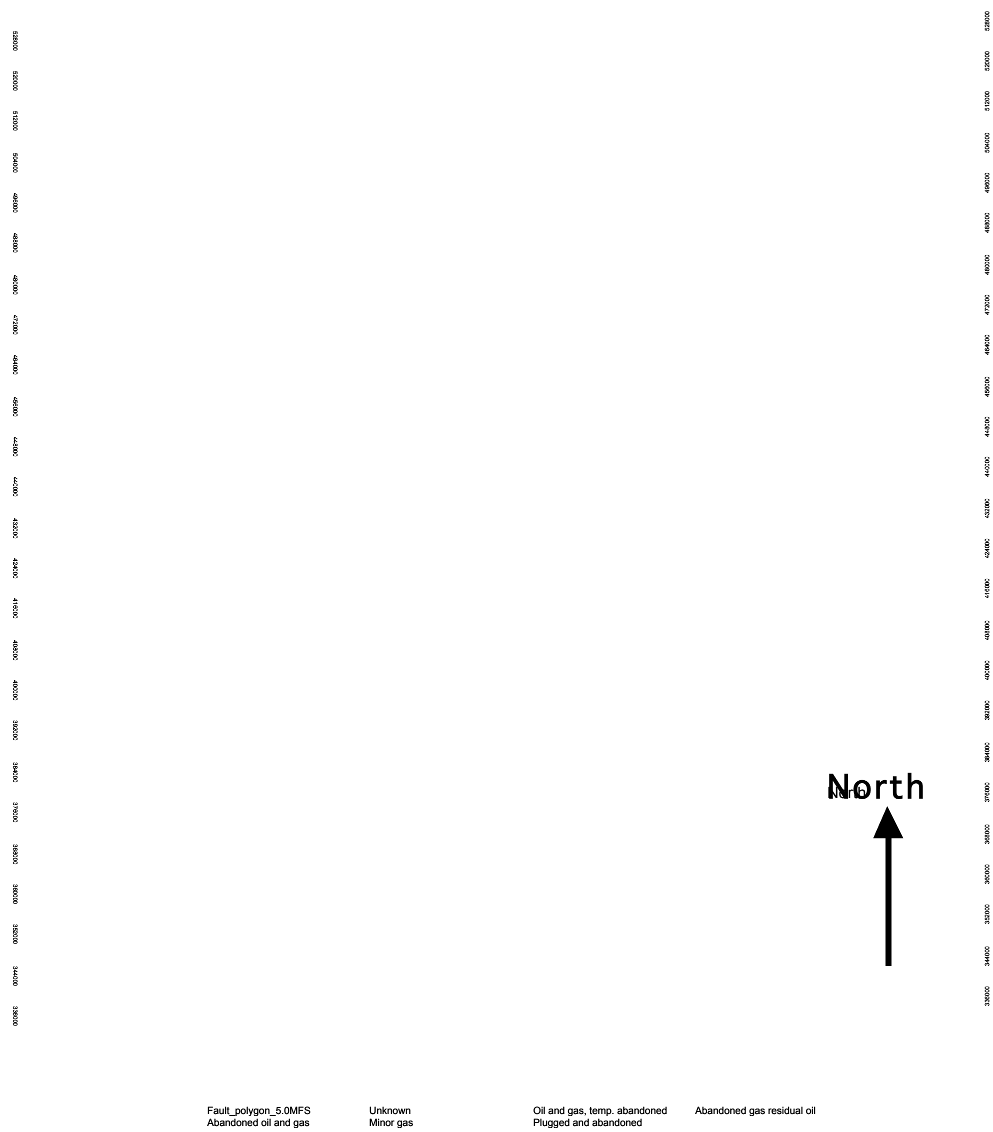
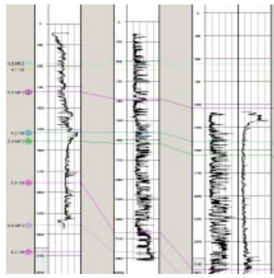


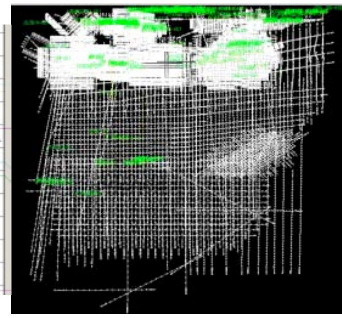
Figure 10: Map showing well locations and interpreted major faults (Black Polygons)

s/n	DEPTH	S.TYPE	ENVIRONMENT	F. DIVERS.	F. POPLN	P. DIVERS.	P. POPLN
1	5230	3	B	0	0	0	0
2	5290	3	B	0	0	0	0
3	5350	3	B	0	0	0	0
4	5410	3	B	0	0	0	0
5	5470	3	B	0	0	0	0
6	5530	3	B	0	0	0	0
7	5590	3	B	0	0	0	0
8	5650	3	B	0	0	0	0
9	5710	3	B	0	0	0	0
10	5770	3	B	0	0	0	0
11	5830	3	B	0	0	0	0
12	5890	3	B	0	0	0	0
13	5950	3	CD	1	1	0	0
14	6010	3	B	0	0	0	0
15	6070	3	B	0	0	0	0
16	6130	3	CD	1	2	0	0
17	6190	3	CD	1	1	0	0
18	6260	3	B	0	0	0	0
19	6320	3	B	0	0	0	0
20	6380	3	IN-MN	6	29	1	1
21	6440	3	MN	6	8	3	4
22	6500	3	IN	5	8	2	2
23	6560	3	SH.IN	2	3	0	0
24	6620	3	SH.IN	1	2	0	0
25	6680	3	SH.IN	2	2	1	1
26	6740	3	SH.IN	1	1	0	0
27	6800	3	SH.IN	2	2	0	0
28	6860	3	IN	3	8	1	2
29	6920	3	SH.IN	2	2	0	0
30	6980	3	CD	2	2	0	0
31	7040	3	SH.IN	2	3	1	1
32	7100	3	IN	4	9	0	0
33	7160	3	SH.IN	1	2	0	0
34	7220	3	IN	2	3	0	0
35	7280	3	SH.IN	1	1	0	0
36	7340	3	SH.IN	1	1	0	0
37	7400	3	SH.IN	2	2	0	0
38	7460	3	SH.IN	2	2	0	0
39	7520	3	SH.IN	2	2	1	1
40	7640	3	SH.IN	2	2	0	0
41	7700	3	SH.IN	2	3	0	0
42	7760	3	SH.IN	2	2	1	1
43	7820	3	IN-MN	7	9	2	3
44	7880	3	IN	3	11	1	1
45	7940	3	SH.IN	2	7	1	3
46	8000	3	SH.IN	2	3	0	0
47	8060	3	IN-MN	7	13	1	1
48	8120	3	IN	5	9	0	0
49	8180	3	IN-MN	8	36	1	1
50	8240	3	IN-MN	6	25	0	0
51	8300	3	IN-MN	6	52	1	1
52	8360	3	MN	8	36	1	4
53	8420	3	MN	4	17	0	0
54	8480	3	MN	7	16	0	0
55	8540	3	CD	1	1	0	0
56	8600	3	MN	6	17	2	2
57	8660	3	MN-ON	12	61	2	6
58	8840	3	IN	5	7	1	2
59	8900	3	IN	2	3	0	0
60	8960	3	SH.IN	2	2	0	0
61	9020	3	IN-MN	8	13	1	2

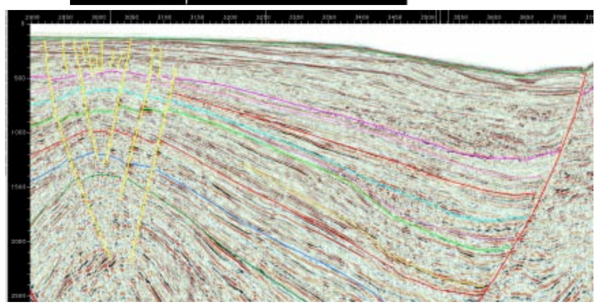
Biostratigraphic data



Wireline Log data



Map showing 2D/3D seismic data (3D data in box outline)



Dip line of 2D data showing shelf -margin delta clinoforms

Figure 11: Available data

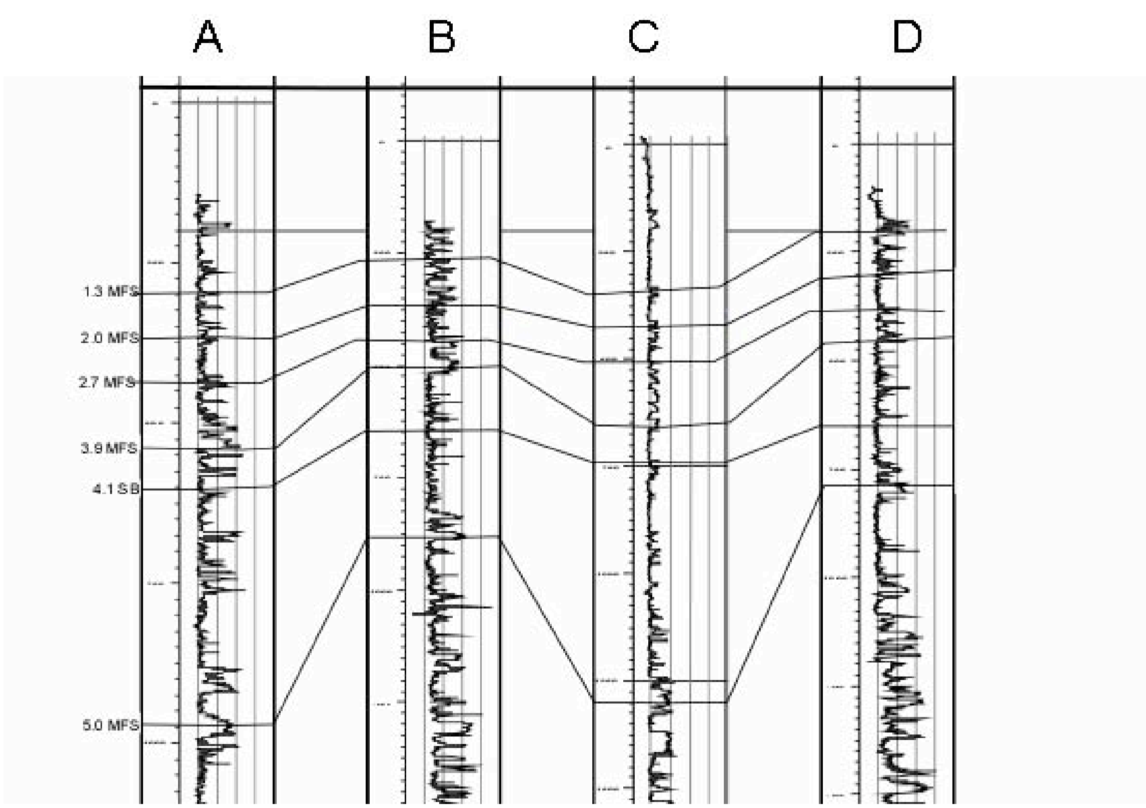


Fig. 12: Key surfaces identified using logs and biostratigraphy

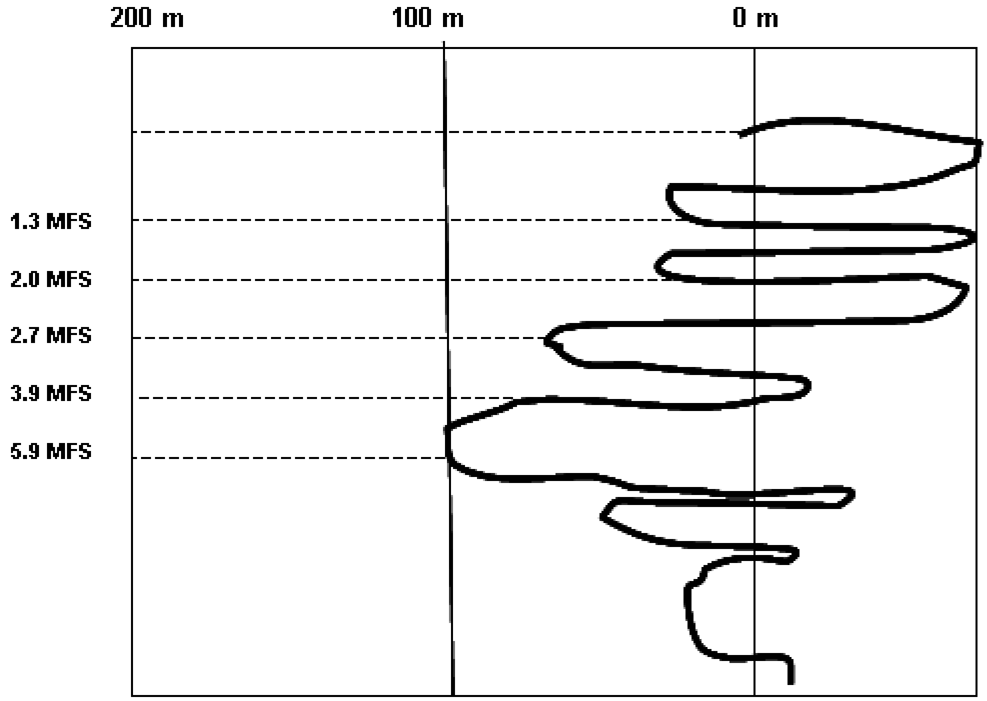


Fig. 13: Key surfaces tied to sea level curve (Sea level curve from Haq et al. 1987)