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Stratigraphy and sedimentology of the Niger Delta

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Abstract

During the Cenozoic, until the Middle Miocene, the Niger Delta grew through pulses of sedimentation over an oceanward-dipping continental basement into the Gulf of Guinea; thereafter progradation took place over a landward-dipping oceanic basement. A 12,000 m thick succession of overall regressive, offlapping sediments resulted that is composed of three diachronous siliciclastic units: the deep-marine pro-delta Akata Group, the shallow-marine delta-front Agbada Group and the continental, delta-top Benin Group.

Regionally, sediment dispersal was controlled by marine transgressive/regressive cycles related to eustatic sea-level changes with varying duration. Differential subsidence locally influenced sediment accumulation. Collectively, these controls resulted in eleven chronostratigraphically confined delta-wide megasequences with considerable internal lithological variation.

The various sea-level cycles were in or out of phase with each other and with local subsidence, and interfered with each other and thus influenced the depositional processes. At the high inflection points of the long-term eustatic sea-level curve, floodings took place that resulted in delta-wide shale markers. At the low inflection points, erosional channels were formed that are often associated, downdip, with turbidites in low-stand sediments (LSTs). The megasequences contain regional transgressive claystone units (TST) followed by a range of heterogeneous fine-to-coarse progradational or aggradational siliciclastic (para)sequence sets formed during sea-level high-stand (HST).

An updated biostratigraphic scheme for the Niger Delta is presented. It also updates a sedimentation model that takes into consideration local and delta-wide effects of sea-level cyclicity and delta tectonics. Megasequences were formed over time intervals of ~5 Ma within individual accurate megastructures that laterally linked into depobelts. The megasequences form the time-stratigraphic frame of the delta and are the backbone for the new delta-wide lithostratigraphy proposed here. Such a new lithostratigraphy is badly needed, in particular because of the vigorous new activity in the offshore part of the Niger Delta (not covered in this contribution). There, as well as in the onshore part of the delta, the traditional lithostratigraphic subdivision of the Cenozoic Niger Delta section into three formations is insufficient for optimum stratigraphic application; moreover, the various informal subdivisions that have been proposed over time are inconsistent.

Keywords: Niger Delta, biostratigraphy, sedimentology, (mega)sequences, cycles

1. Introduction

The Niger Delta (Fig. 1) has been the focus of hydrocarbon exploration since 1937. Now it is Africa's leading oil province. Today, the delta is covered with a dense grid of 2-D and 3-D seismic data and it has been penetrated by more than 5,000 wells. The exploration activity shifted during the past ten years gradually to the offshore part of the Niger Delta, which area – including its sedimentological and stratigraphical aspects – is not covered in the current contribution. The new stratigraphic concepts presented here are, however, certainly helpful for the relatively new activities.

Due to slow thermal cooling of the underlying lithosphere, the delta subsides gradually. Due to increased sediment loading, it flexes in

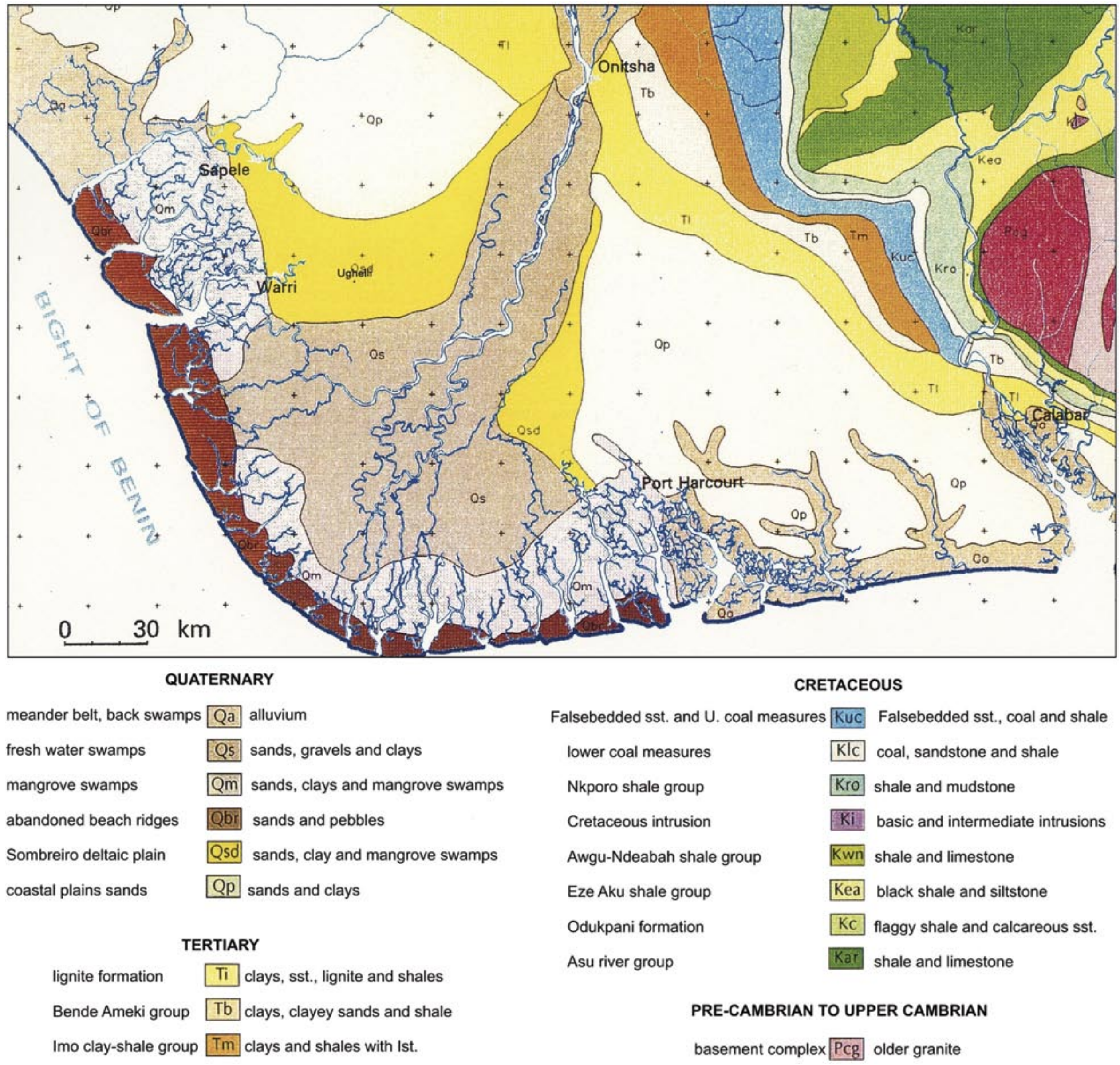

Fig. 1. Geological map of the Niger Delta and surroundings.

a seaward direction. The delta-top Benin Group (red in Fig. 2) overlies the delta-front Agbada Group (yellow) and the pro-delta Akata Group (green). The composition of the subsurface Benin Group reflects the present-day Quaternary land and swamp outcrops (Fig. 1); the Agbada Group reflects the beach ridges, and the Akata Group the offshore sands, silts and clays. In this context, it should be noted that the Benin, Agbada and Akata lithostratigraphic units are currently classified as formations, although they are also frequently referred to as 'facies'. It is proposed here to elevate them to group level, and therefore they are referred to as such.

Previous sedimentological, biostratigraphical and sequence-stratigraphic studies (Ladipo, 1992; Stacher, 1995; Reijers et al., 1997) revealed the combined influence of eustatic cyclicity and local tectonics. Recent new studies in the offshore (Owejemi & Willis, 2006; Magbagbeoloa & Willis, 2007) demonstrate that these concepts are still valid but perhaps could benefit from the stratigraphic information and the new approaches presented here. Depositional sequences as defined by Vail (1987) and consisting of strata bounded by unconformities and their lateral equivalents are only recognised in specific sectors of the delta. In contrast, delta-wide genetic sequences as defined by Galloway (1989) and consisting of strata bounded by maximum flooding surfaces within transgressive shales are more readily identifiable in the Niger Delta. Therefore Galloway's approach is preferred here for delta-wide stratigraphic correlation. Individual sea-level cycles are reflected in the Niger Delta in various sedimentary sequences. Interferences of cycles with different periods result in megasequences that are chronostratigraphically confined and sedimentologically characterised. The present study was aimed at finding out in how far such megasequences reflect second-order sequence sets of Haq et al. (1988) and to what extent interference of global eustatic sea-level movements and local deltaic autocyclic and allocyclic processes can be detected. Use is made of a refined biostratigraphic zonation scheme (integrated in Fig. 2) that helps to define the Niger-Delta megasequences, and the sedimentological facies model of Weber (1971) is updated and incorporated into the sequence-stratigraphic analysis. As a result, a new lithostratigraphy of the Niger Delta is outlined.

2. Methods

The present study builds on work of Short & Stauble (1967), Weber (1971), Weber & Daukoru (1975), Evamy et al. (1978), Ejedawe (1981), Knox & Omatsola (1987), Ladipo (1992) and Stacher (1995). Additional information came from material published by Elf (Durand, 1995) and was acquired through personal communication with Ojoh (1997), Nwajide (1996–1999) and Adesida (1996–1999) and from some unpublished works, while working on a unified approach to the stratigraphy of the Niger Delta.

Cycles and sequences are important features in this study. The term 'cycles' is used here for variations in the relative sea level. Two types exist: autocyclic and allocyclic cycles. Autocyclic cycles result from natural redistribution of energy within a depositional system such as channel meandering or switching and delta avulsion. They result in local patterns of sediment distribution and in sequences such as presented in, for instance, Figures 3 and 4; they are explained below. Allocyclic cycles results from changes in a sedimentary system as a result of an external cause such as eustatic sea-level change, tectonic basin subsidence and climate change. They result in delta-wide sediment distribution patterns (Figs 5, 6) and sedimentary sequences, as explained below. Both types occur in the Niger Delta. The present study uses the curves of Haq et al. (1988) as a reference for eustatic sea-level fluctuations.

Autocyclic cycles are superimposed upon allocyclic ones. Therefore, the resulting sedimentary sequences reflect both delta-wide and local sedimentary processes. A number of clayey marker horizons (Fig. 5) define the sequences. They are shown in the column on the far right of Figure 2. These sequences are described and interpreted below.

The stratigraphical section of the Niger Delta presents evidence for long- and short-term sea-level variations that interact with each other. The flanks of the delta differ clearly from the central sector (Fig. 2), which is the main reason for 'flapping open' and further updating earlier synopses of lithofacies in the Niger Delta that were based on development of lithofacies in the Niger Delta through time (see, for instance, Fig. 4 in Doust, 1987).

In the flanks, extensive submarine canyons formed that are traditionally referred to as 'channels' (Petters,1984; Knox & Omatsola, 1988; Reijers et al., 1997). These have erosional bases and their fills are characterised by a number of internal erosional unconformities that have also been reported from the offshore (Owoyemi, 2006). In contrast, such erosional features are scarce in the central sector of the Niger Delta, where transgressive shales clearly mark maximum floodings.

3. Geological setting

The evolution of the delta is controlled by pre- and synsedimentary tectonics as described by Evamy et al. (1978), Ejedawe (1981), Knox & Omatsola (1987) and Stacher (1995). The delta growth is summarised below. The shape of the Cretaceous coast line (Fig. 1; see also Reijers et

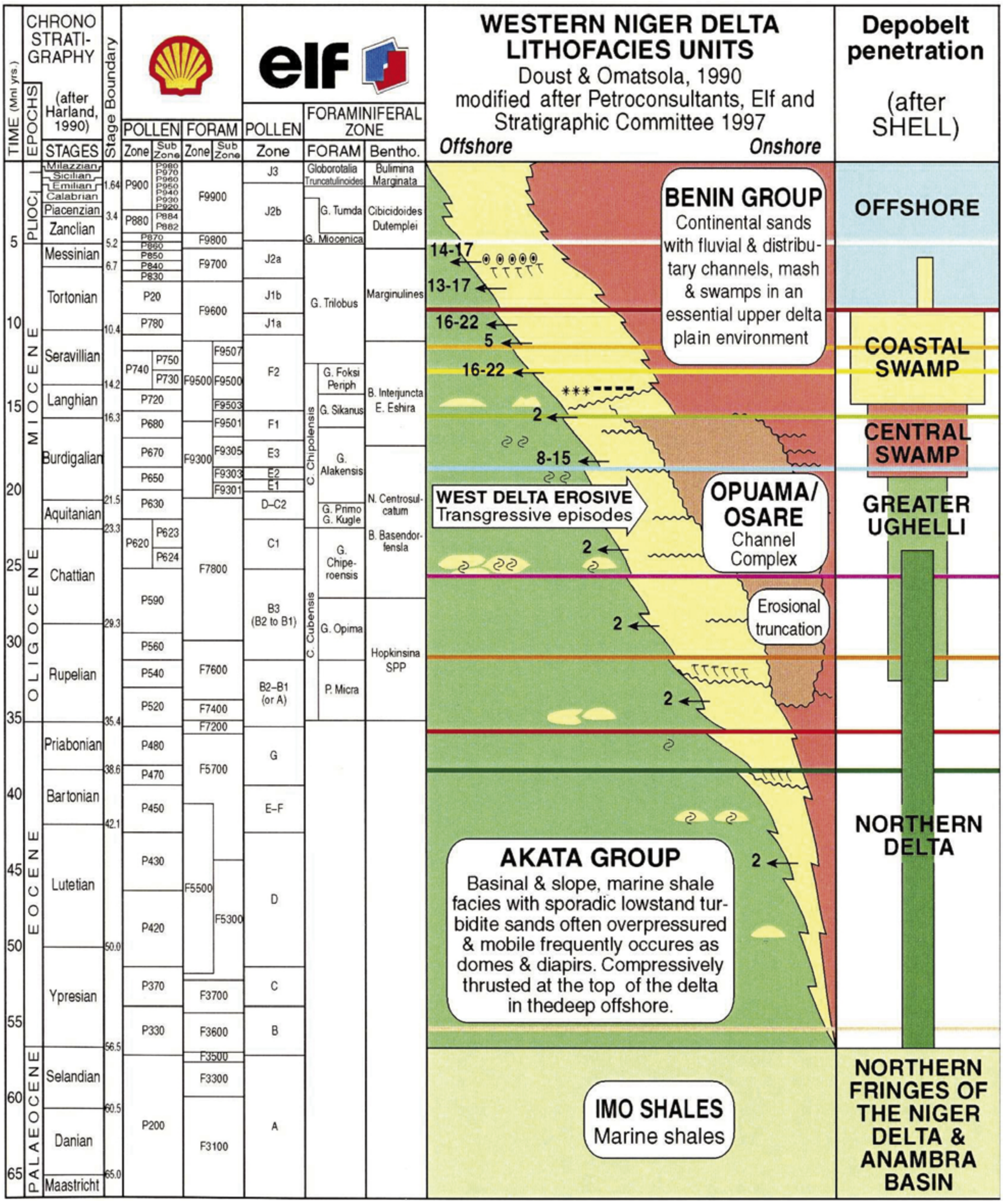

Fig 2. Stratigraphic data sheet (west and east halves combined) of the Niger Delta.

al., 1997) gradually changed with the growth of the Niger Delta (Figs 3, 4). A bulge developed due to delta growth. This changing coastline interacted with the palaeo-circulation pattern and controlled the extent of incursions of the sea (Reijers et al., 1997). Other factors that controlled the growth of the delta are climatic variations and the proximity and nature of sediment source areas.

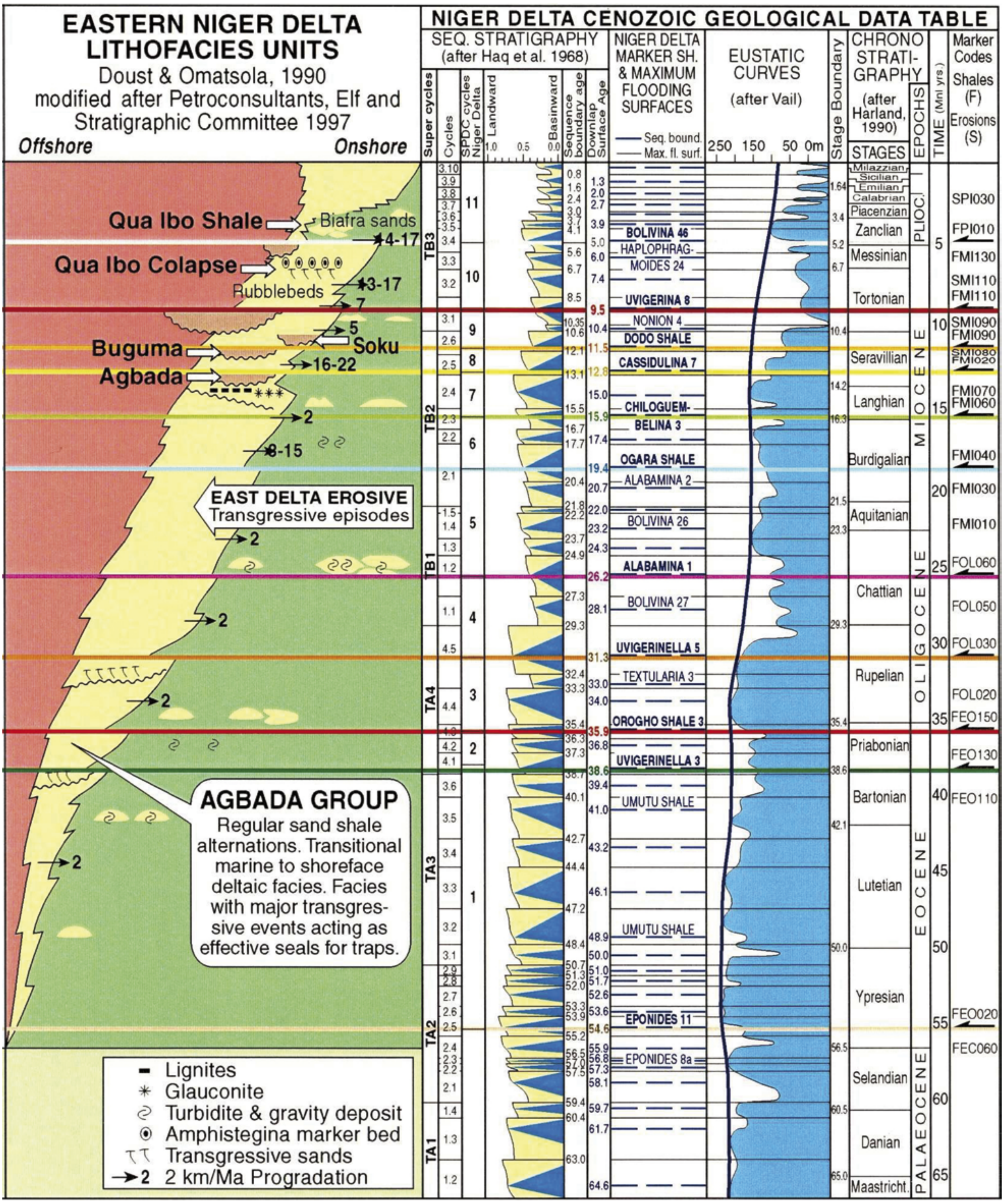

Fig 2. cont.

During the Middle-Late Eocene, sediment was deposited (Fig. 3A) west of the inverted Cretaceous Abakaliki High and south of the Anambra Basin in what became the 'northern depobelt of the Niger Delta' (Figs 1, 3, 4). The first coarse clastic deposits have been dated on the basis of microfloral units (Evamy et al., 1978) (Fig. 2; Table 1) as Early Eocene. Tradewinds generated longshore currents with two cells converging along the western

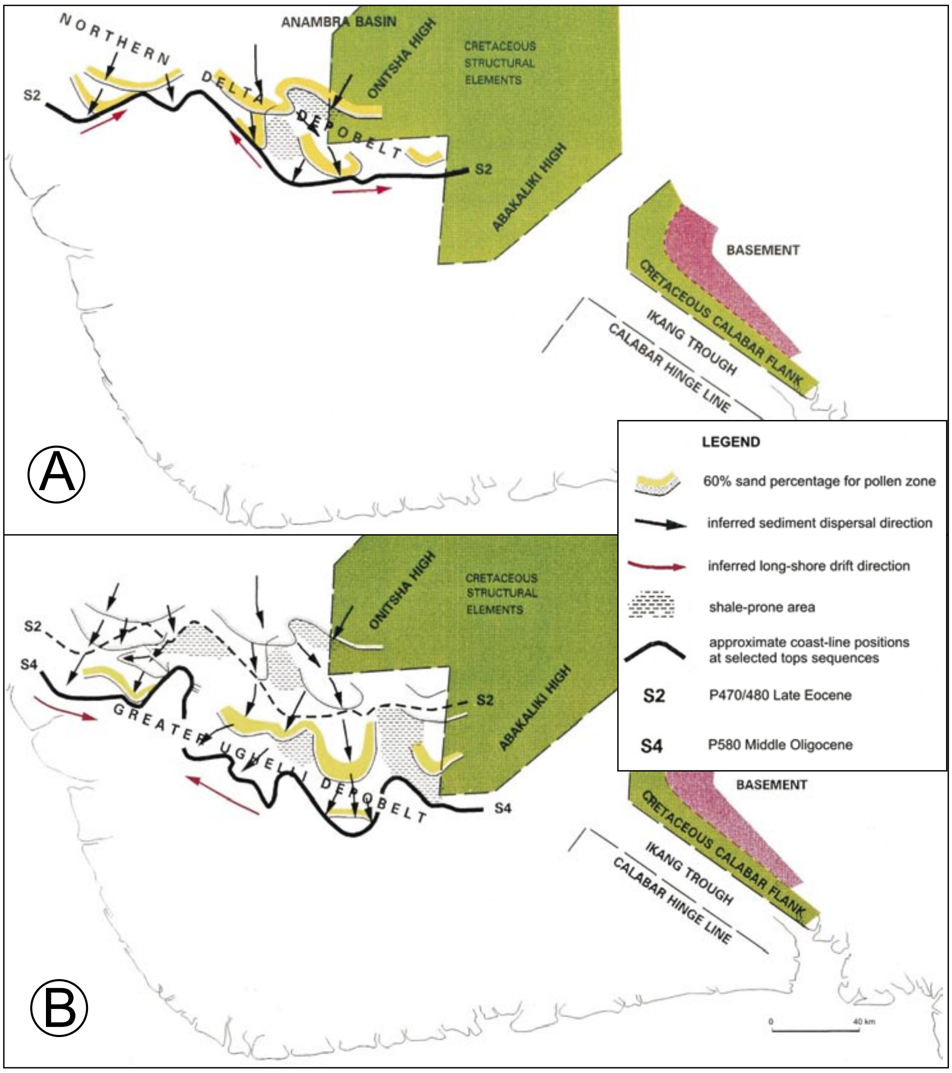

Fig. 3. Palaeo-drainage trend and advancing coastline of the Niger Delta (modified after Edjedawe,1981; Edjedawe et al., 1984). **A** – Position at start of sequence 3 (Orogho-shale transgression); **B** – Position at start of sequence 5 (*Alabamina*–1 shale transgression).

estuarine coast sector (Burke, 1972; Berggren & Hollister, 1974, Reijers et al., 1997) (Fig. 3A). Studies by Weber & Daukuro (1975), Ejedawe (1981) and Ejedawe et al. (1984) clarified that the embryonic delta subsided during the Late Eocene to Middle Oligocene <700 m/Ma and prograded approx. 2 km/Ma along three depositional axes that fed irregular, early delta lobes (Fig. 3) that eventually coalesced. Thick sandy sediment accumulations thus formed in the active 'Greater Ughelli depobelt'.

During the Late Oligocene to Middle Miocene, the delta subsidence remained steady at some 700 m/Ma but delta progradation increased to 8–15 km/Ma. Incision of the Opuama Channel (Figs 2, 3B, 4A) in the western sector of the delta occurred at this time (Patters, 1984; Knox & Omatsola, 1987). From the Middle Miocene onward, the delta prograded over a landward dipping oceanic lithosphere. The 'Escalator Regression Model' of Knox & Omatsola (1987) shows the average delta subsidence rates and progradation figures used here. During the Miocene, the average progradation was some 1000 m/Ma. Depocentres in the eastern sector of the delta merged laterally and the enlarged delta front prograded pulsewise, occasionally advancing at rates of 16–22 km/Ma (Figs 2, 3B, 4). The coastline, now convex, broke up the longshore current into two divergent drift cells. During the Middle-Late Miocene, a rising hinterland supplied substantial amounts of sediment that accumulated in the active Central Swamp and in the northern sector of the Coastal Swamp. Progradation maintained at a steady rate of 13–17 km/Ma (Fig. 2) and stabilised in the Late Miocene-Pliocene when the Coastal Swamp and offshore

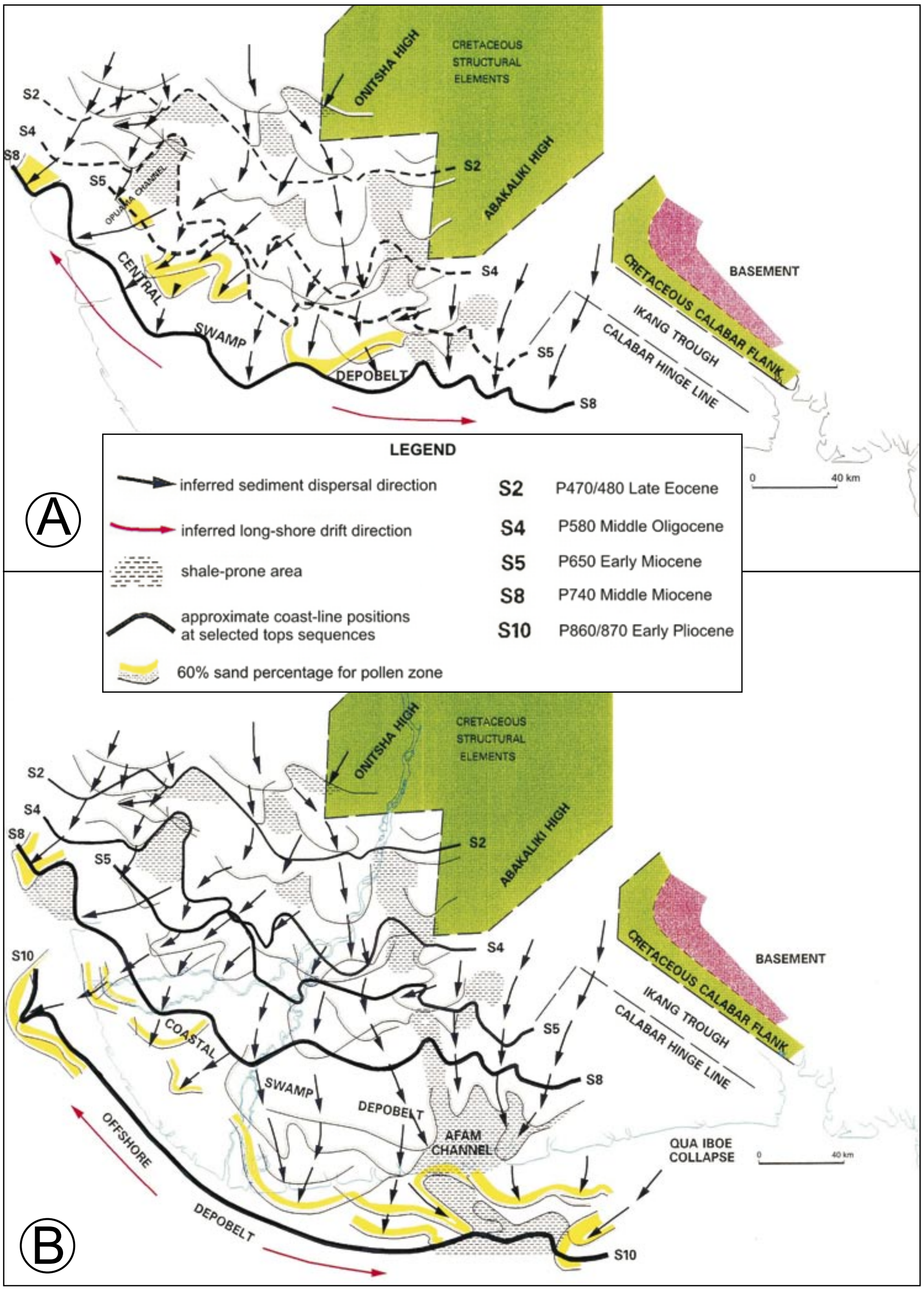

Fig. 4. Palaeo-drainage trend and advancing coastline of the Niger Delta (modified after Edjedawe,1981; Edjedawe et al., 1984). **A** – Position at start of sequence 9 (Dodo-shale transgression); **B** – Position at start of sequence 11 (*Bolivina*–46 shale transgression).

depobelts became active. In the eastern delta, sedimentation was interrupted by cutting-and-filling events (Burke, 1972; Petters, 1984), resulting in the Agbada, Elekelewu, Soku and Afam 'channels' (Figs 2, 4B). During the Pliocene, catastrophic gravity events, possibly related to contemporaneous activity along the Cameroon volcanic line, formed the Qua Iboe Channel in the south-eastern offshore area.

4. The overall delta stratigraphy

The exposed Palaeocene Imo shales north of the Niger Delta (Tm in Fig. 1) are lithostratigraphically continuous with the subsurface diachronous (Eocene-recent) Akata shales. The Eponides-11 mfs (coded FEO020 – Flooding surface Eocene 020 – in Figs 2 and 5) has a downlap surface age (dsa) of 54.6 Ma and is

Table 1. Nature of 3rd-order composite sequences and their parasequence sets in the Niger Delta.

Sequence *MAIN SHALE* (*Secondary shale*)	*(named shales)*	Time span (Ma)	Cycle (Ma)	Cycles (nbr)	Higher order duration (Ma)	Depobelt
Sequence 11 *BOLIVINA*-46 (*6 unnamed*)	*1*	5.00–0.00	5.00 (~)	6	0.83 (–)	Offshore
Sequence 10 *UVIGERINA*-8 (*1 unnamed*) (*Haplophragmoides*-24)	*2*	9.50–5.00	4.50 (~)	3	1.50 (~)	Offshore / Coastal Swamp
Sequence 09 *DODO SHALE* (*Nonion*-4)	*2*	11.50–9.50	2.00 (–)	2	1.00 (–)	Coastal / Central Swamp
Sequence 08 *CASSIDULINA*-7	*1*	12.80–11.50	1.30 (–)	1	1.30 (~)	Central / Coastal Swamp
Sequence 07 *CHILOGEMBELINA*-3 (*Bolivina*-25)	*2*	15.90–12.80	3.10 (–)	2	1.55 (+)	Central / Coastal Swamp
Sequence 06 *OGARA SHALE* (*1 unnamed*)	*1*	19.40–15.90	3.50 (–)	2	1.75 (+)	Central Swamp / Ughelli
Sequence 05 *ALABAMINA*-1 (*2 unnamed*) (*Alabamina*-2) (*Bolivina*-26)	*3*	26.20–19.40	6.80 (+)	5	1.36 (~)	Ughelli
Sequence 04 *UVIGERINELLA*-5 (*Bolivina*-27)	*2*	31.30–26.20	5.10 (~)	2	2.55 (+)	Ughelli / Northern Delta
Sequence 03 *OROGHO* (*Textularia*) (*1 unnamed*)	*2*	35.90–31.30	4.60 (~)	3	1.53 (+)	Northern Delta
Sequence 02 *UVIGERINELLA*-8 (*1 unnamed*)	*1*	38.00–35.90	2.10 (–)	2	1.05 (–)	Northern Delta
Sequence 01 *EPONIDES*-11 (*Umutu*) (*8 unnamed*)	*2*	54.60–38.00	16.60 (+)	11	1.51 (+)	Northern Delta
TOTALS: AVERAGE:	*19 named*		 4.96 (~)		 1.37 (~)	
3rd-order composite sequences or genetic (mega)sequences				3rd-order genetic (para)sequences sets		

(~) within 10% of average total duration
(+) more than average duration
(-) less than average duration

the first delta-wide maximum flooding surface in the Niger Delta; it marks the beginning of the delta fill.

The traditional Benin, Agbada and Akata lithostratigraphic units that compose the delta are currently formations. It is proposed here to elevate them to group level. This facilitates the introduction of several other units at formation level, as proposed below. The present contribution does not go beyond suggestions and proposals for formation 'candidates', as actual implementation is best done

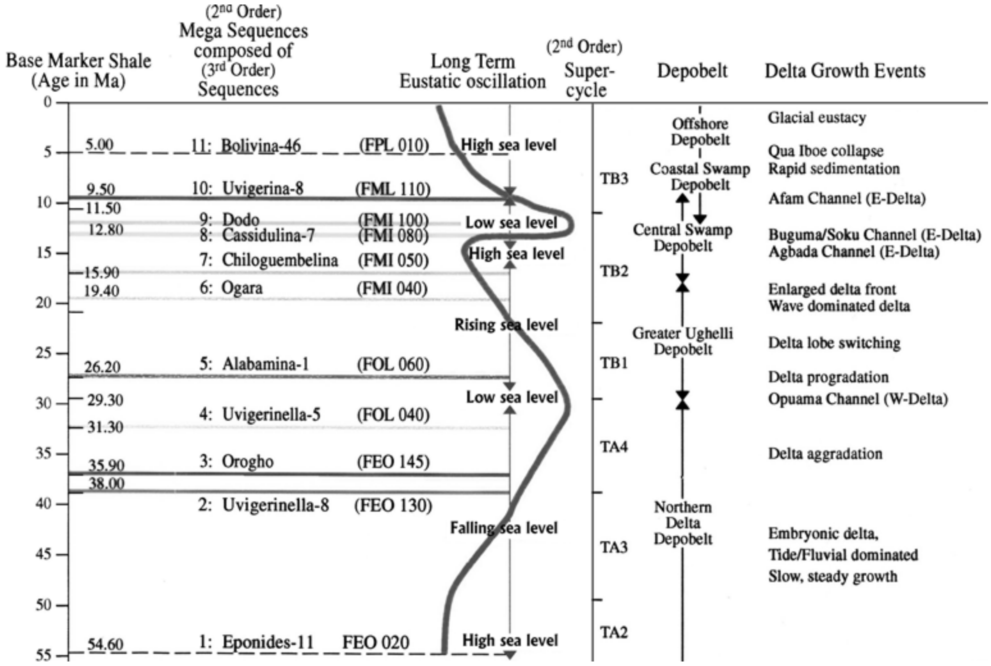

Fig. 5. Phases of delta evolution and some of their characteristics.

by the Niger Delta Stratigraphic Committee, taking into consideration the newest results of the ongoing work. Generally, sediments belonging to the Benin Group represent the subaerially exposed part of the delta (Fig. 6). The main prospective interval, the Agbada Group is a regressive offlap succession that formed under shallow-marine conditions in active depobelts of the delta (Fig. 6) where subsidence rates were 500–1000 m/Ma. Such deposition rates occasionally resulted in gravity-induced mass transport over the overpressured Akata shales and as a result triggered large-scale flows of the overpressured shales that became squeezed out (Fig. 7), such as also reported from the offshore by Owoyemi & Willis (2006) and Magbagbeoloa & Willis (2007). The Agbada Group 'cycles' in the delta have been recognised earlier, but the reports remained unpublished. They are now redefined as chronostratigraphically confined and sedimentologically characterised megacycles. These units form the backbone for the analysis of the cyclicity and the genetic sequences, and thus also form the basis for the lithostratigraphic units proposed here.

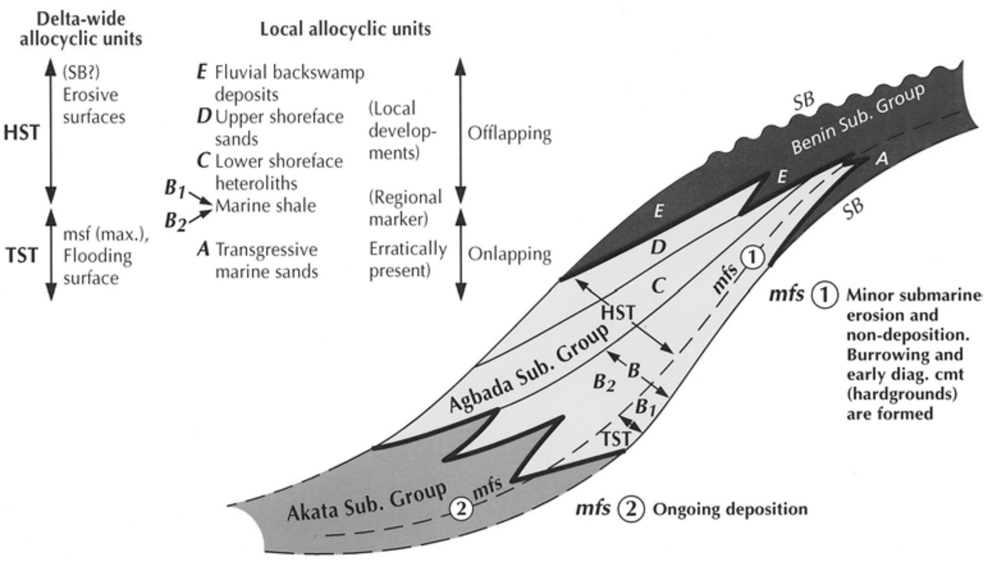

Fig. 6. Standard Vail (1987) sequence with internal allocyclic units in the Niger Delta.

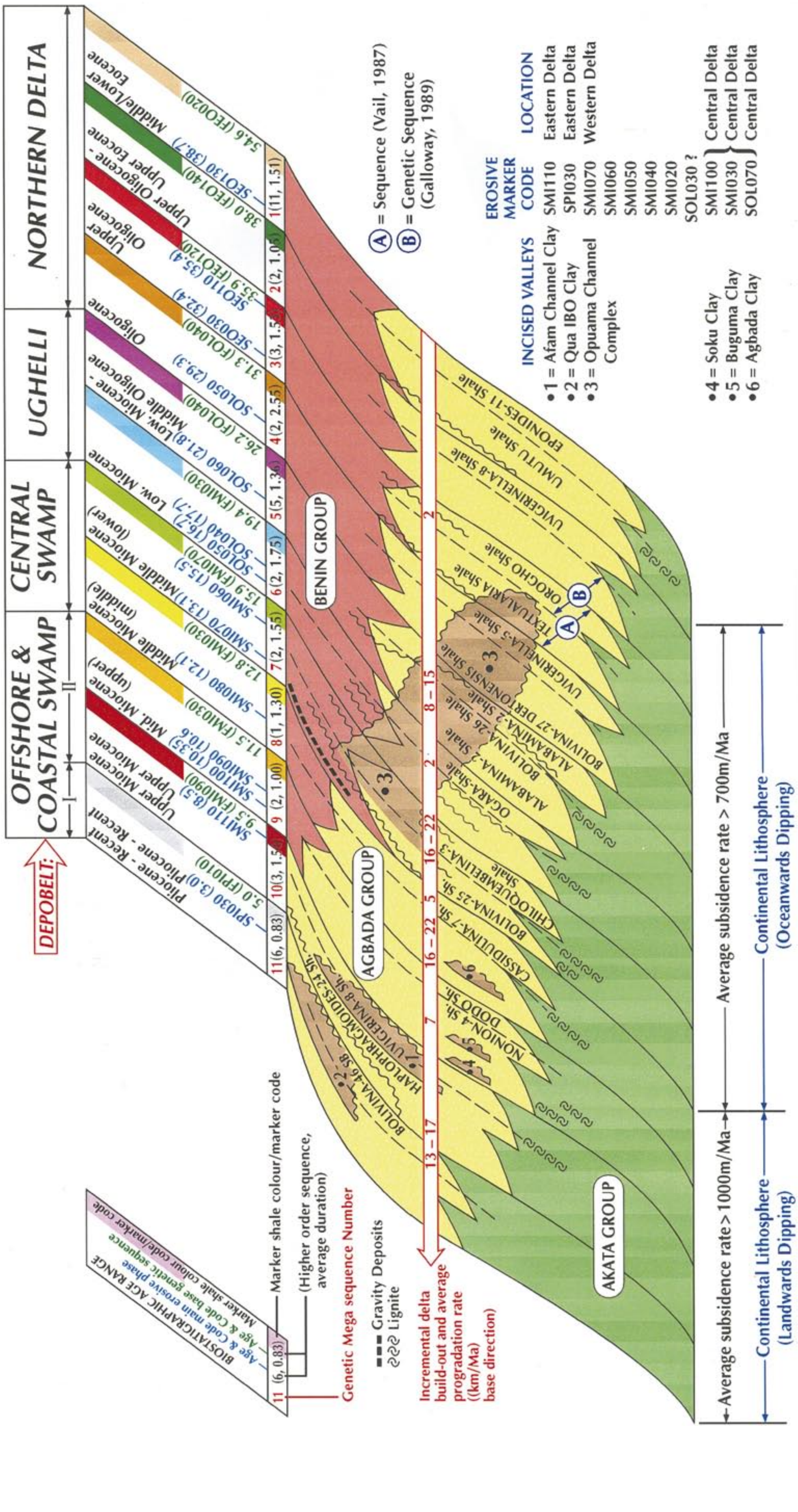

Fig. 7. Diagrammatic representation of the stratigraphic evolution of the Niger Delta.

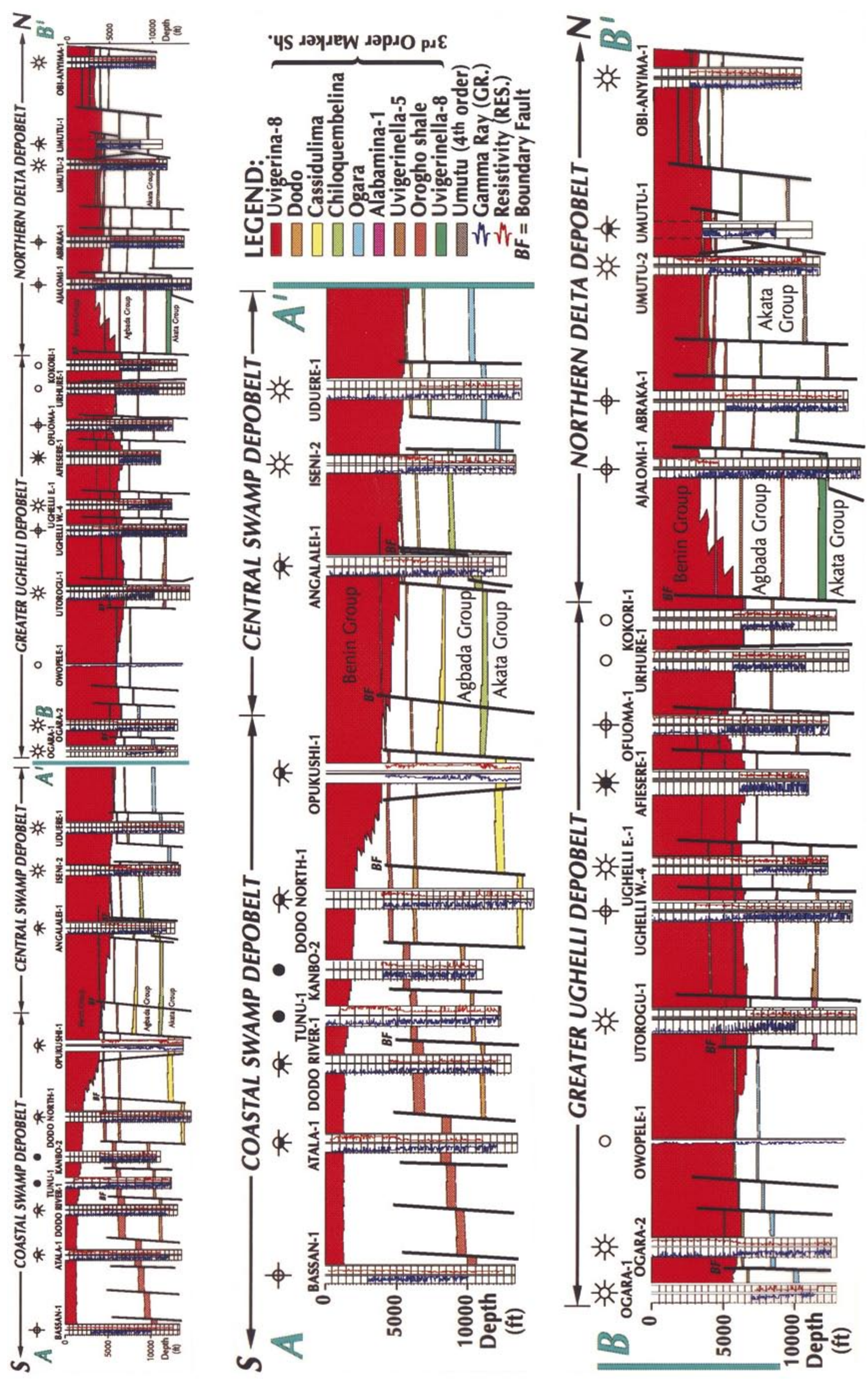

Fig. 8. Regional N-S log correlation (for location see Fig. 8).

4.1. The Middle Eocene (54.6–38.0 Ma) *Eponides*-11 genetic megasequence

4.1.1. Stratigraphy

The *Eponides africana* (*Eponides*-11) marker shale (54.6 Ma) (Figs 2, 3A, 5–7; Table 1) reflects a high eustatic sea-level stand resulting in seismically well correlatable flooding surfaces. It defines the base of the *Eponides*-11 megasequence in the northern delta and the Greater Ughelli depobelts. Comparison with Haq et al.'s (1988) chronostratigraphic scheme shows that the megasequence should contain eleven higher-order sequences (Fig. 2; Table 1). These are, however, poorly represented in the thin sediment packages within the northern delta depobelt.

The *Eponides*-11 megasequence ends with a fossiliferous, glauconitic sand marker (SEO 130 at 38.7Ma) (Figs 2, 7) at Haq et al.'s chronostratigraphic scheme. The higher-order transgressive Umutu shale (41.0 Ma) (Haq et al., 1988) (as 2, 3a, 12) is correlatable in the northern delta depobelt only.

Within the *Eponides*-11 megasequence, three lithostratigraphic units are candidates for formation rank: the basal *Eponides*-11 and the intermediate Umutu transgressive shales, and the glauconitic marker sand.

4.1.2. Sedimentology

An overall progradation of <2 km/Ma and a subsidence rate of <700m/Ma (Knox & Omatsola, 1988) in combination with weak longshore currents influenced delta growth (Fig. 3: coastline S2). The northern delta depobelt was passive during the formation of the upper part of the megasequence. Littoral and lower coastal-plain deposits accumulated. Shoreface sediments formed simultaneously in the active Greater Ughelli depobelt.

Shelf accommodation was reduced during phases of sea-level low-stand, and sediments bypassed the shelf and formed turbidites and gravity deposits as found in wells Aruose-1, Igualaba-1 and Oben-1.

4.2. The Late Eocene (38.0–35.9 Ma) *Uvigerinella*-8 genetic megasequence

4.2.1. Stratigraphy

The Late Eocene *Uvigerinella hourcqi* (*Uvigerinella*-8) isochronous shale of 38.0 Ma (Figs 2, 3A, 5, 7, 8; Table 1) can be traced over some 70 km updip by wireline-log response and on the basis of its seismic characteristics. It defines the base of the Uvigerinella-8 megasequence that extends basinwards into the Greater Ughelli depobelt. Lithostratigraphically the *Uvigerinella*-8 shale is a candidate for formation rank.

4.2.2. Sedimentology

Two higher-order sequences are separated by a yet unnamed local transgressive shale that is a candidate for formation status. Delta subsidence and progradation rates followed those of megasequence 1 (Knox & Omatsola, 1988). In the active Greater Ughelli depobelt, the Late Eocene shoreface deposits grade downdip into pro-delta / open-marine deposits.

4.3. The Early Oligocene (35.9–31.3 Ma) Orogho genetic megasequence

4.3.1. Stratigraphy

The Orogho shale (35.9 Ma) (Figs 2, 3A, 5, 7, 8; Table 1), named after a locality, is particularly rich in dinocyst assemblages which delineate the Eocene/Oligocene boundary at 35.4 Ma. The base of the shale is also the base of the Orogho megasequence. On top of this shale, an areally extensive sand (32.4Ma), a candidate for formation status, occurs.

The locally significant *Textularia*-3 shale marker (34.0 Ma) (Figs 2, 3A, 9) separates the megasequence sands into two units. Locally, the Opuama Formation cuts the megasequence. The Opuama Formation has already been introduced as a stratigraphic unit; the Orogho megasequence and the *Textularia*-3 shales are candidates for a formation rank and the extensive sand perhaps as a member.

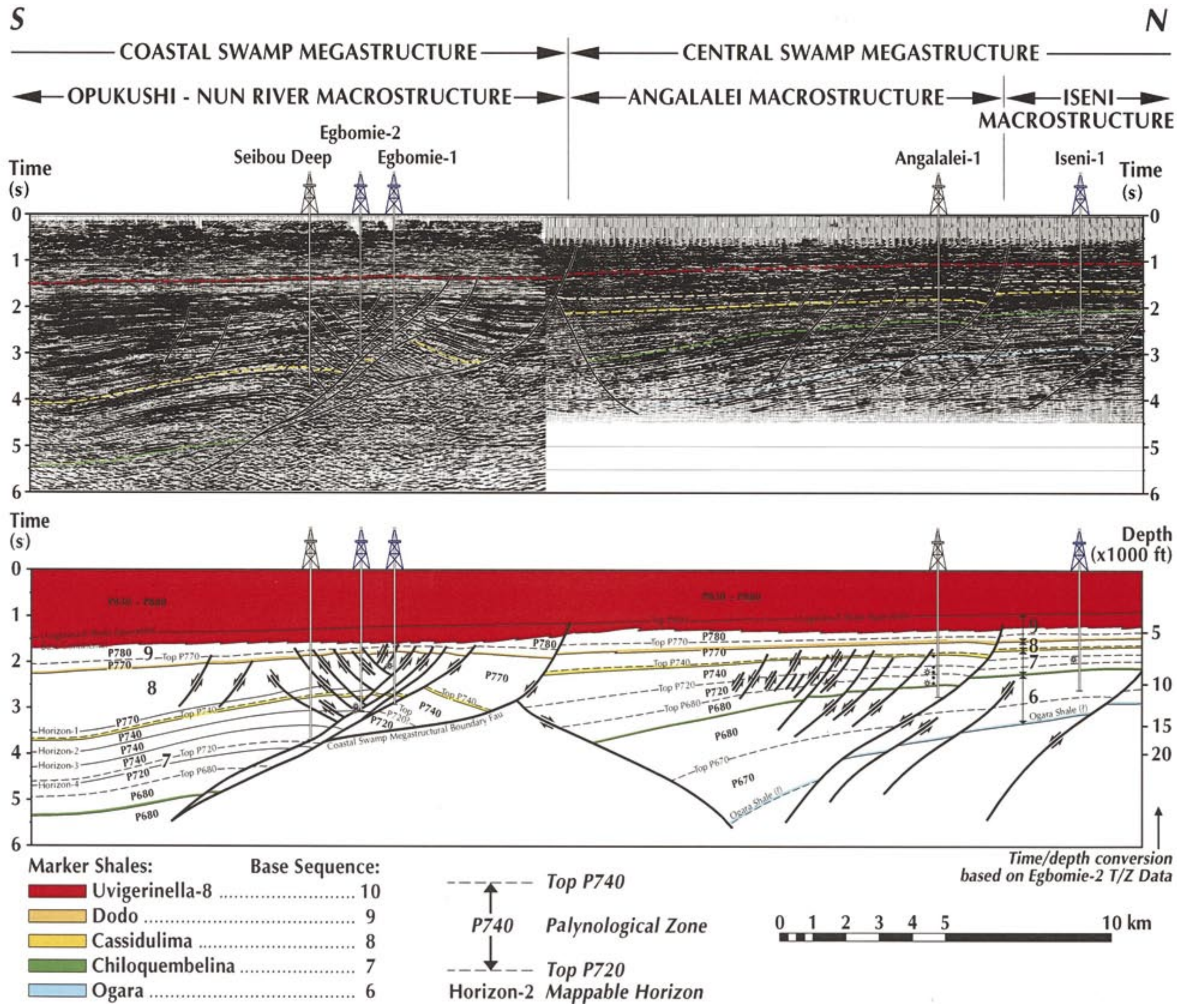

Fig. 9. Seismic section, interpretation and structural cross-section (for location see Fig. 8).

4.3.2. Sedimentology

In the western delta flank, the Opuama Channel cuts into the Orogho megasequence (Figs 3A, 9) (Orife & Avbovbo, 1981; Petters, 1984), thereby locally obscuring the above-mentioned subdivision. Channel formation in the northern section of the active Greater Ughelli depobelt was triggered by a sea level fall at 35.4 Ma (Fig. 7). A sea-level rise as from 29.3 Ma (Fig. 5) destabilised adjacent shore-face sands and triggered slumping and gravity transport, resulting in chaotic sand deposits in the channel. An example is seen in the cored interval of well Egbema-8 (Fig. 10).

4.4. The Middle Oligocene (31.3–26.2 Ma) *Uvigerinella*-5 genetic megasequence

4.4.1. Stratigraphy

The Oligocene *Uvigerinella*-5 shale (31.3 Ma) (Figs 2, 3B, 5, 7, 8, 12; Table 1) can be traced some 90 km updip by wireline-log response and on the basis of its seismic characteristics. It defines the base of the *Uvigerinella*-5 genetic megasequence that is composed of two higher-order genetic sequences. Within the Greater Ughelli depobelt, the *Spiroplectamina biformis* shale (also *Spiroplectamina*-1) (note that the position in Figure 2 and in Table 1 is uncertain)

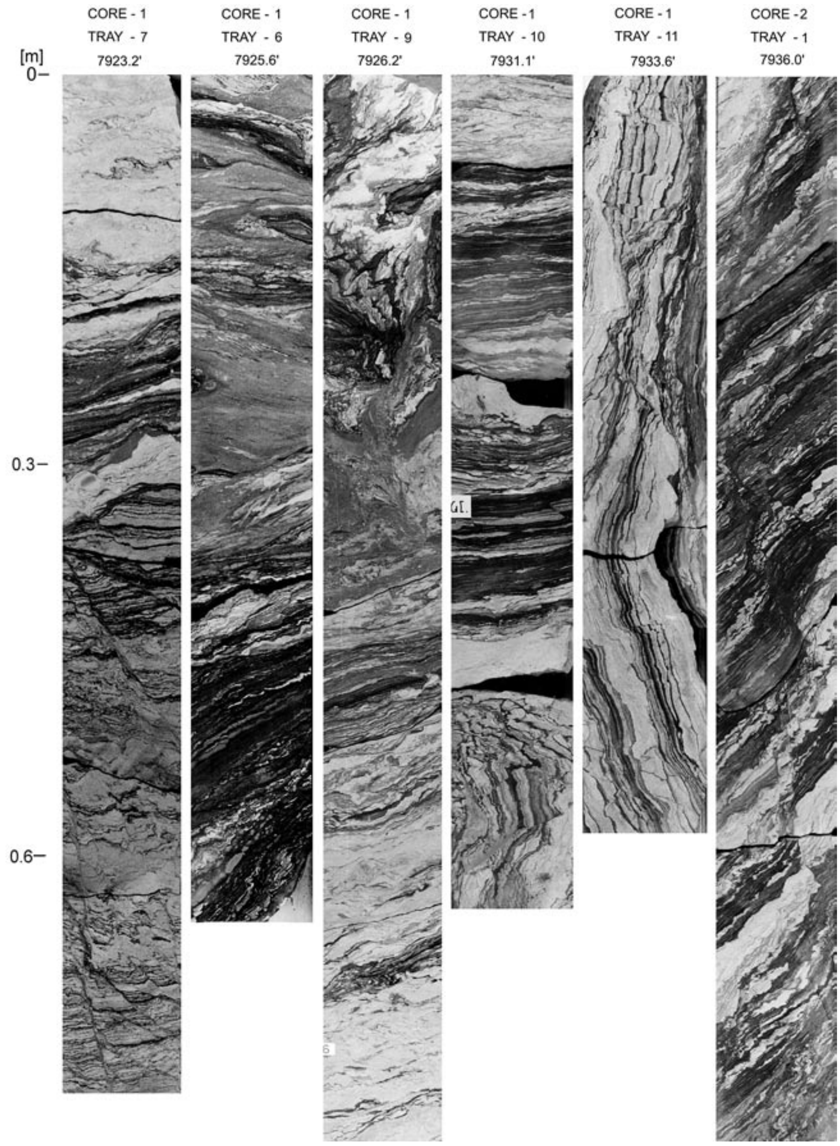

Fig. 10. The *Egbema*-8 core.

and the *Bolivina dertonensis* shale (also *Bolivina*-27) of 28.1 Ma (Figs 2, 3B, 7; Table 1) define the bases of these two local genetic sequences.

Figure 7 shows that the *Uvigerinella*-5 megasequence is locally cut by the Opuama Channel. The *Uvigerinella*-5, *Spiroplectamina*-1 and *Bolivina*-27 shales are candidates for a formation rank.

4.4.2. Sedimentology

The rates of subsidence and of delta progradation remained in line with the values mentioned above. Two higher-order genetic sequences formed around the low-stand inflection marker of the long-term eustatic sea-level curve at 29.3 Ma (Figs 2, 7). The weight of the ensuing sand accumulation triggered growth faulting in the Greater Ughelli depobelt. Cutting and filling of the Opuama Channel may have coincided with local deposition of turbidites on fans developing on slopes and basin floors. Erosional phases during the Early Miocene obscure this, however.

4.5. The Late Oligocene to Early Miocene (26.2–19.4 Ma) *Alabamina*-1 genetic megasequence

4.5.1. Stratigraphy

The Oligocene *Epistominella pontoni* (also *Alabamina*-1) marker shale (26.2 Ma) (Figs 2, 3A, 5, 7, 8; Table 1) can be traced updip over 100 km by wireline-log response and on the basis of its seismic characteristics. It defines the base of the *Alabamina*-1 megasequence. Barrier facies within the Greater Ughelli depobelt are, due to delta-lobe switching, locally punctuated by the *Bolivina beryichi* or *Bolivina*-26 shale (23.2 Ma) (Table 1) and the *Megastomella africana* (*Alabamina*-2) shale (20.7 Ma). The *Alabamina*-1 megasequence is locally cut by the Opuama Channel (Figs 3A, 7).

Various intervals within the Opuama channel fill are candidates for a member rank. The *Alabamina*-1, *Bolivina*-26 and *Alabamina*-2 shales are candidates for a formation rank.

4.5.2. Sedimentology

In the Greater Ughelli depobelt, up to five higher-order sequences reflect phases of prograding barrier complexes. Delta subsidence remained stable, but a sudden Early Miocene sea-level drop was followed by irregular progradational pulses (8–15 km/Ma) (Fig. 3B: S4) coinciding with an increased sediment supply and delta-lobe switching. This may have triggered renewed incision of the Opuama Channel at 21.8 Ma (Knox & Omatsola, 1987) and associated basin-floor sand deposition within the open-marine part of the active Greater Ughelli depobelt. These events alternated with clay infilling of the channels during intermediate and high sea-level stands.

4.6. The Early Miocene (19.4–15.9 Ma) Ogara genetic megasequence

4.6.1. Stratigraphy

The base of the 'Ogara shale' (19.4 Ma) (Figs 2, 3A, 5, 7, 8; Table 1) marks the base of the Ogara megasequence. The shales are defined on palynology only as the base of P670 zone. They are a candidate formation.

4.6.2. Sedimentology

The basal shales are overlain by a prospective heterogeneous sandy unit, mainly composed of barrier facies and channel complexes that are locally punctuated by marine shales ranging in thickness between 500 m (Owopele-1) and 1100 m (Ogara-1) (Fig. 8). Thus the megasequence is broken up into two higher-order genetic sequences.

Overall subsidence rates remained as before but abundant local sediment supply triggered in places pulse-wise progradation of 8–15 km/Ma along an extended delta front. This happened particularly near the SW boundary fault between the active Greater Ughelli and Central Swamp depobelts (Fig. 4A: coastline S5). During formation of the Ogara megasequence, sea-level falls at 17.7 and 16.7 Ma triggered erosion in the Opuama Channel resulting in erosional markers. This may have triggered gravity deposition downdip.

4.7. The early Middle Miocene (15.9–12.8 Ma) *Chiloguembelina* genetic megasequence

4.7.1. Stratigraphy

The *Streptochilus dubeyi* (or *Chiloguembelina*-3) shale (15.9 Ma) (Figs 2, 3A, 5, 7, 9, 12; Table 1) can, based on wireline-log response and its seismic characteristics, be traced 85 km updip. It marks the base of the *Chiloguembelina* megasequence. Higher up, the semi-regional *Bolivina interjuncta* (*Bolivina*-25) marker shale (15.0 Ma) (Figs 2, 3A, 5, 7, 9, 14; Table 1) occurs.

The *Chiloguembelina*-3 and the *Bolivina*-25 shales and a sandy glauconite lag deposit are candidate formations.

4.7.2. Sedimentology

The basal shale of this megasequence reflects a eustatic sea-level rise. A coarse clastic progradational wedge overlying the basal shale is composed of two higher-order genetic sequences. Sea-level low-stands formed erosional intraformational markers in the Opuama Formation at 15.0 Ma and particularly at 13.1 Ma (Petters, 1984). In the Middle Miocene, delta progradation had advanced to the suture between the continental and the oceanic lithosphere (Knox & Omatsola, 1987) and the overall delta subsidence rate increased to >1000 m/Ma, markedly contrasting with earlier rates of subsidence (<700 m/Ma). New accommodation space was thus formed in the active

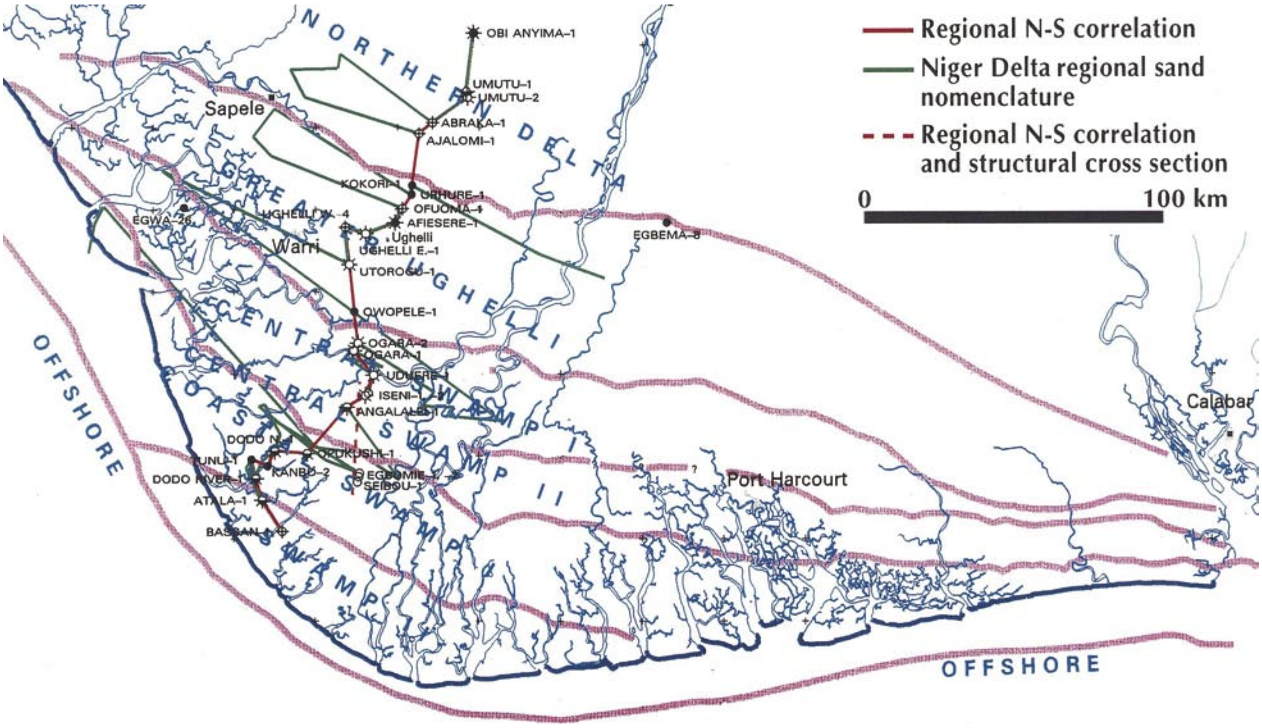

Fig. 11. Location map of depobelts, main regional trajectories and wells.

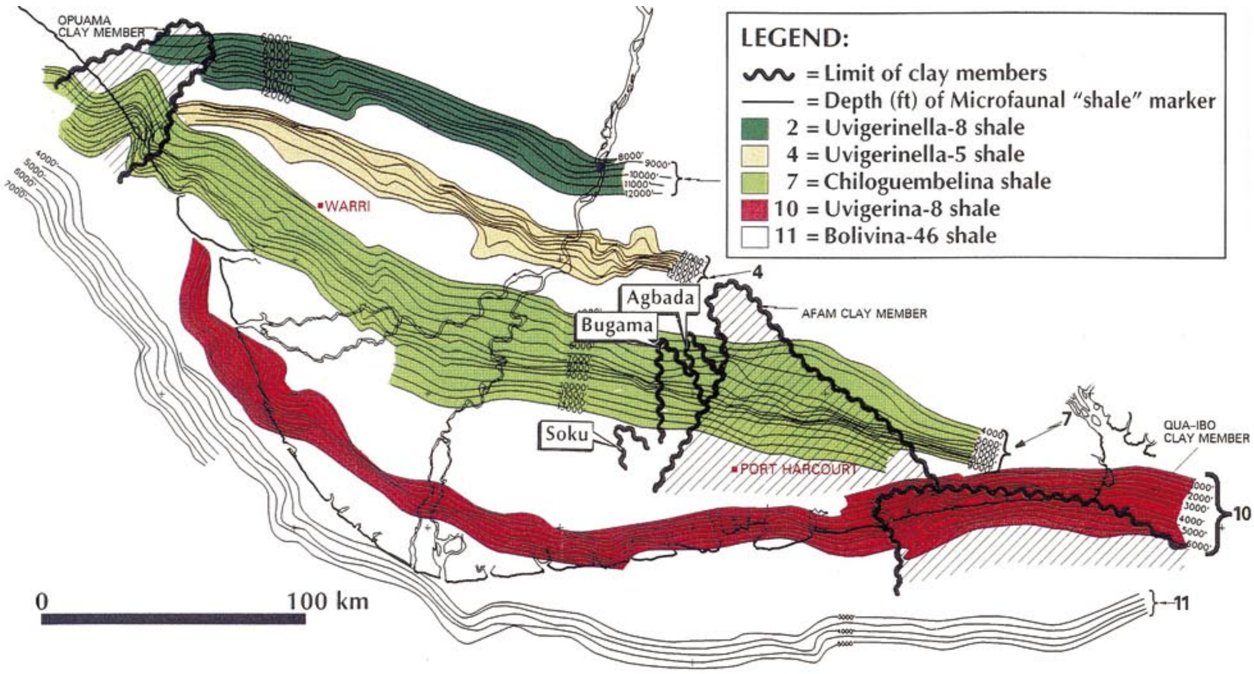

Fig. 12. Regional 3rd-order shale markers. The 'bands' shown are contours of subcropping marine shales within specific depobelts (see also Fig. 8).

Central Swamp depobelt, which triggered increased sedimentation. Both counter-regional and down-to-basin faulting slowed down.

Along an enlarged delta front, sediment progradation proceeded on average some 2 km/Ma, but this sharply increased to 16–22 km/Ma between 14.4–14.0 Ma. Thereafter it sharply decreased to some 5 km/Ma.

The megasequence is topped by a regional glauconitic lag deposit (13.1 Ma), recognised in well cuttings and cores. It grades updip into lignites which seismically form a continuous high-amplitude reflection surface.

4.8. The Middle Miocene (12.8–11.5 Ma) *Cassidulina*-7 genetic megasequence

4.8.1. Stratigraphy

The *Cassidulina neocarinata* (*Cassidulina*-7) marker shale (12.8 Ma) (Figs 2, 7, 9, 11, 12, 13A,

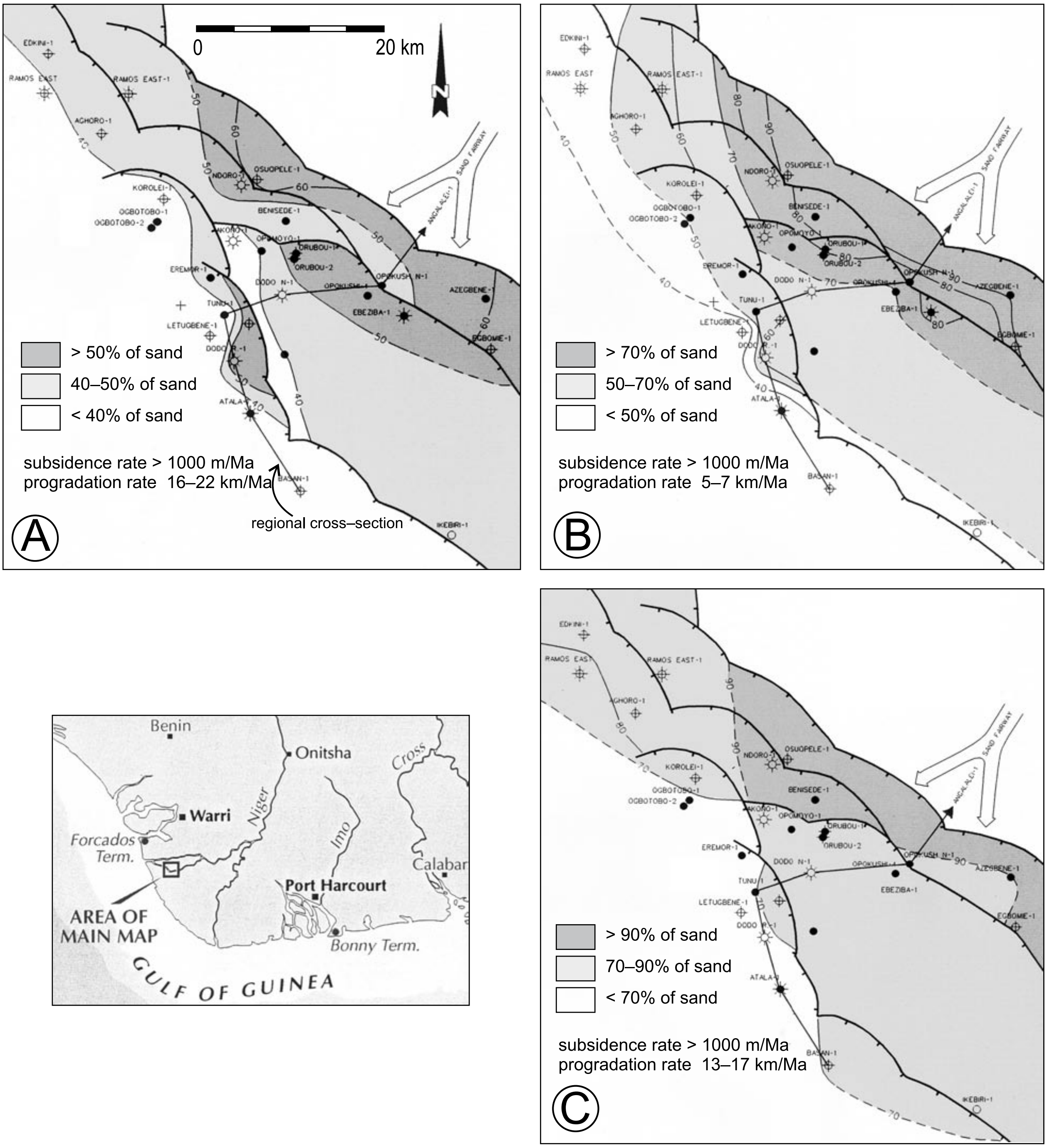

Fig. 13. Approximate sand-percentage maps in OML 35/46 (based on and modified from Edjedawe,1981; Knox & Omatsola, 1988).
A – in sequence 8 (*Cassidulina*–7); **B –** in sequence 9 2 (Dodo shale); **C –** in sequences 10/11 (*Uvigerina*–8 / *Bolivina*–8). For the segment of regional trajectory see Figure 9.

14; Table 1) within the P740 zone (the P750 subzone; Fig. 9) coincides with the extinction of the planktonic foraminifer *Globigerinoides subquadrofar*. It straddles the boundaries between the Coastal Swamp, Central Swamp and Greater Ughelli depobelts (Figs 9, 13). With its 1.3 Ma, this unit has the shortest duration of all the delta megasequences. Not being subdivided, it actually is a third-order genetic sequence. It contains the *Cassidulina*-3 candidate shale formation. The Agbada Channel clay is a candidate formation.

4.8.2. Sedimentology

Within the Coastal Swamp, a prolific barrier complex prograded obliquely with respect to the current coastline (Fig. 13A–C) with a rate of some 16–22 km/Ma. The high rate of sediment supply needed to maintain this progradation, reflects increased uplift of the hinterland (Cahen et al., 1984). Subsidence rates remained >1000 m/Ma. A sea-level fall caused the Agbada Channel to form in the eastern delta at 12.1 Ma (Figs 2, 7).

4.9. The late Middle Miocene (11.5–9.5 Ma) Dodo shale genetic megasequence

4.9.1. Stratigraphy

The 'Dodo Shale' (11.5 Ma) (Figs 2, 4A, 5, 7–9, 13; Table 1) close to the top of zone P770 (Figs 2, 9, 13), is not characterised by a specific foraminiferal assemblage. It reflects the eustatic sea-level rise that is marked by the extinction of the planktonic foraminifer *Globorotalia menardi*. Its base defines the base of the genetic Dodo shale megasequence. In the East, the *Nonion costiferum* (*Nonion*-4) shale at 10.4 Ma (Figs 2, 5, 7; Table 1) punctuates shorefaces. The Dodo shale megasequence (named after a well location) contains the Dodo, Nonion and Soku/Ekulama shales that are candidate formations.

4.9.2. Sedimentology

The basal Dodo Shale is part of the lower of two higher-order genetic sequences which reflect ongoing subsidence rates of >1000 m/Ma. Within the active Coastal Swamp depobelt, the lowermost sequence is a progradational barrier complex and a prolific hydrocarbon zone (Fig. 13B). In the proximal part of the Coastal Swamp depobelt, subparallel to the Ogbotobo-Tunu growth fault, synsedimentary fault activity controlled the main axis of sand deposition (Figs 11, 13B). The overall progradation was some 5 km/Ma.

The upper and lower sequences are separated by a significant sea-level fall during which, in the East, the Buguma Channel formed at 10.6 Ma (Figs 2, 7, 14). During another sea-level fall, the Soku/Ekelewu Channels formed at 10.35 Ma (Figs 2, 7, 14). The latter sea-level fall coincides with the lowest inflection point of the long-term eustatic sea-level fluctuation (Figs 2, 5). Basin-floor fan deposits are believed to be associated with these two low-stands that succeed each other close in time.

4.10. The Late Miocene (9.5–5.0 Ma) *Uvigerina*-8 genetic megasequence

4.10.1. Stratigraphy

The *Uvigerina peregrina* (*Uvigerina*-8) at 9.5 Ma (Figs 2, 5, 7, 8, 12, 13; Table 1) marker shale defines the base of the *Uvigerina*-8 megasequence. It straddles the inactive Central Swamp and the active Coastal Swamp and Offshore depobelts. In the Offshore depobelt, the base of the highest of the three lower-order genetic sequences is characterised by the local *Haplophragmoides bradyi* (*Haplophragmoides*-24) marker shale of 6.0 Ma (Figs 2, 14; Table 1). Each lower-order genetic sequence is followed by a significant sea-level fall.

The *Uvigerina*-8, *Haplophragmoides*-24 and the Afam Shale as well as the *Amphistegina gibbsa* sands within the *Uvigerina* megasequence are candidates for a formation rank.

4.10.2. Sedimentology

Thick fluvially influenced deltaic sands overlie the basal marker shale in the distal part of the active Coastal Swamp and Offshore depobelts (Fig. 13C). They formed in response to subsidence rates of >1000 m/Ma while the overall progradation rate was 13–17 km/Ma. Three higher-order genetic sequences are sepa-

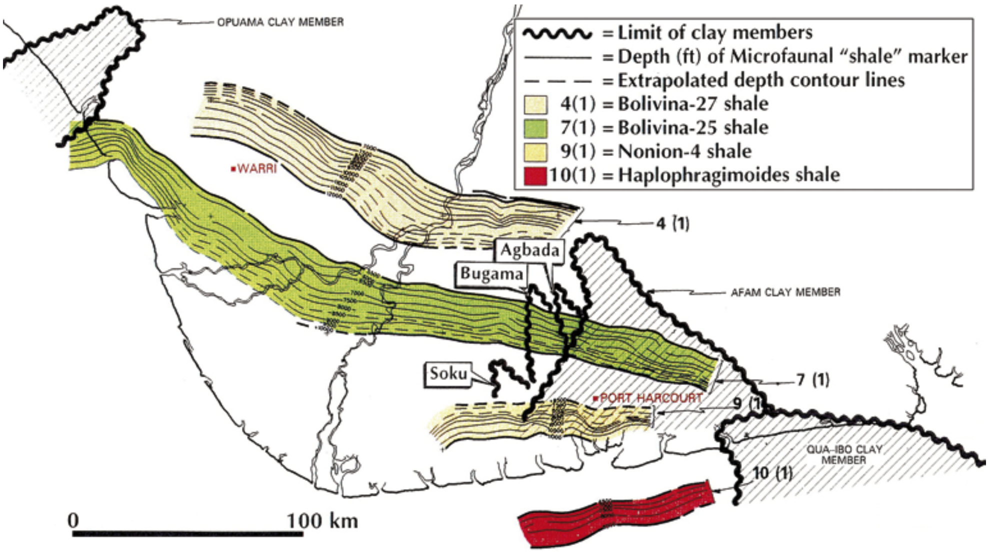

Fig. 14. Local 4th-order shale markers. The 'bands' shown are contours of subcropping marine shales within specific depobelts (see also Fig. 8).

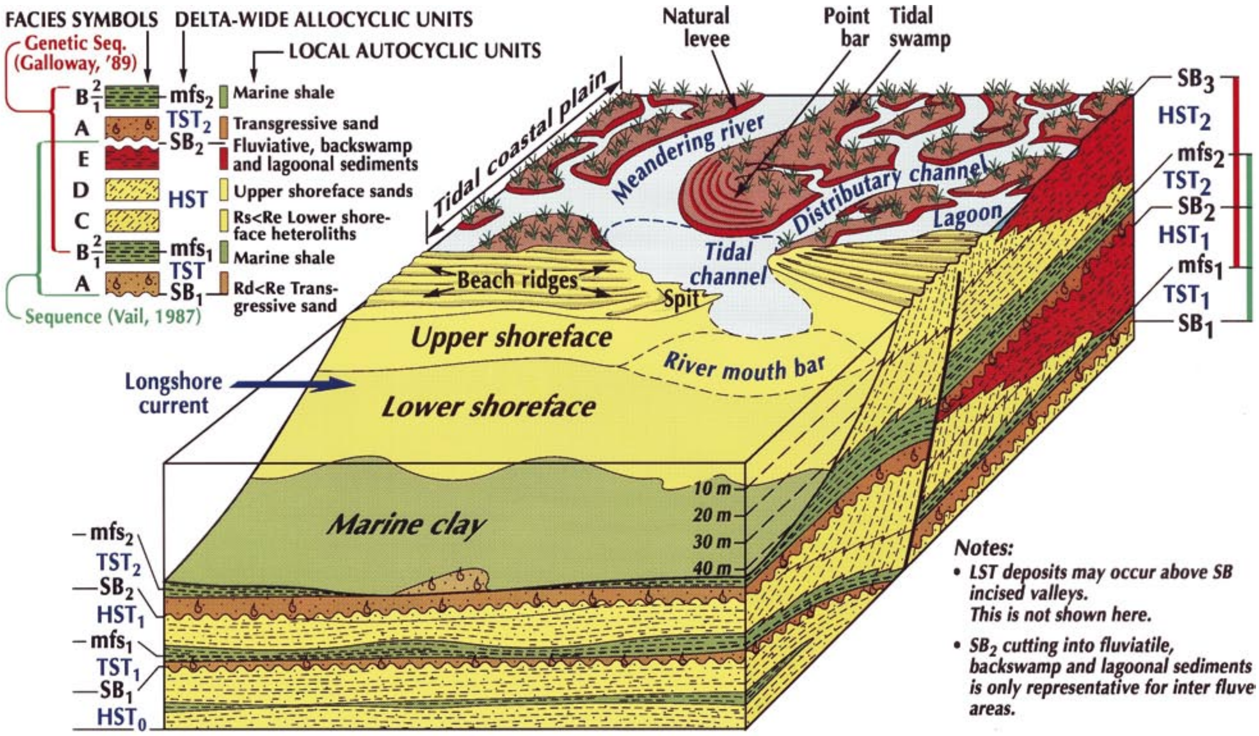

Fig. 15. Geomorphology, cyclic sedimentation and an active fault in the Tertiary Niger Delta coastal zone (modified after Weber, 1971).

rated from each other by significant sea-level drops. In the eastern delta, erosive events at 8.5 Ma (Fig. 2) formed the salt-water embayment, the Afam Channel (Figs 4B, 7). It grades basinwards into a submarine canyon that incised sands that thus became part of a deep-water setting (Knox & Omatsola, 1987; Jubril & Amajor, 1991).

The sequence is topped by a highly fossiliferous (*Amphistegina gibbosa*) transgressive marker sand of 5.6 Ma (Fig. 2) that becomes disconformable landwards.

4.11. The Pliocene-Holocene (5.0-0.0 Ma) *Bolivina*-46 genetic megasequence

4.11.1. Stratigraphy

The base of the *Bolivina aenariensis* (*Bolivina*-46) shale defines the base of the *Bolivina*-46 megasequence (5.0 Ma) (Figs 2, 5, 7, 8, 12, 13C; Table 1). Locally unnamed higher-order transgressive claystone beds occur.

The *Bolivina*-46 megasequence contains the candidate Qua Iboe Formation, that has been subdivided by Mobil into the Biafra Sand, the Rubble Bed and the Qua Iboe Clay Members.

4.11.2. Sedimentology

Seismically the basal shale is a high-amplitude event within a low-frequency transparent seismic facies (Fig. 9). Repeated severe sea-level fluctuations gave rise to six higher-order genetic sequences that formed while subsidence rates were >1000 m/Ma. In the active offshore depobelt, 350–2,500 m thick wedge-shaped sedimentary units reflect progradation of barrier complexes as fast as 14–17 km/Ma. Downdip, towards the offshore depobelt, these sediments grade into open–marine facies, and updip into fluviomarine and terrestrial facies (Fig. 13C). In the offshore depobelt, thicknesses of >3,500 m are common. The barrier complexes are locally punctuated by unnamed transgressive claystone beds. Hydrocarbons are mainly confined to delta-front sediments, but are also known from prodelta sands. In the easternmost delta, the Qua Iboe collapse – a result of volcanic activity in the Cameroon hinterland – took place at 3.0 Ma and the channel thus formed was filled by products of mass-transport processes, leaving a complex succession of lithological units.

5. Biostratigraphical framework

The stratigraphy of Niger Delta sections has traditionally been based on biochronological interpretations of fossil spores and foraminifers (Fig. 2). Palynological and foraminiferal biozones have proved to be reliable tools for large-scale correlations between wells. The delta-wide biostratigraphic framework and alphanumeric codes used in the present contribution is based on biostratigraphic zonations established by the Shell Petroleum Development Company of Nigeria (SPDC) and calibrated with data from Elf (Durant, 1995 and pers. comm.). The Shell zonation was published by Evamy et al. (1978) and is used in Figures 3 and 4. This zonation allows correlation across all facies types from continental to marine. Currently, the Shell zonation contains 18 foraminiferal biozones and 7 sub-zones. Hierarchically, 9 partial range zones, 6 taxon zones, 2 assemblage zones and 1 concurrent range zone are included. Fifteen of these zones are based on index planktonic foraminifers recognised from transgressive marine shales (Petters, 1983), while eight zones, previously unpublished, are based on benthonic foraminifers. The regionally persistent marine marker shales, as well as some of the more local shales (Fig. 5), have usually been named after one of the marker species and are coded systematically (Figs 2–4; Table 1).

Due to the world-wide distribution of the index planktonic zones, and because the first and last appearance data of these taxa have been calibrated in millions of years (Ma), the Niger Delta foraminiferal zones have been correlated and integrated into the global geochronological and chronostratigraphical scheme of Harland et al. (1990) (Fig. 2). This integration has made it easier to apply sequence stratigraphy to the Niger Delta succession with the help of the eustatic curves of Haq et al. (1988) (Fig. 2).

Attempts to mutually validate and integrate the SPDC framework of Evamy et al. (1978) with published and unpublished work of other industry groups is hampered by the use of different numerical coding systems for the foraminiferal systematics (Fig. 2). Petters (1982), however, presented a comprehensive atlas of taxonomic identifications of Niger-Delta foraminifers and their age and palaeoenvironmental interpretations. Between 1995 and 1999, a Stratigraphic Committee of the Niger Delta aimed at mutually validating and integrating the various biostratigraphic schemes. Some results are shown in Figure 2. As the ongoing work of the Stratigraphic Committee is not yet completed, the present contribution still refers to Evamy et al.'s (1978) alphanumeric coding system.

6. Genetic megasequences

Depositional sequences bounded above and below by unconformities of regional or local extent or their correlative conformities (Vail, 1987) are interpreted to represent the stratigraphic record of relative sea level changes resulting from significant changes of tectonic or eustatic regime while the delta grew. Internally such sequences are composed of allocyclic units including a maximum flooding surface (Fig. 6). Daily practice in the Niger Delta shows that erosion features on seismics and in well logs and cores cannot be traced delta-wide. They are usually confined to incised valleys or 'channels' at the flanks of the delta (examples are given by Orife & Avbovbo, 1981;Petters, 1984; Knox & Omatsola, 1987; see also Figs 2, 12, 14). Galloway's (1989) genetic units between mfs's, however, are extensively recognised in the Niger Delta. The bounding shales of such units are therefore preferred for delta-wide correlation (Figs 12, 14).

From the Eocene onwards, the long-term eustatic sea-level curve (Fig. 5) shows a global sea-level drop. Together with the large sediment supply from the hinterland, this caused delta progradation (Figs 3, 4). On the Haq et al. (1988) time scale (Table 1; Fig. 2), however, thirty-nine 3rd-order eustatic sea-level rises with associated maximum flooding surfaces (mfs) have been recognised worldwide, overprinting the lower-order overall sea-level drop.

The earliest Niger Delta sediments date from 54.6 Ma, and only nineteen significant mfs shale units have been recognised and dated in the Niger-Delta succession. They are labelled 'Base Marker Shales' (BMS) in Figure 5 and they define 2nd-order megasequences. Most shales and overlying megasequences are named after a prominent faunal element. Eight shales are locally present, four of which are shown in Figure 14. Eleven occur delta-wide and are traceable across depobelt boundary faults, merging updip with continental deposits; five of them are shown in Figure 12. The bounding shales of the genetic megasequences are distinct seismic markers that facilitate mapping (Figs 12, 14) and regional correlation (Figs 8, 9). Such genetic units straddle Vail sequences (Figs 6, 7). Such genetic units or megasequences are diagrammatically shown in space in Figures 9 and 10, and in time in Figures 2 and 7. They will be discussed successively underneath.

7. Discussion of the cycles, sequences and depobelts

7.1. Cyclicity

The Niger Delta fill (Fig. 5) formed during 54.6 Ma, entirely within the Cenozoic Tejas megacycle 'T' (66.8 Ma-recent) originally defined by Sloss et al. (1949) and Sloss (1963). Subsequent work by the Exxon group and others broke up this megacycle into seven worldwide second-order supercycles (TA1, TA2, TA3, TA4 between 66.8 and 29.3 Ma, and TB1, TB2, TB3 between 29.3 Ma and today). These supercycles are shown in Figure 2 together with the eleven Niger Delta megasequences (Figs 5, 7) defined above. These eleven megasequences straddle supercycles TA2 and TB3. As stated in the 'Methods' section, the present contribution differentiates between cycles (i. e. sea-level movements) and the way they are reflected in sequences (i.e. sediment packages).

Figure 2 shows the eleven Niger Delta megasequences that are the result from local allocyclic 'drivers' and global autocyclic processes that 'drive' the five-and-a-half global supercycles. The Niger Delta genetic megasequences (Figs 6, 7) thus are hybrid: they simultaneously reflect global eustatic movements, local delta tectonics and allocyclic and autocyclic sedimentation processes.

The Haq et al. (1988) eustatic curve in Figures 2 and 5 show two long-term cyclic oscillations with durations of 41.8 Ma and 12.80 Ma, respectively. The first oscillation started with a maximum sea level at 54.6 Ma that is reflected in the Niger Delta in the basal shale of megasequence 1. It continues in a shallowing mode until a major (but not a maximum) deepening event took place, reflected in megasequence 4 at 29.3 Ma. It then deepened again and the next maximum sea level is reflected in the basal shale of megasequence 7 at 12.8 Ma. The falling limb of this oscillation spans part of supercycle TA2 and the whole of supercycles TA3 and TA4, while the rising limb includes TB1 and part of TB2. The second long-term eustatic oscillation is reflected by the remainder of TB2 (partial) on the falling limb until the low-stand at 10.35 Ma; TB3 reflects the glacially influenced rising limb until the present (Fig. 5).

These long-term eustatic cycles affected the coastline at several stages of the evolution of the Niger Delta (Figs 3, 4). High-stands from long-term cycles coinciding with those from short-term cycles reinforced each other and triggered significant delta-wide floodings, whereas low-stands from long-term cycles, reinforced by those from short-term cycles, gave rise to erosive events. In addition, the coastline initially advanced slowly over a relatively short and straight front and an oceanward dipping basement, but from ~14 Ma ago progradation speeded up and took place in pulses over a longer, lobate delta front and a landward dipping basement. Increased sediment supply from the rising Cameroon mountain range accelerated the progradation.

7.2. Sequences

Figure 2 shows how the Niger Delta megasequences formed over 2–7 Ma, averaging 4.96 Ma (Table 1). This markedly contrasts with the average of 10 Ma for the duration of a 2nd-order and of 1–3 Ma for a 3rd-order marine cycle as cited in literature (Miall, 1997). Therefore it is thought that the Niger Delta megasequences are composed of third- and possibly higher-order genetic sequences superimposed on each other while forming depobelts as follows (see also Figs 3, 4, 5, 7–10, 13; Table 1):

(1) Northern depobelt: 4 megasequences with 18 3rd-order sequences formed over 28.4 Ma;
(2) Ughelli depobelt: 2 megasequences with 7 3rd-order sequences formed over 10.3 Ma;
(3) Central Swamp: 2 megasequences with 3 3rd-order sequences formed over 4.4 Ma;
(4) Coastal Swamp: 2 megasequences with 5 3rd-order sequences formed over 6.5 Ma;
(5) Offshore depobelt: 1 megasequence with 6 3rd-order sequences formed over 5.0 Ma.

This shows that (mega)sequences in the young delta formed depobelts with a higher resolution and progradation rate in less time than in the old delta. This results from the effects of high-order eustatic cyclicity and of delta tectonics with various periodicities, combined with the effects of the rising and falling limbs and of the inflection points of 2nd-order supercycles. Thus eleven Niger Delta megasequences originated that took, on average, 4.96 Ma to form and that are composed of 3rd-order sequences that formed, on average, over periods of 1.37 Ma (Figs 5, 7–9; Table 1).

Mitchum & Van Wagoner (1990, 1991) addressed the role of sediment-supply rates and accommodation space that led to the formation of 4th-order sequences, or "sequence-sets that represent the systems tracts of 3rd-order composite sequences" in the Eocene Gulf of Mexico. Brink et al. (1993) carried out a similar study for the Cretaceous Pletmos Basin in South Africa. Results of these studies can be used to explain the internal architecture of megasequences in the Niger Delta (Fig. 6) that reflect 3rd-order eustatic cycles superimposed on the rising and falling limbs of 2nd-order supercycles.

The effects of either sea-level falls of 3rd-order eustatic cycles or of short-lived uplifts (relative sea-level falls) due to delta tectonics, or of both, are reinforced if in phase with the falling limb of 2nd-order eustatic supercycles and may result in erosional features or unconformities. Typically, such unconformities are confined to the flanks of the delta. This is illustrated by the distribution of 'channels' (Figs 7, 12, 14) of which the origin can be linked with compressive intraplate stresses during the growth of the delta that produce short-lived uplift (relative sea-level fall) and with associated localised unconformities in the flanks of the basin (Cloeting et al., 1985). Downdip channel fills are commonly associated with time-equivalent gravity deposits.

Likewise, sea-level rises of 3rd-order eustatic cycles are reinforced if in phase with the rising limb of a 2nd-order eustatic supercycle and additional accommodation space is created. During flooding, transgressive shales and lag deposits formed (Figs 8, 9, 14) and earlier erosional features became filled with clays, sands and heteroliths (Fig. 11).

High-periodicity sea-level movements that are out of phase with long-period cyclicity subdued the erosional or the flooding features. The Opuama Channel in the western Niger Delta shows ample evidence of this feature as it underwent several phases of incision and filling, resulting in a set of nested channels that reflect high- and low-periodicity cycles that interfered with each other (Knox & Omatsola, 1989).

During the 2nd-order long-term fall of the eustatic curve, megasequences 1–4 (Fig. 2) formed in the active but embryonic and fluvially dominated northern delta. The coastline remained more or less stationary. At the junction between supercycles TA4 and TB1, around the long-term eustatic low-inflection point (at 29.3 Ma), cutting and filling of the Opuama Channel started in the western delta. Subsequent high-period sea-level fluctuations on the rising limb of the curve triggered the formation of megasequences 4 (partially) through 7, with alternating erosion and fill of the Opuama Channel. In megasequence 5, delta-lobe switching in the Greater Ughelli and the Central Swamp depobelts triggered pulses of delta progradation (<8–15 km/Ma) but during formation of megasequence 6 in the southern Ughelli and the northern Central Swamp depobelts, progradation rates fell off to some 2 km/Ma.

7.3. Depobelts

The long-term eustatic sea-level high-stand inflexion point at 13.1 Ma marks cycle TB2.4 and coincides with active deposition in the Central Swamp depobelt. Delta progradation speeded up to 16–22 km/Ma and the delta front enlarged. Simultaneously, movements along growth faults increased (Fig. 13). Cycles TB2.5–6 on the falling limb of the curve triggered the formation of megasequences 7–9 (Fig. 2). Deposition shifted to the Coastal Swamp depobelt. The high-stand inflection point at 13.1 Ma marks a switch from delta aggradation to progradation over oceanic basement (Fig. 9) on the falling limb of the curve. This limb coincides with a sea-level low-stand at 12.1 Ma when, in the eastern delta, the Agbada Channel was incised in the Coastal Swamp depobelt. During formation of megasequence 9, delta progradation alternated between a rapid rate of 16–22 km/Ma and a more steady rate of 5 km/Ma. The Coastal Swamp was marked by erosion through two successive major sea-level falls at 10.6 and 10.35 Ma, resulting in the formation of the Buguma and the Soku/Ekelewu Channels. A period of increased delta subsidence (>1000 m/Ma) and progradation (13–17 km/Ma) stopped the formation of megasequence 9. In megasequence 10, in the Coastal Swamp and Offshore depobelts, a high-period sea-level fall, superimposed on the rising limb of the long-term eustatic curve, triggered erosion of the Afam Channel (8.5 Ma).Thereafter, the hinterland shredded extensive amounts of clastic sediment, triggering pulses of delta progradation of 14–17 km/Ma (Fig. 13). On the rising eustatic curve, a transgressive clay marks the base of megasequence 11 at 5.0 Ma (Figs 2, 5, 7, 9). The Offshore depobelt formed and the Qua Iboe collapse took place at 3.0 Ma. The upper part of genetic megasequence 11, including the present-day delta surface, was strongly influenced by glacially induced eustacy.

8. Lithostratigraphy

In a cartoon-like cross-section, approximately NE-SW and parallel to the regional N-S correlation line shown in Figures 9 and 11, the eleven genetic megasequences have roughly a sinusoidal shape, broadly reflecting the profile of the delta (Figs 6–7) that incrementally built out through time (Fig. 2). Each megasequence is internally organised similarly, as pictured in the sedimentation model of Figures 6 and 15. Within each of the units, the sandiest developments are growth-fault-controlled Agbada lithofacies (Figs 13, 15) while basinwards thin synchronous toe-set deposits grade into the Akata sediments. Landwards, top-set deposits grade into the Benin sediments. As the eleven megasequences get younger, the Benin, Agbada and Akata lithofacies cross time lines (Fig. 9). Lateral linkage of these lithofacies turns them into the diachronous Benin, Agbada and Akata units, traditionally at formation level. A different lithostratigraphic approach is suggested in the present contribution, for which it is proposed that these three lithological units are elevated to group level.

The sigmoidal composite lithological units or megasequences (Fig. 7) are the primary subdivisions of the sedimentary record on a time base. Each megasequence includes a 'segment' of the Benin, the Agbada and the Akata Formations and these 'segments', joined across the megasequence boundaries, should become the Benin, Agbada and Akata Groups. Thus, the Akata Group is composed of eleven 'Akata segments'; each one reflecting one of the megasequences. The autocyclic growth phases within the various Agbada segments result in various lithologies that can be further subdivided, fully in accordance with the rules of the North American Stratigraphic Code (1983), into formations and members if and when needed. In the preceding text several suggestions have been made for new lithostratigraphic units.

Obvious candidates, up till now mainly shales, have been referred to in the preceding discussion. More candidates, particularly sands, will have to be defined in the future as a result of ongoing work, and the Niger Delta Stratigraphic Committee is the first body that comes to mind to implement such a lithostratigraphy. Thus a gradual replacement can take place by formal lithostratigraphic units of the hydrocarbons-containing reservoir intervals that have traditionally been labelled informally with alphanumeric 'sand' codes (Fig. 16).

Sorting out irregularities and discrepancies is the work of the Stratigraphic Committee of the Niger Delta. After completion, a comprehensive and practical lithostratigraphy can be introduced for the entire delta that is both time-constrained and genetically meaningful.

9. Integrated facies model

Evamy et al. (1978) suggested that delta sedimentation styles depend on relative rates of deposition (Rd) and of subsidence (Rs). This hypothesis was built upon an earlier Niger Delta facies model proposed by Weber (1971) and Weber & Daukoru (1976), and was also guided by the model of delta development of Curtis (1970) for the Gulf Coast. It reflects sedimentological thinking before eustacy was systematically taken into account. It can be sum-

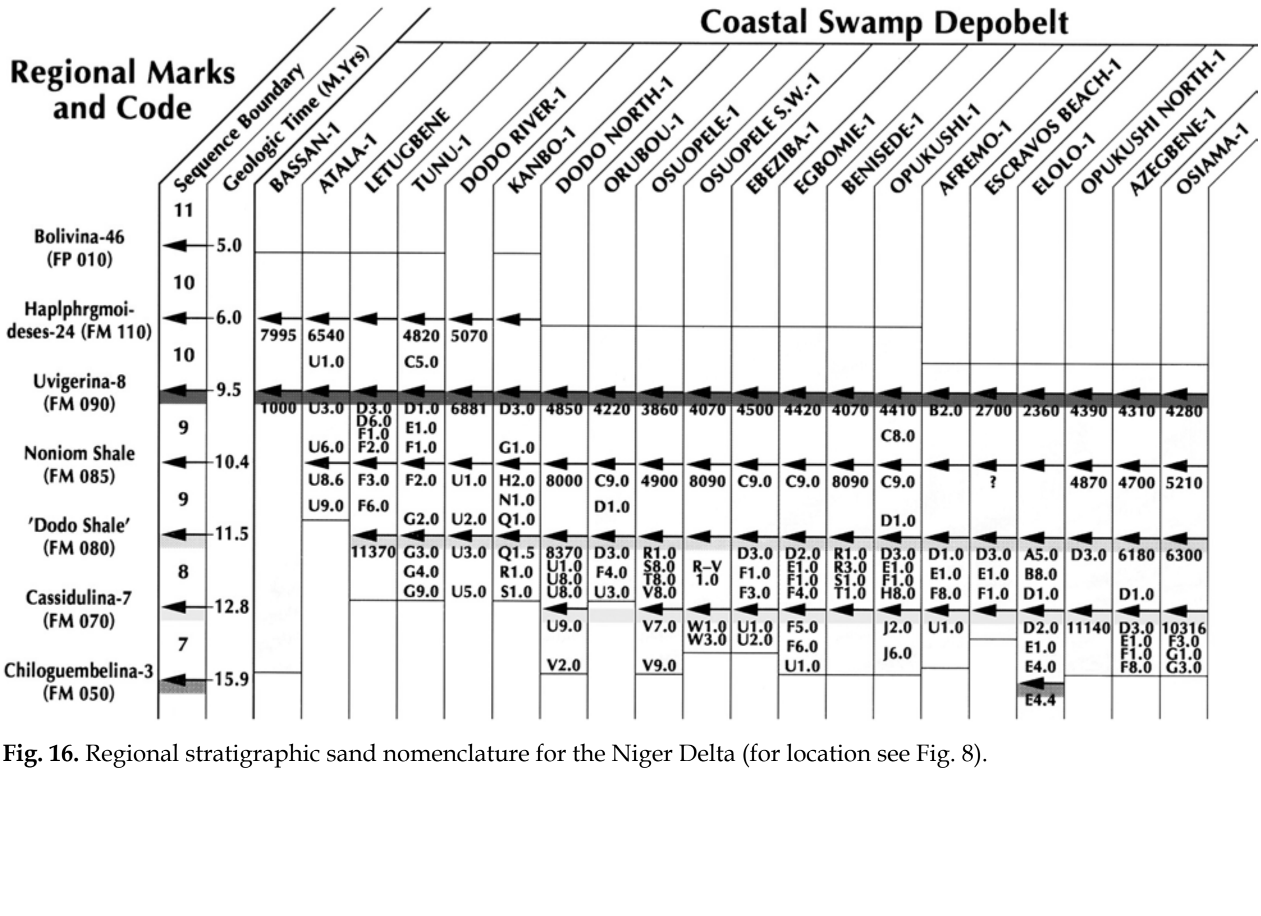

Fig. 16. Regional stratigraphic sand nomenclature for the Niger Delta (for location see Fig. 8).

marised as follows: a delta progrades if Rd>Rs, remains stationary and aggrades if Rd~Rs and retrogrades if Rd<Rs.

Newer insights on the effect of eustasy in the evolution of deltas call for modifications (Fig. 17). It is true that delta development depends on loading by sediment input (Rd) and on subsidence (Rs), but it also depends on global sea-level changes or eustasy (Re). Both Rs and Re are key controls of accommodation space. Eustatic sea-level changes (Re) affect sedimentation simultaneously over large areas (Figs 5, 12, 14), whereas subsidence patterns (Rs) are usually local, irregularly spaced in time and different in manifestation in different parts of the delta. Therefore, Rd as a function of Re refers to regional (allocyclic) sediment input, whereas Rd as a function of Rs refers to local (autocyclic) sediment input (Fig. 17).

The old, up-dip part of the delta is overall characterised by Rd>Rs. Rs results from gradual thermal cooling of the shallow continental lithosphere with low subsidence rates. The young, downdip part of the delta, with higher subsidence rates, has potential for higher Rs through crustal flexuring under an increased sediment load. The suture between the continental and oceanic lithospheres marks the location of the preferred sediment catchment area, which is reflected in sediment thickness of the Middle Miocene. Rd reflects varying sediment supplies from nearby source areas, resulting in progradation rates of 2 km/Ma on average for the old delta with progradational pulses up to 22 km/Ma for the young delta.

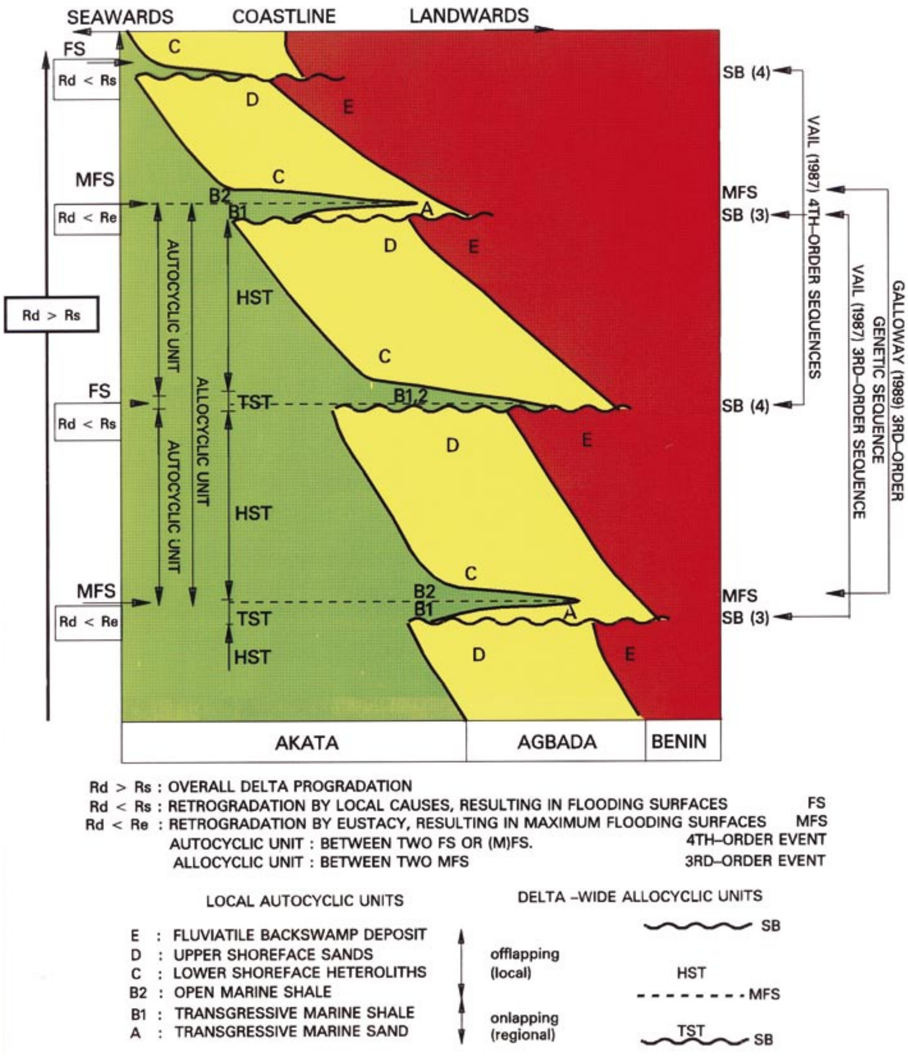

Fig. 17. Mechanisms and units of delta evolution.

Under conditions of Rd>Rs, the delta progrades and regressive, offlapping sands are deposited over uncompacted clays with low shear strength. This triggers counter-regional and down-to-basin faults. Under conditions of Rd~Rs, and as long as counter-regional faults prevent progradation of the barrier facies complex, the delta aggrades (Figs 10, 13). However, once the barrier facies complex crosses the counter-regional fault, progradation starts again in a newly activated depobelt. Under conditions of Rd<Rs, retrogradational breaks and short-lived transgressions occur in the overall prograding/aggrading delta. Local imbalances in Rd are related to delta-lobe switching, whereas variations in Rs reflect tectonic activity in various megastructures of the delta. Therefore imbalances in Rd and Rs may result in retrogradational breaks within specific sections of the delta only. By contrast, Rd<Re reflects eustatic sea-level changes that result in transgressive events, usually affecting major parts of the delta (Figs 2, 5, 12, 14, 18; Table 1).

Delta-front sedimentation patterns are schematically depicted in Figure 15, a modified Weber (1971) facies model that includes sequence-stratigraphic nomenclature. It shows the standard lithological composition of Vail's (1987) sequences and Galloway's (1989) genetic sequences. Onlapping transgressive lithological units (A and B1) typically range in thickness between 15 and 110 m. Under conditions of Rd<Re, the B1 shales occur delta-wide (Figs 5, 12, 14), but if Rd<Rs, they are usually locally confined. The B1 shales are marked by peak faunal and floral abundances, pointing to (maximum) flooding surfaces. Locally, the transgressive claystones may be preceded by thin, fossiliferous transgressive gravel lags (facies A). Together with facies B1, such lags form a parasequence set of a transgressive systems tract (Figs 15, 17).

Characteristically, transgressive marine clays grade landwards into mud-filled estuarine channels and continental deposits. Upwards, the TST are followed by facies reflecting Rd<Rs (Fig. 17) that are respectively (see Fig. 15):

E: fluviatile backswamp deposits with erosional surfaces;

D: upper shoreface silts and (in the older delta) tidally influenced reservoir sands;

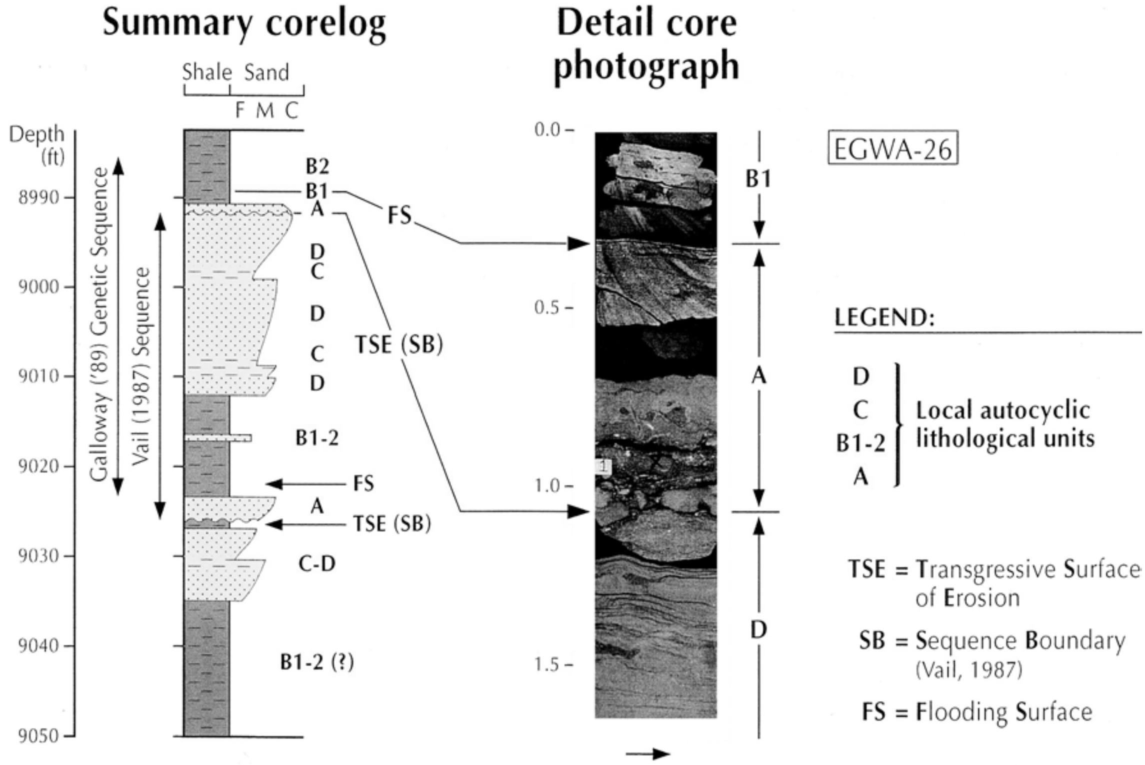

Fig. 18. 4th–5th-order stacked coastal barrier autocyclic lithological units.

C: lower shoreface heteroliths;

B2: open-marine shales and sands with neritic delta-fringe faunal elements. Some of these facies units are seen in cores of well Egwa-26 (Fig. 17).

Units B2, C, D, E together form offlapping parasequence sets in a high-stand systems tract. The parasequence sets of the systems tracts reflect changes in accommodation space by eustatic movements of different periods and by differential subsidence. Most high-stand (HST) lithologies are autocyclic offlapping parasequences, directly responding to local subsidence patterns, whereas the transgressive (TST) sands and the delta-wide shales defining the megasequences are regional allocyclic onlapping parasequence sets responding to eustatic fluctuations. A typical Niger Delta genetic sequence contains a HST-TST couplet. In megasequences 5 and 9, some low-stands (LST) are recorded in association with erosional features updip. Because erosional features are also present in megasequences 1, 6, 7, 8 and 10, mass-transport deposits in LST's are expected downdip. The discrete time interval between successive maximum (= delta-wide) flooding surfaces reflects periods during which the delta incrementally prograded. In the Niger Delta, the eleven megasequences, from the base of each of the delta-wide transgressive shales to the base of the next one, are used as the basic units to subdivide the delta succession.

Internally the parasequence sets may be variable, as is shown by a delta lobe advancing towards a curved or oblique down-to-basin fault that extends upwards to the sea bottom (Figs 10, 13, 15). Such a delta-lobe movement triggers rotation of the hanging wall and associated subsidence at the sea bottom, which increases the accommodation space and triggers autocyclic processes. Sedimentation takes place and excess sediments (Rd>Rs) spill over the shelf edge. On an irregular shelf slope, they could accumulate in local depocentres while remaining attached to the shelf sands. By contrast, spilled sands bypassing a smooth slope may accumulate as turbidites and other mass-transport deposits on the basin floor and are usually detached from the shelf sands. The formation of such attached or detached deeper marine 'spill-over' sands in the delta front zone typically took place when the younger

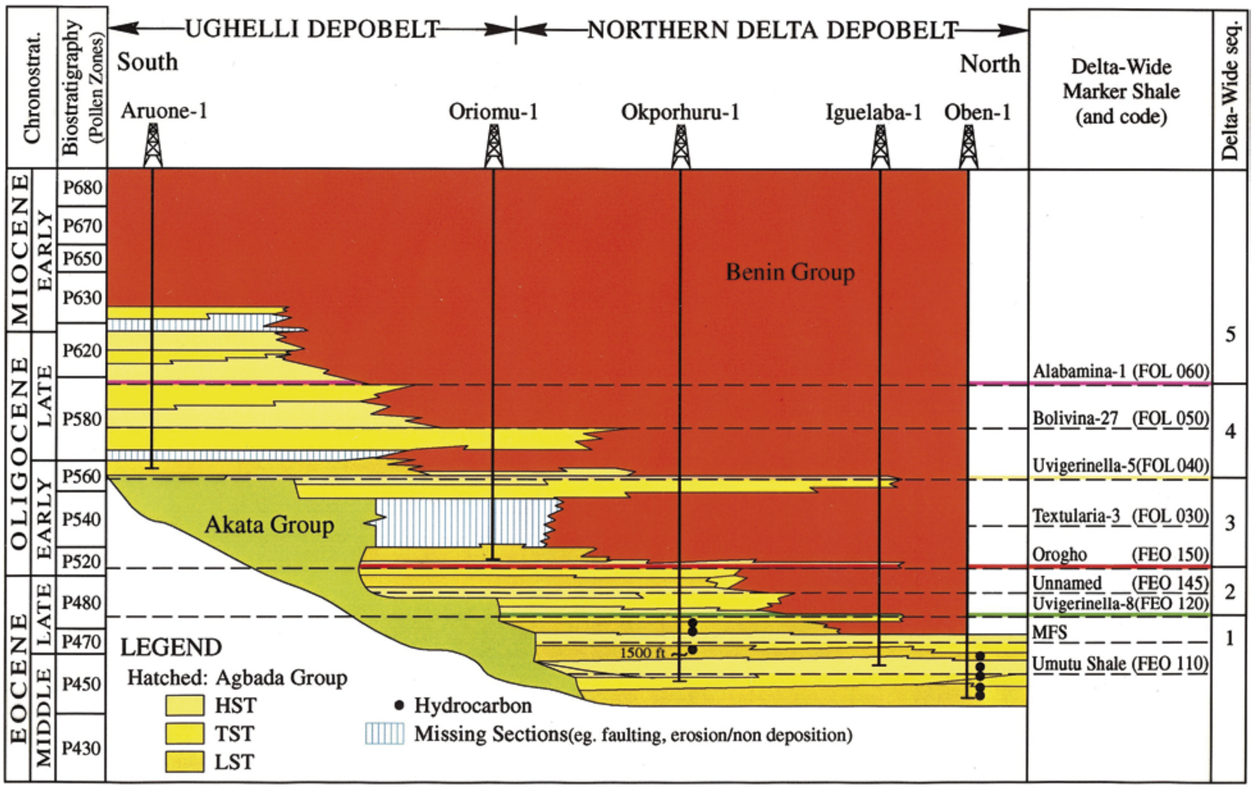

Fig. 19. Time-rock synopsis in OML–38 (Ughelli/Northern Delta depobelt).

delta was formed. There may be a relationship between abundant sediment supply from the hinterland, pulsating delta progradation and significant sea-level falls resulting in updip incising channels. Further study is needed to confirm this hypothesis.

Over the years, subsurface mapping has clarified the progradational nature of the continental Benin and the coastal to shallow marine Agbada units. The mechanism that drives this process has been referred to as 'escalator regression' (Knox & Omatsola, 1988) and this model now dominates the ideas on the stratigraphic evolution of the Niger Delta. The 'steps' in this model are the formation of the depobelts, reflecting phases of structural delta evolution (Figs 3, 4). Fast and slow progradation alternate, regulated by available sediment, the nature of the basement, its subsidence and synsedimentary faulting styles. Accumulation of sandy sediments over mobile claystones triggers growth faulting, which concentrates sands in certain areas (Fig. 13). This, in turn, triggers further loading. Ongoing synsedimentary activity along counter-regional faults controls progradation of shallow-marine sand/shale couplets of the Agbada unit during outbuilding of the delta (Fig. 13). Decreasing movement along such counter-regional faults and increased sediment supply (Rd>>Rs) allows Agbada barrier complexes to cross counter-regional faults (Fig. 10). The distal Agbada parasequences (the B2 lithologies) merge basinward with the Akata. Simultaneously, the alluvial continental Benin sands advance across the older depobelt. Thus the base level is maintained in the old depobelt, and deposition becomes transferred to the new one. Eventually this process yielded the strongly diachronous Agbada and Benin sediments (Figs 2, 6, 9, 17, 19).

10. Conclusions

The publication of this renewed focus on the sedimentology and stratigraphy of the Niger Delta offers, though unfortunately somewhat delayed, the building stone for the introduction of an up-to-date practical stratigraphic framework. The improved tie of biozones to the radiometric time-scale considerably improved the accuracy of detailed stratigraphic analyses, and increasingly more well sections are available that can be interpreted in this way. Thirty-nine eustatic sea-level rises are reflected in the Niger Delta, nineteen of which are named and eleven of which occur delta-wide. These produced sinusoidal sediment bodies or genetic megasequences that are marked at the base by delta-wide transgressive shales. They are the key lithological elements of the Niger Delta and the starting point for a new delta-wide lithostratigraphy. The genetic megasequences are interpreted to reflect allocyclic events superimposed on which occur a series of autocyclic events. A modified facies model reflects deltaic sedimentation patterns as a function of the rates of deposition, subsidence and eustacy. It explains and predicts sediment patterns within a series of third-order genetic sequences, composed of genetic parasequence sets. At several levels, pronounced seismic horizons reveal relics of incised valleys which are the Niger Delta 'channels'. They reflect favourable erosional conditions at the combined 2nd-and 3rd-order levels of eustatic sea-level fluctuations and are associated with mass-transport deposits in a downdip position.

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