Three-dimensional analysis of syndepositional faulting and synkinematic sedimentation, Niger Delta, Nigeria

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General Introduction


Activity along large deltaic growth-faults can influence the development of depositional system by fault-controlled subsidence providing accommodation (Thorsen, 1963; Bruce, 1983; McCulloh, 1988; Cartwright et al., 1998; Imber et al. 2003; Back et al. 2006; Jackson and Larsen 2009). Accommodation creation in the hanging-wall side of growth faults is not homogenous and increases to the bounding fault plane. Wedge-shaped stratal geometry reflects differential
accommodation development and associated differential sediment accumulation on the hanging wall of the bounding fault, with the maximum of accommodation creation and deposition in the immediate vicinity of the master fault. The differential thickness of the syn-kinematic strata, in turn, causes a differential loading of the underlying deltaic substratum, with the maximum of the sedimentary load (and therefore compaction below) associated with the thickness maximum of the hanging-wall fill.

Several important aspects regarding to the understanding of synsedimentary deltaic faulting and fault-controlled deltaic sedimentation are yet not fully understood, including 1) the explanation of the initiation, maintenance, and abandonment of deltaic faults, 2) the controlling mechanisms for the often diverse spatial and temporal development of synsedimentary faults (growth faults) in large deltas that is characterized either by fault propagation through time into hanging-wall terrain or by the backstepping of deltaic faults into footwall areas, and 3) the delineation of the parameters controlling the reactivation of deltaic faults.

The first objective of this work is to increase the understanding of the initiation, maintenance and abandonment of deltaic growth faults by generating detailed 3D seismic interpretations of selected growth faults and associated horizons of the study area providing the base for a study-area wide 3D palinspastic retrodeformation. The regional 3D balancing approach will enable monitoring of the interplay between sediment fill, fault nucleation and fault growth over time.

The second objective is to provide a detailed analysis of the spatial development and propagation of faults; several authors have proposed that deltaic faulting is not exclusively restricted to hanging-wall terrain, but might include footwall collapse where the main bounding fault steps back into the previously undeformed footwall of the fault (e.g. Gibbs 1984, Vendeville 1991, Imber et al. 2003). The comprehensive 3D balancing approach of this Niger Delta case study
ultimately provides new information on the location and respective timing of deltaic faulting across the entire survey area, particularly focusing on the diverse fault history in the southeastern and northwestern parts of the study area. This issue of faults backstepping into footwall terrain and hanging-wall fault progression is additionally discussed.

The last objective of the research presented in this thesis mainly concerns the complex issue of the reactivation of deltaic growth faults: the activity of all or part of a deltaic growth fault might post-date a particular interval in a growth sequence, so the terms syn- and post-sedimentary might not only distinguish one fault from another but also distinguish between segments of the same fault surface active at different times. Similarly, a sedimentary horizon may be pre-kinematic in one place and synkinematic in another, with respect either to a single fault or to different faults. The key aim of this part of research was the analysis of medium- to large-scale growth faults of the study area for their possible structural reactivation, and to carefully document similarities and differences between reactivated and non-reactivated fault surfaces in 3 dimensions.

**Parts of this dissertation that have been published by the author**


Fazli Khani, H., Back, S., 2010. Gravity Driven Faulting and Syn-kinematic Depositions in Deltas; A Case Study From the Western Niger Delta, Nigeria. 162th Annual Meeting of the


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Chapter 1: Temporal and lateral variation in the development of
growth faults and growth strata in the western Niger Delta,
Nigeria

Abstract

This study examines eight syn-depositional faults and syn-tectonic sediments in five major fault blocks in the western Niger Delta offshore Nigeria on three-dimensional (3D) seismic data. The initiation, the lateral growth and retreat, periods of activity and quiescence, and the decay of faulting around these blocks can be ascertained by analyzing a series of time-structure and isopach maps. The study area can be subdivided into three structural zones, (1) a northwestern zone characterized by a major counter-regional growth fault in the deep subsurface. This deep-seated structure is superposed by an array of younger, regional growth faults displacing a kilometer-thick sedimentary overburden that accumulated on the former footwall; (2) a central to eastern zone that seems largely unaffected by young deltaic faulting. This zone is characterized by the thinnest sedimentary record of the study area; and (3) a southeastern zone that is dominated by a large, listric, backstepping master fault-zone associated with a kilometer-scale rollover system. Regional structural and stratigraphic analyses document an apparently strong relationship between syn-tectonic sedimentation and syn-depositional fault activity in that phases of significant fault activity, lateral fault growth and fault migration concur with major depositional phases; in turn, areas and intervals characterized by the least sediment accumulation also record the lowest fault activity. However, one particularity of the studied system is that it underwent at least one period of seaward fault progression that
coincided with a backstepping of faulting on the landward side. Whilst the forward stepping of faulting near the delta front can be interpreted as the consequence of the progressive loading during delta progradation, the contemporaneous backstepping of faulting further inboard likely reflects the sustained lateral growth of mature deltaic faults into previously undeformed, proximal parts of the depocenter. The results of this study thus document that although on a regional scale an apparent correlation with the superimposed depositional system exists, inboard deltaic faults may persist to grow irrespective of sedimentary loading. The recognition of such fault trends is particularly important for estimating the influence of late-stage fault movement on hydrocarbon migration or the discovery of subtle, fault-controlled hanging-wall reservoirs.

**Keywords:** Growth fault, syn-kinematic sedimentation, seismic interpretation, Niger Delta

**Introduction**

Large deltas are commonly characterized by high sedimentation rates and gravity-driven, syn-depositional deformation. Syn-sedimentary faults in deltaic strata are particularly well documented in the US Gulf of Mexico (e.g. Thorsen, 1963; Bruce, 1983; Lowrie, 1986; McCulloh, 1988; Lopez, 1990; Edwards, 1995; Cartwright et al., 1998; Brown et al., 2004), the Nile Delta (e.g. Sestini, 1989; Beach & Trayner, 1991), the Brunei part of the NW Borneo shelf (e.g. Sandal, 1996; Van Rensbergen & Morley, 2000; Hodgetts et al., 2001; Hiscott, 2003; Saller & Blake, 2003; Morley et al. 2003; Back et al., 2005; Hesse et al. 2009) and the Niger Delta (e.g. Doust & Omatsola, 1989; Ajakaiye & Bally, 2002; Hooper et al., 2002; Pochat et al., 2004; Back et al. 2006; Magbagbeola & Willis, 2007). In these settings, the close interrelation between tectonics and sedimentation often makes it difficult to determine to which extent sedimentary loading influenced faulting, or, in turn, fault movement influenced depositional processes. For example,
the rapid accumulation of syn-tectonic delta sediment can contribute to the activation or reactivation of deltaic faults by differential loading above a weak substratum (e.g. Lundin, 1992; Damuth, 1994; Corredor et al., 2005), whereas once active, deltaic faulting can influence depositional-systems development by fault-controlled subsidence providing accommodation (Thorsen, 1963; Bruce, 1983; McCulloh, 1988; Cartwright et al., 1998; Imber et al. 2003; Back et al. 2006; Jackson and Larsen 2009). Consequently, deltaic faulting and sedimentation can form a series of internal tectonic-sedimentary feedback processes that contribute considerably to the self-organized development of delta systems.

To delineate the key controls for deltaic faulting and sedimentation and discuss their potential feedback mechanisms, this study presents a detailed 3D-seismic and well-based analysis of the tectonic and sedimentary development of a 400 km² (154 mi²) study area in the western Niger Delta. This part of the Niger Delta is unusual in that it records the contemporaneous seaward progression and landward backstepping of deltaic faults bounding one deltaic depocenter, a fault migration pattern that has been documented in many previous studies separately (e.g. Evamy et al., 1978; Rider 1978; Worall & Snelson, 1989, Bruce, 1983; Vendeville, 1991; Sandal, 1996; Van Rensbergen & Morley, 2000; McClay et al., 2003; Imber et al., 2003), but – to our knowledge – not yet simultaneously. Interpretation of this temporal co-existence of fault progression and backstepping requires detailed information on both fault activity and sedimentary history over time, data that is provided in a series of time-structure, sediment-isopach and fault-history analyses. The data and interpretation results of this study ultimately offer detailed insights into the vertical and lateral evolution of deltaic faults and stratigraphy through time, highlighting the often complex interaction between fault growth and the development of syn-tectonic delta stratigraphy. An increased understanding of the rules and exceptions of this dynamic relationship provides perspectives that can improve hydrocarbon prediction in comparable settings.
**Seismic data and subsurface geology**

The 3D seismic data presented in this study are from the uppermost 3 km (2 mi) of a 400 km² (154 mi²) survey area in the offshore swamp belt of the western Niger Delta (Fig. 1-1). The seismic data has been processed using pre-stack time migration. Coherency volumes were derived from the reflectivity data using a semblance algorithm that highlights lateral amplitude variations between adjacent seismic traces. Figures 1-2A and 1-2B show the coherency signature extracted from two selected horizons (coherency horizon-slices of horizons C and D), emphasizing contrasting structural conditions in the northwestern and southeastern part of the study area.

![Figure 1-1: Location of the study area in the shallow offshore of the western Niger Delta.](image)

The northwestern part of the study area is characterized by several medium-to large-scale, arcuate-shaped, seaward-dipping normal faults that extend laterally over several kilometers, dividing the area into four main fault blocks (Fig. 1-2C, Blocks 1 to 4). The vertical reflectivity section of Figure 1-3 (location on Fig. 1-2C) shows the relation between fault development and stratigraphy: all large-scale faults in the northwestern part of the study area show a syn-
sedimentary growth pattern, i.e., thickened intervals or additional sedimentary units on their downthrown sides. Across the slightly listric deltaic faults, syn-tectonic strata thicken seaward by several tens of milliseconds two-way-time (ms TWT); within the respective fault blocks 1 to 4, most growth successions thicken landwards (Fig. 1-3).

Figure 1-2: (A) Coherency signature of Horizon C, and (B) Horizon D, documenting contrasting structural conditions in the NW and SE of the study area (coherency = white, incoherency = black; horizons shown in Figure 1-3). The NW is characterized by the medium- to large-scale, seaward-dipping (regional) normal faults F1, F2, F3 and F4; the SE is dominated by two major subparallel faults (F6, F7) in the E, and numerous small-scale faults bound to the collapsed crest of a kilometer-scale rollover anticline in the center of the study area. (C) The principal fault blocks of the study area and the distribution of the main bounding faults F1 to F7 (as on horizon D). Fault F1 consist of two segments, a NW segment (F1NW) and a SE segment (F1SE).
In contrast, the central and southeastern parts of the study area are characterized by a large-scale deltaic rollover system in fault block 5 (Fig. 1-2) that is bound on its landward side by a series of subparallel, seaward-dipping, highly listric growth faults (Figs. 1-4, 1-5 and 1-6). On its seaward side, the rollover is bound by a slightly listric, seaward-dipping fault system (southeastern segment of fault F1, Fig. 1-2C). In its center, fault block 5 exhibits a NW/SE-trending zone of crestal collapse over 5 km (3 mi) wide (Figs. 1-2A, 1-2B, 1-4, 1-5 and 1-6).

**Interpretation Methodology**

The following analysis of the activity of the studied deltaic faults through time is fundamentally based on the comparative interpretation of their footwall and hanging-wall sedimentary record on seismic data. The uncertainty of seismic-stratigraphic correlation across these faults was minimized by the consequent interpretation of semblance facies on series of successive reflectivity and coherency horizon slices (sensu Back et al. 2006), tied at well locations to wireline-facies interpretations. To be able to define periods of activity and inactivity of the faults and document their spatial development through time, seven seismically defined, laterally continuous marker horizons (A to G from young to old) were mapped throughout the study area. These horizons were primarily used to provide thickness maps (i.e., isopach maps in m), and as reference levels for the measurement of the active length of faults. On the horizon-based isopach maps, the syn-depositional activity of deltaic faults was expressed in two ways, by (1) the occurrence of significant differences in the sedimentary thickness of contemporaneous strata on the footwall and hanging wall of the active fault, and (2) the thickening of sediments on the hanging wall into the active fault plane. Another indicator for the activity of the studied faults was provided by the analysis of the vertical and lateral growth of faults, with the lateral growth component measured at each horizon level as the length of each active fault or fault segment. Since horizon-based thickness maps only indirectly measure the activity or inactivity of syn-
sedimentary faults (i.e., the sedimentary consequences of faulting), and fault-length analysis alone cannot illustrate the depositional response to faulting, we combined both approaches to differentiate between periods of fault activity and quiescence, as well as between times of significant syn-kinematic deposition and intervals lacking syn-tectonic sedimentation.

Figure 1-3: Vertical reflectivity section across the NW of the study area. Horizon and fault interpretation illustrates medium- to large-scale, regional, syn-sedimentary faults displacing the syn-kinematic deltaic overburden above a large-scale counter-regional (landward dipping) fault (CRF) in the deeper subsurface. The location of the cross section is shown on Figure 1-2.


**Fault Description**

The seven major regional (seaward-dipping) syn-sedimentary faults within the study area are labeled F1 to F7 from the west to the east (Fig. 1-2C).

**Figure 1-4:** Vertical reflectivity section across the SE of the study area imaging fault block 5 on the hanging wall of a major listric, regional growth-faults (Faults F6 and F7). Note kilometer-scale rollover anticline with collapsed crest in the center of fault block 5, and stratal thickness maxima associated with the rollover flanks. The location of the cross section is shown on Figure 1-2.
At the deepest stratigraphic level, an additional, large-scale, counter-regional (landward-dipping) fault characterizes the NW of the study area (CRF in Fig. 1-3). The seven regional growth faults chosen for detailed analysis are not single, straight, isolated features; instead, several of these faults are curved, consist of more than one segment (Fig. 1-2), and some of the individual fault segments exhibit differential growth and displacement histories during fault development.

![Seismic and wireline section](image)

**Figure 1-5:** Seismic and wireline section of the centre of fault block 5 along a vertical reflectivity section. Sonic and caliper log signatures indicate the presence of overpressured, undercompacted sediment in the core of the rollover anticline, a zone that corresponds to a chaotic reflection pattern on seismic data. Note the subsurface presence of an earlier rollover affecting horizons F and G basinward of the present-day anticline crest. The location of the cross section is shown on Figure 1-2.
The following paragraphs firstly provide a detailed description of the respective fault geometries (also see Table 1-1), before documenting the depositional characteristics of the syn-kinematic sediments associated.

The counter-regional fault CRF offsets the basal horizon G (Fig. 1-3). During the depositional interval between horizons F and E, fault CRF becomes inactive. The depositional units above remain unaffected by counter-regional faulting (e.g. Fig. 1-3), but are offset by faults F2, F3 and F4 that displace the former footwall block of fault CRF (Figs. 1-2C and 1-3). The hanging wall of counter-regional fault CRF comprises in places a small rollover (Fig. 1-3) that is only marginally developed in comparison to the major hanging-wall rollover anticline above faults F6 and F7 (Figs. 1-4, 1-5, 1-6).

The regional, SW-dipping fault F1 is the longest fault in the study area (Fig. 1-2; Table 1-1). The fault shape exhibits a series of connected arcs indicating that this fault formed from at least 4 fault segments that grew through time into a single fault system. For simplification, this fault is subdivided in the following into two sub-segments, a NW segment (F1_{NW}) and a SE segment (F1_{SE}). The separation point between these segments is the intersection of fault F1 with faults F2 and F4 (Fig. 1-2C).

Fault F2 dips in western direction displacing the footwall strata of fault F1_{NW} (Fig. 1-2C). To the south, this fault is bounded by fault F1, whereas its northern tip is outside of the study area. The maximum displacement of fault F2 is ca. 1200 ms (TWT) in the very NW of the fault (Table 1-1). The seaward-dipping fault F3 is located in the footwall of fault F2, trending over significant distances subparallel to fault F2 (Fig. 1-2C). On vertical seismic sections, this fault is only slightly listric. Fault F3 is located immediately above the basal counter-regional fault CRF (Fig. 1-3). The displacement on fault F3 (Table 1-1) decreases towards the NW, contrasting the displacement
pattern on the neighboring fault F2. Towards the SE, fault F3 terminates at the intersection with fault F5 (Fig. 1-2C).

**Figure 1-6:** Vertical reflectivity section across the very SE of the study area illustrating the presence of two rollover generations on the hanging wall of faults F6 and F7. The older, southwestern rollover formed on the hanging wall of fault F6; the younger, superposed rollover formed in response to the activity of fault F7. Gamma-ray log signature at wells B and C shows coarsening-upward trend within younger rollover. The location of the cross section is shown on Figure 1-2.
Fault F4 is located in the center of the study area between faults F1 landward and F5 seaward (Fig. 1-2C). This fault terminates in the west against fault F1, and dies out towards the SE in the major rollover seaward of Fault F6. A maximum displacement of ca. 820 ms (TWT) is observed on its western termination at the junction with fault F1. Fault F5 is almost E-W oriented and located on the footwall of fault F4 (Fig. 1-2C). The displacement on fault F5 (Table 1-1) generally decreases towards the west. To the east, fault F5 is bound by fault F7, and to the west it terminates against fault F4 (Fig. 1-2C).

Fault F6 is a basinward-dipping, listric fault with its root located in chaotic seismic reflections that correspond, where drilled, to a zone of undercompaction and possibly overpressure (see sonic and caliper data on Fig. 1-5). Fault F6 bounds the crestal collapse of fault block 5 on its northeastern side, and records in its central portion the maximum stratal displacement (Table 1-1). Fault F7 parallels fault F6 close to the edge of the study area.

<table>
<thead>
<tr>
<th>Fault name</th>
<th>Fault type</th>
<th>Max. length</th>
<th>Max. displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRF</td>
<td>Counter regional</td>
<td>10 km (6.2 mi)</td>
<td>Not measured</td>
</tr>
<tr>
<td>F1 NW/SE</td>
<td>Regional</td>
<td>24 km (15 mi)</td>
<td>F1 NW = 1100 ms (1300 m, 0.8 mi)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>F1 SE = 700 ms (900 m, 0.55 mi)</td>
</tr>
<tr>
<td>F2</td>
<td>Regional</td>
<td>9.5 km (5.9 mi)</td>
<td>1200 ms (1600 m, 1 mi)</td>
</tr>
<tr>
<td>F3</td>
<td>Regional</td>
<td>8 km (4.9 mi)</td>
<td>200 ms (250 m, 0.12 mi)</td>
</tr>
<tr>
<td>F4</td>
<td>Regional</td>
<td>10 km (6.2 mi)</td>
<td>820 ms (1050 m, 0.65 mi)</td>
</tr>
<tr>
<td>F5</td>
<td>Regional</td>
<td>11.5 km (7.1 mi)</td>
<td>900 ms (1150 m, 0.71 mi)</td>
</tr>
<tr>
<td>F6</td>
<td>Regional</td>
<td>16 km (9.9 mi)</td>
<td>220 ms (300 m, 0.18 mi)</td>
</tr>
<tr>
<td>F7</td>
<td>Regional</td>
<td>17 km (10.5 mi)</td>
<td>Not measured</td>
</tr>
</tbody>
</table>

*See Figure 1-2 for location. Maximum length (in kilometers) measured on map data at time of maximum lateral extent. Maximum displacement (ms two-way traveltime, TWT) measured on vertical sections perpendicular to fault. Maximum displacement on faults CRF and F7 was not measured due to insufficient footwall information.
Due to the significant uncertainty for an across-fault horizon interpretation (Figs. 1-4, 1-6), the displacement of this fault was not measured (Table 1-1); however, the considerable length of the fault and its apparently long record of stratal displacement (e.g. Fig. 1-4) suggest that this fault might comprise the largest displacement of all faults analyzed.

**Horizon interpretation and isopach analysis**

Across-fault interpretations of horizons A to G (Figs. 1-3 to 1-7) were carried out following the methodology of Back et al. (2006), including cross-checks between coherency horizon-slice interpretations and wireline-log data at numerous well locations. Subsequently, isochron (ms TWT) and isopach (m) maps were generated between successive horizon pairs by measuring true stratigraphic thickness in time and depth, respectively. This way, six depositional units were defined, named GF and FE (Fig. 1-7A), ED and DC (Fig. 1-7B), and CB and BA (Fig. 1-7C). These units were then analyzed on isochron and isopach maps for thickness variations across the respective target faults, concentrating on thickness differences of > 20 ms (TWT; ca. 20 to 30 m on isopach data of Figs. 1-7A to C depending on depth level) to account for seismic-interpretation inaccuracy. Therefore, all isochron- and isopach-based measurements of the active fault length presented are conservative (minimum) estimates for the length of syn-depositionally active faults and fault segments carrying a lateral measurement error of < 200 m, which is in all cases < 3 % of the total fault length measured. Figures 1-7A, 1-7B and 1-7C comprise on their respective left sides time-structure maps of the marker horizons interpreted in this study overlain by a coherency attribute, in the center series of isopach maps illustrating the stratigraphic thickness of each horizon-bound stratal unit, and on their right sides a fault-activity interpretation based on across-fault isopach variations.
Figure 1-7A: Time-structure maps of interpreted horizons A to G overlain by a coherency attribute (left side of figure), isopach maps of horizon-bound depositional units in true stratigraphic thickness (m; centre of figure), and interpretation of syn-depositionally active faults and fault segments (right side of figure). Time structure, isopach and fault-activity data between horizons G and E.

Stratal unit GF

Basal horizon G (Fig. 1-7A) was mapped on a prominent reflectivity peak close to the lower tip of most faults of the study area (Figs. 1-3 to 1-6). In depths below 3 seconds (TWT), the reflection signature of horizon G locally deteriorates or vanishes (Fig. 1-3), which is also the case at higher stratal levels in the footwall of faults F6 and F7 (Figs. 1-4, 1-5 and 1-6). At this location, well data exhibit irregular wireline-log trends (see e.g. sonic and caliper data of well A, Fig. 1-5) most likely related to the presence of an overpressured, undercompacted footwall substratum.
However, other deep-seated parts of the study area exhibit thick, continuous seismic reflection packages below horizon G, which is best documented in the hanging walls of faults CRF and F6 (Figs. 1-3 to 1-6).

**Figure 1-7B and C:** Time-structure maps of interpreted horizons A to G overlain by a coherency attribute (left side of figure), isopach maps of horizon-bound depositional units in true stratigraphic thickness (m; centre of figure), and interpretation of syn-depositionally active faults and fault segments (right side of figure). (B) Time structure, isopach and fault-activity data between horizons E and C. (C) Time structure, isopach and fault-activity data between horizons C and A.
The overlying stratal unit GF (Fig. 1-7A) shows prominent internal thickness differences across the study area interpreted to record activity at faults F2 and CRF in the northwest, at fault F5 in the center and at fault F6 in the southeast. In the northwest of the study area, fault F2 records at least 7 km (4 mi) active length during this interval, whereas the active length of fault CRF is probably >10 km (6 mi). The active lengths of faults F5 and F6 are 7.5 km (4.5 mi) and 15 km (9 mi), respectively (Fig. 1-7A, unit GF). Stratal thickening both landwards and basinwards in the hanging wall of fault F6 documents the activity of a deep-seated rollover anticline on the southwestern side of fault block 5 (also see Figs. 1-5 and 1-6). The lack of thickness variation at faults F1, F3 and F4 (Fig. 1-7A) is interpreted to relate to the initiation of these faults after the deposition of unit GF.

Stratal unit FE

Horizon F follows a reflectivity peak (e.g. Figs. 1-3 and 1-5) within sub-parallel to parallel reflections at the base of stratal unit FE. This stratal unit (Fig. 1-7A) shows considerable thickness variations across the study area, with the most prominent relative maxima located on the hanging walls of faults F2, F4 and F7. Fault F6 remains active during deposition of stratal unit FE, fault F7 initiated in its footwall, providing additional accommodation on the eastern side of the deep-seated rollover of basal unit GF (Figs. 1-4, 1-5). Furthermore, the thickness minimum of unit FE in fault block 5 shifted at this interpretation level up to 3 km (1.8 mi) eastward (Fig. 1-7A, unit FE), indicating a considerable lateral migration of the central rollover axis towards fault F7 with respect to the underlying sedimentary unit (e.g. Fig. 1-5). Towards the north, fault F5 continued its activity as indicated by differential thicknesses in its hanging wall, and the lateral propagation of the fault tips (NW-tip towards the W; SE-tip towards the E). The contemporaneous propagation of faults F5 and F7 towards each other caused the connection of these faults at the very top of depositional interval FE.
The accumulation of considerable unit thickness in the hanging wall of fault F4 (Fig. 1-7A) witnesses its initiation during interval FE. In map view, fault F4 is of arcuate shape, with its eastern tip dying out in fault block 5. Its western tip is located close to the southern limit of Fault F2, a fault that remains active during depositional interval FE. In comparison to the underlying interval GF (Fig. 1-7), the southern tip of fault F2 propagated laterally in a southeastern direction.

**Stratal unit ED**

Horizons E and D form the base and top of depositional interval ED (Fig. 1-7B). Major thickness variations in unit ED are related to significant accommodation development in the hanging walls of faults F1, F2, F4 and F7. More subtle lateral thickness variations are observed in the crestal-collapse zone of the rollover anticline in the center of fault block 5. At fault F1, thickness differences between the hanging wall and footwall record the initiation of fault movement on both northwestern segment F1_NW and southeastern segment F1_SE with significant lateral fault growth towards the SE (Fig. 1-7B). At fault F2, differential thickening on the hanging wall indicates ongoing fault activity, which is also suggested by the lateral growth of its southern fault tip towards the junction with faults F1 and F4 (Fig. 1-7B). Fault F4 also remained active during deposition of unit ED, attaining its maximum length of ca. 10 km (6 mi). Several small-scale synthetic normal faults offset the southern part of the hanging wall of fault F4 (Fig. 1-7B), distributing displacement in the most western part of fault block 5 to a wider area. At fault F5, the hanging-wall thickness of unit ED increases towards the east, gradually stepping over into the hanging wall of faults F6 and F7. Both faults remain active as indicated by upward growth (Fig. 1-5), with fault F7 exhibiting further lateral propagation of its northwestern fault tip (Fig. 1-7B). The initiation of another, younger boundary fault (fault F7-1) in the footwall of fault F7 at the very eastern edge of the study area (Figs. 1-4, 1-5, 1-6) is recorded by a local thickness maximum.
Stratal Unit DC

The isopach map of unit DC shows that fault F1 now became active along its entire length, with maximum accommodation developing in the NW (Fig. 1-7B). Lateral growth of the F1NW and F1SE segments into each other and towards the NW and SE resulted in the formation of the longest fault zone in the study area (Fig. 1-7B). On the hanging wall of fault F2, unit DC decreases in thickness from the NW to the SE. Towards the intersection with fault F4 and fault

Figure 1-8: Zoomed 3D view in northern direction onto time-structure map of horizon D overlain by coherency attribute, and fault interpretation. Note the presence of small-scale, oblique transfer faults (marked in black) interpreted to accommodate differential subsidence and stress between the landward-dipping fault blocks in the NW of block 5 (Fig. 2), and the generally seaward-dipping southern flank of the hanging-wall rollover in the SW of fault block 5.
F1, large parts of the footwall and hanging wall of fault F2 record the same unit thickness, indicating fault inactivity in its southernmost part. At the same time, subtle thickness variations in the footwall of fault F2 document the initiation of fault F3 (Fig. 1-7B). Faults F4, F5 and F6 remain active over their entire length, with fault F5 now connected by lateral growth to fault F7. Despite the linkage with fault F5, the SE part fault F7 remains active, with major fault-controlled subsidence reflected by the wedge-shaped sediment accumulation on its hanging wall (Fig. 1-5).

Besides the large-scale faults of the study area, horizons D and C and the isopach map of unit DC (Fig. 1-7B) also document the activity of numerous small-scale, syn-depositional faults in the study area, most of which are located in the central crestal-collapse domain of fault block 5. However, particularly at the edges of the rollover near the SE termination of fault F4, there are several small-scale faults that trend oblique to the main fault trend in W-E orientation (Fig. 1-8). These oblique faults seem to have initiated during deposition of unit DC to accommodate differential subsidence between the rising SW flank of the central rollover anticline and the contemporaneously subsiding hanging wall of fault F4.

**Stratal Unit CB**

In comparison to depositional interval DC, stratal unit CB is interpreted to record an overall diminution of syn-sedimentary fault activity as indicated by a decrease of thickness variation across the study area (Fig. 1-7C). Fault $F_{1_{SE}}$ branches in its southern part into several sub-parallel segments, resulting in a subtle, distributed displacement pattern below the resolution of the isopach data. However, smaller differences between the footwall and hanging-wall sedimentary record still characterize its northern portion (Fig. 1-7C). Contemporaneously, fault segment $F_{1_{NW}}$ remains tectonically active as documented by significant sediment accumulation on its hanging-wall. In contrast to the preceding interval, fault F2 is now active over its entire length, growing
laterally in southern direction joining faults F1 and fault F4 in a triple junction. Further thickness
differences between the footwall and hanging-wall sedimentary record are observed at faults F3
and F4, suggesting a displacement pattern similar to that of depositional interval DC. However,
tectonic activity along faults F5 and F6 seems to decrease, as fault F5 is shortened by
northeastward retreat of its western tip (Fig. 1-7C, unit CB). Fault F7 exhibits less thickness
variation between its footwall and hanging wall, but remains visibly active in its central part and at
its northwestern tip.

**Stratal Unit BA**

In the topmost depositional interval BA (Fig. 1-7C), thickness variation across the study area
further decreases. Fault F1$_{NW}$ still stores a significant amount of sediment in its hanging wall,
whilst syn-depositional movement along fault F1$_{SE}$ seems restricted to its very northernmost part.
Subtle thickening of depositional unit BA on the hanging wall of Fault F2 documents ongoing
fault activity in the very north of the study area, which applies similarly to Fault F3. In the center
of the study area, minor thickness variations between footwall and hanging-wall strata are
observed at faults F4, F5 and F6. Fault F7 shows a localized thickness maximum in its central
part.

**Structural development through time**

Figure 1-9 summarizes the observations derived from the vertical fault analysis and the lateral
fault development provided by the isopach data. Tectonic elements that initiated, grew and
waned during the depositional interval under study are (1) the kilometer-scale growth faults
bounding the main fault blocks, (2) two rollover systems in the subsurface of fault block 5, (3)
numerous medium- and small-scale normal faults in the collapsed crests of the rollovers, and (4)
a limited number of oblique-trending, small-scale faults dominantly located at the edges of the large-scale structural elements.

**Figure 1-9**: Overview of the lateral distribution and migration pattern of active faults and rollovers through time, documenting that individual faults or fault segments initiated, grew and ceased during the studied depositional interval. Red arrows indicate a diverse fault-migration pattern particularly affecting units FE and ED, with fault progression in the northwestern part of the study area coinciding with a landward backstepping of faulting in the eastern part. The landward fault migration in the east can be explained by segment linkage across a relay zone between faults F5 and F7; contemporaneous fault progression in the northwest is interpreted to reflect progressive loading and delta-front failure. Note landward migration of rollover zone during intervals GF and FE responding to the initiation and activity of fault F7.
The oldest tectonic element in the study area is the counter-regional fault CRF that is already at a mature stage at horizon G level, ceasing activity latest at unit FE level (Fig. 1-9). At its flanks, fault CRF is superseded by regional growth faults F2 and F5, whereas fault F6 further south develops contemporaneously an early hanging-wall rollover at horizon G and F levels. In the following, the northwestern part of the study area records a general basinward progression of faulting with the development of regional faults F4 (unit FE level) and F1 (unit ED level); at the same time, the southeastern part of the study area shows a general backstepping of faulting (and the associated rollover zone) by the initiation of fault F7 in the footwall of fault F6 (unit FE level). This co-existence of fault progression in one part of the study area and fault backstepping in another is maintained throughout horizon D into the early unit DC level (Fig. 1-9). The initiation and activity of some of the oblique-trending, small-scale faults in the central part of the study area seems to be limited to areas that experienced differential subsidence and stresses between the neighboring northwestern, progressing, and southeastern, backstepping tectonic domains. The development of fault F3 in footwall terrain of fault F2 in the northwestern part of the study area (unit DC level) then leads into an interval where fault zone F1_{NW/SE} has developed its maximum length and offset, coinciding with the onset of a decrease in syn-sedimentary fault activity at all other faults during the accumulation of stratal unit CB (Fig. 1-9). At unit BA level, fault F1_{NW/SE} has shortened and lost regional importance; fault-related stratal growth in the other parts of the study area becomes subtle and restricted to the few fault segments remaining active (Fig. 1-7C).

**Discussion**

The tectonic-stratigraphic analyses presented in this Niger Delta case study document a considerable lateral variability in structural and stratal style within (and around) one tightly defined deltaic depocenter. This variability reflects the co-existence of areas that remained
relatively stable and unfaulted throughout the studied time interval (block 1; Figs. 1-2, 1-7A to C); blocks with a significant landward subsidence segmented by a few, medium- to large-scale, regional, mainly seaward-progressing normal faults (e.g. blocks 2, 3; Figs. 1-2, 1-7A to C); and terrain located in the hanging wall above a major backstepping, listric bounding fault system (block 5). The latter recorded strong subsidence on both landward and seaward sides, which resulted in significant stratal bending forming two successive, kilometer-scale rollover systems (Figs. 1-2, 1-7A to C). The isopach record of these areas shows the least sediment accumulation on stable, unfaulted terrain; more sediment deposited in the areas characterized by few medium- to large-scale faults; and most sediment accumulated on the landward and seaward sides of the succession of rollover systems in the subsurface of fault block 5 (Figs. 1-4, 1-5, 1-6). Besides this lateral variability in structural and isopach style, the study area also shows a distinct temporal variation in fault development (Fig. 1-10). The analysis of fault growth through time documents that individual faults or fault segments initiated, grew and ceased during the studied interval, with a local growth maximum characterizing their initiation and early growth phase (Fig. 1-10). Once initiated and considerably active, most faults maintained their active length and displacement pattern over at least two or three depositional intervals, indicating that syn-sedimentary fault movement, once activated, remained relatively constant.

However, one particularity of the studied system is the occurrence of a contemporaneous landward retrogression and seaward progression of faulting during the deposition of stratal units FE and ED at the respective southeastern and northwestern edges of fault block 5 (Fig. 1-9). Previous studies have documented either a general forward-stepping trend of consecutive deltaic growth structures (e.g. Evamy et al., 1978; Rider 1978; Worall & Snelson, 1989, Bruce, 1983; Sandal, 1996; McClay et al., 2003) or the backstepping of bounding faults into previously undeformed footwall terrain (e.g. Gibbs, 1984; Vendeville, 1991; Sandal, 1996; Bhattacharya & Davies, 2001; Imber et al., 2003). Yet, the temporal co-existence of fault progression on one side
and the backstepping of faults on the other side of a depocenter is rather unusual. This triggers questions on the fundamental controls for growth faulting in the study area, and in particular whether one or several factors influenced the initiation, activity and migration of growth faults.

**Figure 1-10:** Synoptic plot of the development of the length of active faults through time as measured from isopach data (see Figs. 1-7A, B, C). A maximum of change in the length of active faulting is observed during the early fault history, interpreted to mainly reflect the tectonic response to sedimentary loading. Once initiated and active, most faults seem to maintain their active length with little temporal variation. This trend can be interpreted to reflect lithology-driven compaction differences on either side of a fault maintained by well-balanced sedimentary loading. However, the plot does not properly show the development of multi-segment fault systems such as the linked system F5 - F7 (that forms during ED-time; see asterisk). The consideration of such multi-segment faults is essential for the identification of out of sequence faulting, a process that can significantly influence syn-tectonic deposition.

The consecutive progression of deltaic growth faults is commonly interpreted as the natural consequence of a progressive loading during delta progradation. Denser sandstone units prograde over less dense prodelta mudstones (e.g. Rider, 1978; Evamy et al., 1978; Bruce, 1983) and growth faults are initiated by gravity gliding above an undercompacted, overpressured shale substratum (sensu Mandl & Crans, 1981) or differential compaction associated with fluid expulsion (sensu Van Rensbergen & Morley, 2000). Once active, these faults often show a growth history linked to sediment loading (e.g. Lowrie, 1986), but fault movement out of phase with depositional loading has also been documented (Cartwright et al., 1998).
Backstepping of faults into former footwall terrain has been related in previous studies to (1) large-scale gravity-induced failure along prominent fault scarps bounding underfilled basins (e.g. Gibbs 1984; Hesthammer & Fossen 1999), (2) footwall collapse above a rising diapir (e.g. Morley & Guérin, 1996; Imber et al., 2003), and (3) segment linkage across relay zones between en échelon normal faults by footwall breaching (e.g. Peacock & Sanderson, 1991; Trudgill & Cartwright, 1994; Childs et al., 1995; Imber et al., 2003). Gravity-induced failure can likely be excluded as an explanation for the backstepping of faulting in the study area as there is neither evidence for the existence of a prominent fault-scarp palaeotopography (by e.g. slump or slide deposits in the hanging-wall record) nor evidence for a temporal underfill (by e.g. unconformities or incised valleys) of the generally sediment-rich system. The interpretation of an active rise of a shale diapir in the footwall of a growth fault, in turn, highly depends on the correct identification of a formerly overpressured, undercompacted, mobile substratum on seismic-reflection data; this can be particularly ambiguous on the footwall sides of low-angle faults due to an often low-quality, noise-prone seismic response caused by energy loss and signal scattering along the overlying zone of deformation. Relatively shallow-seated zones of present-day overpressure have been encountered by several wells in the study area, primarily in core of the central rollover anticline of fault block 5 (Fig. 1-5) where they are associated with a generally distorted seismic-reflection signature. However, most distorted seismic facies seems to descend from the rollover core in fault block 5 in a landward direction (Figs. 1-4, 1-5 and 1-6), exposing near the roots of faults F7 and F7-1 rather stratified than chaotic seismic reflections. This observation suggests that though re-active mobile shale (sensu Van Rensbergen et al. 1999) probably migrated into the core of the deltaic rollover (retaining overpressures until today), there is not much evidence for an active shale diapir that consecutively rose from the footwall of fault F6 into the neighbouring footwalls of faults F7 and F7-1. This thus leaves the linkage of normal-fault segments across a relay zone as the most plausible explanation for the backstepping of the boundary faults in the southeast of the study area.
Figures 1-7, 1-9 and 1-10 document that lateral fault growth is clearly an important factor for the structural development of the study area, and that many originally isolated faults linked laterally over time into extensive, multi-segmented fault systems. Evidence for the linkage of faults F5, F7 and finally F7-1 by footwall breaching across a relay zone is provided by the documentation of an eastward growth of fault F5 towards fault F7 during depositional intervals FE and ED, a growth direction that deviates from the initial strike direction of fault F5 (Figs. 1-7A, 1-7B, 1-9, 1-10). Another argument supporting footwall breaching as key mechanism is the contemporaneous development of a localized, fault-bound triangle zone in the relay between faults F5 and F7 (Fig. 1-9), a feature that records a local isochron high, thus increased fault activity, during the deposition of stratal unit ED (Fig. 1-7B). Inferences about footwall breaching based on faults F7 and F7-1 are difficult to make as both faults have an incomplete footwall record due to their location at the very edge of the dataset. Yet, if segment linkage across a relay zone indeed controlled the backstepping of bounding faults on the landward side of the study area, the interpretation of a contemporaneous progression of growth faulting in a more basinward position sensu Mandl & Crans (1981) or Van Rensbergen & Morley (2000) remains possible. For example, a fault-prone delta front could have migrated during depositional intervals FE and ED across the western study area initiating distal, progressive faulting. This could have coincided with delta-topset deposition in a more easterly, landward position that maintained the activity and lateral growth of the pre-existing inboard faults ultimately leading to fault-segment linkage by footwall breaching. The local subsidence pulse associated with such a process might have had important consequences for the depositional system: it is for example possible that sediment input from the stable fault block 1 (Fig. 1-2C) was constantly sufficient to outpace seaward tectonic subsidence thus driving progradation and associated fault progression in the western part of the study area. At the same time, fault-segment linkage further landward could have produced an areally restricted inboard subsidence exceeding sediment input, potentially triggering a backstepping of deltaic depositional environments in the vicinity of the breaching location. If additional factors
such as the autocyclic switching of delta lobes, the potential abandonment of distributary channels in the feeder part of the system, or the response of the delta system to eustatic change are taken into account, it becomes clear that although documentable in much detail on a local scale, it will remain challenging to determine the respective primary control for delta development, whether tectonic or sedimentary, on a regional scale. Consequently, gross predictions of depositional change and syn-depositional faulting in deltas will most likely underestimate the tectonic-stratigraphic variability within and between individual delta depocenters, which is yet crucial to document in detail for e.g. analyzing the influence of fault movement on fluid migration or searching for subtle, unconventional tectonic-stratigraphic traps.

**Conclusions**

1. Detailed structural and stratigraphic analysis of a 3D seismic volume of the shallow offshore Niger Delta documents a considerable lateral variability in the style of syn-sedimentary normal faults and associated syn-kinematic strata within one tightly defined deltaic depocenter. This variability is due to the co-existence of tectonically stable, unfaulted areas, regions with significant landward subsidence that are segmented by medium- to large-scale normal faults, and terrain located above a major listric bounding fault that experienced major subsidence on both landward and seaward sides of a kilometer-scale rollover anticline. Isopach maps document that least sediment accumulated on the stable, unfaulted terrain, more in the areas affected by medium- to large-scale faults, and most on both sides of the major deltaic rollover.

2. The study area further exhibits a significant temporal variation in faulting during the studied interval that is expressed by the initiation, growth, decline and cessation of individual faults or fault segments. Maximum changes in stratal displacement and fault-length development are documented to occur primarily during the early growth phase of the studied faults. Once mature,
most faults maintain their active length and displacement pattern with little variation unless linking with neighboring faults into extensive, multi-segment fault systems.

3. The studied part of the Niger Delta is unique in that it exhibits at times a contemporaneous progression and backstepping of growth faults bounding one deltaic depocenter. This structural configuration is interpreted to reflect the sustained activity of mature faults feeding back into sedimentary processes in form of a cause-and-effect loop; this late-stage fault activity records - on a local scale - a deviation of the gross correlation between sediment loading and fault activity. It can be thus documented that although on a large scale an apparent correlation with sediment loading exists, deltaic fault growth remains an process that may act out of sequence, irrespective of the regional sedimentary trend. The awareness of such a potentially complex history of deltaic faults is e.g. important for fluid migration studies that rely on accurate fault-movement predictions and facies-juxtaposition analyses.

4. The development of local depositional sinks due to late-stage faulting can produce sedimentary patterns within a delta that oppose regional trends. This observation indicates that sedimentary facies predictions based on system-wide, generalized depositional models are likely to overlook a significant part of the sedimentary detail stored in deltas, possibly including important occurrences of reservoir facies.
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References


Chapter 2: Normal fault segmentation, lateral linkage, reactivation and the effects on the geometry of hanging-wall sedimentary units on a deltaic setting, Niger Delta

Abstract

Three dimensional seismic-reflection data from the western Niger Delta were used to investigate the progressive segmentation and linkage of a syn-sedimentary normal fault array and to estimate the influence of the pre-existing normal fault on the geometry and growth of both younger faults and the hanging-wall sedimentary units. The nucleation, growth and linkage of a large, regional (seaward-dipping) deltaic fault system were analyzed on reflectivity time-/horizon slices and vertical seismic sections. In the deep subsurface, the studied master fault consists of two segments that grew through time into a single fault by lateral tip propagation, to reach finally a maximum of about 15 km in length. After reaching its maximum extent, the activity along the deltaic fault system decayed non-uniformly through time. Subsequent sedimentation in the study area generated new fault arrays at stratal levels above the master fault. The analysis of time slices of the hanging-wall sedimentary units shows two different processes of vertical linkage above the northwestern (NW) and southeastern (SE) segments of the deep-seated master fault. The NW segment links vertically to a fault initiating contemporaneously to the activity of the fault segment, whereas the vertical fault linkage in the SE segment occurred only after the quiescence of the underlying master fault. Here, the pre-existing older fault segment linked vertically to several younger faults at different times, recurrently reactivating the deep-seated master fault. The results of this work suggest that although kilometer-scale multi-segmented deltaic faults can develop and grow as a single
fault system after lateral segment linkage their pre-existing segments may retain individual pre-linkage characteristics. These can be transmitted to younger faults in the overburden. The geological interpretations presented highlight that large deep-rooted structures influence the distribution and geometry of shallow deltaic faults in the overburden ultimately documenting the control of an older structural grain on delta tectonics and the associated syn-tectonic sedimentation in deltas.

**Keywords:** Normal fault segmentation, linkage, fault reactivation, 3D seismic, Niger Delta

**Introduction**

Detailed analyses of the sedimentary units on the hanging-wall side of large deltaic faults can be used to reveal the spatial and temporal segmentation and linkage pattern of an array of syn-sedimentary normal faults. Normal fault segmentation, linkage and growth have been studied previously in various scales and settings using outcrop data (Cartwright et al., 1995, Schlische and Anders, 1996, McClay et al., 1998, Gupta et al., 1999, Acocella et al., 2000), seismic studies (Petersen et al., 1992, Mansfield and Cartwright, 1996, Morley, 1999, McLeod et al., 2000, Dawers and Underhill, 2000, Contreras et al., 2000, Meyer et al., 2002, Nicol et al., 2005, Baudon and Cartwright, 2008, Dutton and Trudgill, 2009, Frankowicz and McClay, 2010, Giba et al., 2012, Fazli Khani and Back, 2012) and also numerical and analogue modeling (Childs et al., 1993, Gupta et al., 1998, Mansfield and Cartwright, 2001, Hus et al., 2005, Henza et al., 2011). In deltaic settings, the progradation of the sedimentary wedge can be seen as a primary control on fault initiation and development (Schlische, 1991, Gawthorpe et al., 1994, Childs et al., 1995, Meyer et al., 2002, Childs et al., 2003, Fazli Khani and Back, 2012). Here, isolated small-scale faults commonly grow by the process of radial tip propagation, and individual faults may link laterally as well as vertically (Cartwright et al., 1995, Walsh et al., 2003). In many deltas, the
depositional record of the hanging-wall side of faults forms both, before and after the linkage of two fault segments, and this stratal architecture can thus reflect a pre-linkage and post-linkage sediment-accumulation pattern. In the studied setting, syn-sedimentary deformation processes are active throughout the delta evolution, and consequently offer the opportunity for an integrated analysis of sedimentary and tectonic processes. This study now combines the interpretation of vertical seismic-reflection sections and time-/horizon-slice data to identify and map faults, fault segments, lateral and vertical fault-linkage patterns as well as evidence for fault reactivation through time with the analysis of the hanging-wall sedimentary record of a major fault-bound deltaic depocentre. The 3D seismic interpretations and results presented attempt to highlight the role of a pre-existing multi-segmented master-fault on the development of younger syn-sedimentary deltaic faults in the overburden, focusing in particular on the nucleation, growth and the vertical and lateral linkage between individual deltaic faults. An increased understanding of such tectonic processes is particularly important for estimating the influence of fault activity on hydrocarbon migration, or the discovery of yet unrecognized, subtle fault-controlled hanging-wall reservoirs.

Figure 2-1: a) Location of the study area in the western offshore shelf area of the Niger Delta, Nigeria. b) Horizon interpretation overlain by coherency attribute signature showing the structural patterns in the study area (top) and the structural interpretation of the same horizon (bottom). Dotted lines show the location of vertical seismic cross sections in figures 2-2, 2-3, 2-4 and 2-5.
Datasets and Methods

The 3D seismic-reflection data used for this study are from the uppermost 4 km of a 400-km² survey area in the coastal zone of the western Niger Delta (Fig. 2-1a). The seismic-reflection data have been processed using pre-stack time migration, and coherency volumes were derived from the reflectivity data using a semblance algorithm that highlights lateral amplitude variations between adjacent seismic traces (e.g. Fig. 2-1b). The detailed mapping and analysis of faults in the seismic dataset was based on interpreting a combination of vertical reflectivity sections of varying orientation together with time and horizon slices in reflectivity and coherency display.

Figure 2-2: Vertical seismic section shows the structural patterns in the northwestern edge of the study area. Note the presence of Counter Regional Fault (CRF) in this area; this fault stores thick sediments on its hanging-wall side below the oldest mapped horizon H. See figure 2-1 for the location.
Figure 2-1b shows an example of a horizon slice, i.e. a 3D surface overlain by – in this case – an extraction of the coherency volume-attribute. This attribute highlights the occurrence of faults in the study area, emphasizes a series of arcuate-shaped, seaward-dipping, normal deltaic faults that extend laterally over several kilometers. The vertical reflectivity sections of Figures 2-2 to 2-5 illustrate the relation between the fault development and the stratigraphy: most faults of the study area show a syn-sedimentary growth signature i.e. comprise thickened or additional sedimentary units on their respective downthrown sides.

Figure 2-3: Reflectivity seismic section through the central part of the study area illustrating the development of wedge shaped sedimentary units and several sub-parallel normal listric faults. The central part of the study area is characterized by presence of faults FX and FY generating a graben structure. See figure 2-1 for the location of cross-section.
The uncertainty of seismic-stratigraphic correlations across the syn-sedimentary deltaic faults of the study area was minimized by a consequent interpretation of the 3D-seismic facies pattern on series of successive reflectivity and coherency horizon-slices (sensu Back et al., 2006), tied at well locations to wireline-facies interpretations (Figs. 2-2 to 2-5; horizons labeled A to L from top to bottom). Seismic-based horizon interpretations were converted to gridded surfaces to provide time-structure data used for thickness measurements in the time domain (TWT thickness). Horizon- and time-slices in coherency and reflectivity display were finally used at all interpretation levels to visualize and analyze the studied faults and their hanging-wall sedimentary record in detail at different stratigraphic levels.

**Structural framework of the study area**

The area of investigation is located in the extensional structural belt (Doust and Omatsola, 1989, Damuth, 1994, Hooper et al., 2002) of the western Niger Delta (Fig. 2-1a). Neogene sediment progradation caused the initiation of gravity-driven deltaic faults and the generation of local mini-basins on the hanging-wall side of major deltaic growth faults (Thorsen, 1963, Bruce, 1983, McCulloh 1988, Lundin, 1992, Cartwright et al., 1998, Jackson, and Larsen, 2009). Figure 2-1b illustrates the major bounding faults (faults F1 to F10) of the study area at horizon level C, and several of the ubiquitous secondary faults. Figures 2-2 to 2-5 show that most of the large-scale faults are associated with wedge shaped reflector packages that either thicken towards the fault surface or exhibit additional reflections on the downthrown sides (Pochat et al., 2004, Back et al., 2005, Back et al., 2006, Jackson, and Larsen, 2009, Fazli Khani and Back, 2012). The principal bounding faults are listric (Figs. 2-2 to 2-5) and strike NW-SE. Major rollover systems with collapsed crests trend in a similar NW-SE orientation (Fig. 2-1b). The multitude of collapse faults at the rollover crests accommodate a large amount of the tectonic deformation on the hanging-wall side of the main bounding growth faults.
Figure 2-4: Vertical seismic section highlighting the rollover anticline and collapse graben faults in the southeastern part of the study area. At the subsurface fault FZ displaces the footwall sedimentary units of fault FXSE. See the figure 2-9 for more details on the structural and sedimentary patterns and figure 2-1 for the location.

The main seismic interpretation target of this study is the subsurface of the central seismic survey area (Figs. 2-1b, 2-3, 2-4) that is characterized by several sub-parallel, kilometer-scale basinward dipping normal faults. These dominantly arcuate faults all show a syn-sedimentary growth on their hanging-wall sides. Figure 2-2 shows the presence of faults CRF, F1NW, F2 and F3 in the northwest of the study area. The counter-regional fault (CRF) is located in the deeper subsurface in the northeast of the dataset beneath fault F3 (Fig. 2-2).
Further basinwards (Figs. 2-1b, 2-2), the northwestern segment of fault F1 (F1\textsubscript{NW}, 10 km length) displaces the sedimentary succession between horizons G and C up to 1100 ms (TWT). Fault F2 joins fault F1 at its SE termination (Fig. 2-1b) dipping basinward displacing the footwall strata of fault F1\textsubscript{NW} (Figs. 2-1b, 2-2). The northwestern tip of faults F1\textsubscript{NW} and F2 is beyond the limit of the study area. Fault F3 is located in the footwall of fault F2 and is only slightly listric. This fault displaces the studied sedimentary succession by ca. 200 ms (TWT). In SE direction, fault F3 terminates at the intersection with fault F5 (Fig. 2-1b).

**Figure 2-5:** Northwest to southeast seismic section on top and its interpretation below. This section is perpendicular to the seismic sections presented on figures 2-2, 2-3 and 2-4, demonstrating the interrelation between fault F5, CRF and fault FX. See figure 2-2 for location.
The central and southeastern parts of the 3D seismic survey exhibit several multi-segmented, kilometer-scale normal faults in the E and W (Figs. 2-2 and 2-3), as well as two kilometer-scale rollover anticlines, each with a collapsed crest (Fig. 2-4). The main rollover structure extends over more than 10 km in length in NW-SE direction (Fig. 2-1b) and numerous synthetic and antithetic normal faults accommodate the collapse of the anticline crest. Figure 2-3 shows the vertically segmented fault F1_{SE} (SE segment of fault F1) basinward in the SW part of the study area (see figure 2-1b for the fault location). The separation point between the two segments of Fault F1 (F1_{NW} and F1_{SE}) is the intersection with faults F2 and F4 (Fig. 2-1b). In contrast to the rather uniform fault segment F1_{NW}, fault segment F1_{SE} consist of several sub-segments each of a few kilometers length which amounts in total to about 15 km of length (Fig. 2-1b).

Further towards the centre of the study area, fault F4 terminates in the W against fault F1, and dies out towards the SE in the major rollover seaward direction of Fault F6. A maximum displacement of ca. 800 ms (TWT) is observed on its western termination at the junction with fault F1. Fault F5 of the central study area is almost E-W oriented (Fig. 2-1b) displacing the footwall of fault F4 (Figs. 2-3 and 2-5). Faults F6 and F7 in the very E of the survey are both basinward dipping listric faults that bound the rollover structure at the centre of study area (Figs. 2-1b and 2-4).

Below depths of ca. 2500 ms (TWT), the seismic data shows further faults or fault segments that appear in places as the root of some of the overburden faults, but are in other parts of the data detached from these. These deep seated structures are labeled faults FX_{NW}, FX_{SE}, FY and FZ (Figs. 2-3, 2-4 and 2-5). Figure 2-6 is a reflectivity time-slice at a depth of 3000 ms (TWT) that illustrates the map-view geometry, lateral continuity and multi-segmented nature of these deep-seated faults, and their relationship to the reflection signature of the sedimentary fill in their respective hanging walls.
**Fault description**

In the north of the study area, the deep-seated landward-dipping fault CRF is the main structural element in depths below 2500 ms (TWT; Fig. 2-2). This counter-regional fault extends laterally over a length of ca. 10 km. The sedimentary units in its hanging wall thicken in a lens shape towards the fault plane, witnessing the syn-sedimentary development of fault CRF.

Deep-seated fault FX is located in the central part of the study area and trends from the NW to the SE (Figs. 2-6 and 2-7). Fault FX attains a maximum horizontal length of 15 kilometers. In plan view, fault FX is not linear but of irregular to an arcuate shape suggesting the interconnection of several fault segments to build this multi-segment fault. However, fault FX appears nearly planar in vertical section (Figs. 2-3 and 2-4). It offsets hanging-wall sediments to the southwest; the footwall succession is in many places (Fig. 2-4).

**Figure 2-6:** The reflectivity time-slice map of -3000 ms (TWT) on the left and the interpretation of faults and horizons on the right side. Reflectivity deep map shows the studied faults CRF, FX, FZ and FY and interpreted horizons in the study area (horizons G to L, young to old respectively). On the map view, studied faults are interpreted at the contact location between continuous signature of peaks and troughs and the area of chaotic reflectors. Interpreted horizons are mapped on the reflectivity time slice showing present day geometry of hanging-wall horizons.
The oldest horizon on the hanging-wall side of fault FX is horizon K (Fig. 2-7) above basal horizon L. Fault FX vanishes within the stratigraphic interval below Horizon L (Fig. 2-3, 2-4 and 2-5).

Figure 2-7: Cross line subparallel to the studied fault FX showing the geometry of fault and hanging-wall sediments. a) Studied fault FX and both segment FXNW and segment FXSE and the geometry of sediments on the hanging-wall, b) Uninterpreted cross section and c) structural and sedimentary horizon interpretation. An erosional surface is interpreted within the sedimentary units between horizons I and J. Note the presence of fault F5 in upward termination of segment FXNW.
Fault-segment $FX_{NW}$ forms the NW part of fault FX and was identified firstly on the reflectivity time slice map at -3225 ms (TWT). Figure 5a shows the arcuate shape of this segment with about 3.5 km in length on map view. An antithetic normal fault, Fault FY is displacing the hanging-wall strata of fault $FX_{NW}$ forming a local fault-bound depocentre (Figs. 2-8a and b). The presence of the counter regional fault CRF on the footwall of fault segment $FX_{NW}$ is also shown. Seawards to the southwest, the sedimentary units located on the hanging-wall of segment $FX_{NW}$ are displaced by normal fault F4 (Fig. 2-8b). The younger horizons in the hanging-wall of fault segment $FX_{NW}$ are deformed by fault F5 at the level of horizon G (Figs. 2-7 and 2-8b).

The oldest horizons mapped on the hanging-wall of segment $FX_{NW}$ are horizons K and L close to the downward termination of both faults $FX_{NW}$ and FY (Fig. 2-8). Both horizons extend further basinward into the footwall of fault FY, but are lacking in landward direction on the footwall of fault $FX_{NW}$ (Fig. 2-8b). Figure 2-8 further shows the strongly landward dipping reflection signature of the hanging-wall strata of fault $FX_{NW}$, exhibiting in map view a series of curved reflections that bend towards the fault plane laterally creating a synformal depression (Fig. 2-8a).

The SE fault segment $FX_{SE}$ (also see Figs. 2-2 to 2-6) is crossed by the time slice of Figure 2-8a near its lower tip. In map view, the trace of fault segment $FX_{SE}$ trace is not entirely linear but less arcuate than in the NW (Figs. 2-6 and 2-7). Above horizon H, fault segment $FX_{SE}$ is linked with fault F6 (Fig. 2-8c), while its footwall sediments are displaced by fault F7 and a minor fault (Fig. 2-8c). As for fault segment $FX_{NW}$, the oldest horizons on the hanging-wall of segment $FX_{SE}$ are horizons K and L (Fig. 2-8c). The hanging-wall sediments of fault segment $FX_{SE}$ are not planar as their counterparts on the hanging-wall of segment $FX_{NW}$ and show an antiformal geometry (Figs. 2-8a, 5).
Deep-seated fault Z is located at the southern edge of the study area (Fig. 2-6) on the footwall of fault segment FX\textsubscript{SE}. Fault Z is about 7.5 km in length on the time-slice section at -3000 ms (TWT).

**Figure 2-8:** Structural geometry and hanging-wall sedimentary architecture of segments FX\textsubscript{NW} and FX\textsubscript{SE} shown in this figure. a) seismic reflectivity map at depth of −3125 ms (TWT) illustrating segments FX\textsubscript{NW} and FX\textsubscript{SE} highlighting the existence of fault FY on the hanging-wall of segment FX\textsubscript{NW}. Sediments on the hanging-wall of segment FX\textsubscript{NW} are synform. b) Vertical seismic section showing the hanging-wall and footwall structural patterns of segment FX\textsubscript{NW}. c) Is demonstrating segment FX\textsubscript{SE} and its hanging-wall mapped horizons. The sedimentary units in the hanging-wall of segment FX\textsubscript{SE} are wedge shape and showing an antiform geometry.
In the study area, fault FZ strikes approximately N-S, which is oblique to the general NW-SE trend in the study area (Figs. 2-6 and 2-7a). The vertical reflectivity section of Figure 2-9a shows the downward tip of fault FZ in chaotic reflections that is confirmed by the vertical seismic cross-section of Figure 2-9b (see Fig. 2-5 for location). The hanging-wall strata of fault FZ are highly deformed and displaced in the lower part of the section by fault segment FX_{SE} (Fig. 2-9a) and further to the top by numerous secondary faults.

Figure 2-9: Structural and sedimentary architecture of southeastern part of the study area, on the left side uninterpreted cross section and on the right side interpreted cross section. a) Inline section showing deeply sited fault FZ located on the footwall side of segment FX_{SE}. b) Cross line section perpendicular to the fault FZ shows two segments of fault FZ enclosed by an erosional surface. Note the absence of faults F6, F7 and F8 on upward termination of fault FZ.

Fault FZ is almost horizontal on the vertical seismic section of Figure 2-9a; towards its upper tip, the fault seems to be linked to the faults F7 and F8. However, Figure 2-9b further shows the linkage of fault FZ to a single fault system at depth that is labeled as the root of faults F6, F7 and F8. Since the vertical section of Figure 3a is oblique to fault FZ, it does not clearly differentiate fault FZ from the root of faults F6, F7 and F8. On Figure 6b however, fault FZ shows a
vertically segmented geometry that is reactivated by a later activity on faults F6, F7 and F8. To the top, the upward termination of fault FZ can interpret to occur below horizon H at a prominent erosional surface (Fig. 2-9b). To the northwest, this erosional surface is displaced by fault FX (segment FX_{SE}, Fig. 2-9b).

**Structural evolution of NW part of study area**

Figure 2-10 summarizes the fault activity through time in the NW part of the study area, with the structural development strongly controlled by the presence of a deep-seated counter regional growth fault. This fault formed a mini basin on its landward hanging-wall side that stored sedimentary beds of a thickness of about 1200 ms (TWT) before the development of horizon H (and most likely I, J, K, L as well; see Fig. 2-4). Fault CRF was most likely the first active structure in the study area (Fig. 2-10a). Its hanging-wall sedimentary units show a lens-shaped geometry thickening into the fault plane confirming the syn-sedimentary activity of the fault. On Figure 2-6, the hanging-wall sedimentary units of CRF show a semicircular shape and the units become younger in age close to the fault plane. This overall concave geometry of hanging-wall sediments reflects the downward movement along the fault surface with the offset maximum at the fault centre, decreasing laterally towards the fault tips. The activity of fault FX_{NW} on the footwall of CRF started probably just before the accumulation of marker horizons L to H, and continued for a considerable time (probably until the development of horizon G) which is expressed by the significant tilting and thickening of the hanging-wall sedimentary units into the fault plane (Figs. 2-10, b and c). The seaward progradation of the deltaic sedimentary wedge caused the initiation of the fault F5 on the footwall side of basal fault CRF, forming a new depositional mini basin in this area storing more than 400 ms (TWT) of sediment between horizon G and H (Figs. 2-8b and 2-11). Though time, fault F5 displaces the footwall strata of fault CRF finally cutting through its hanging-wall area around the southeastern tip of fault CRF (Fig. 2-10, c and d).
Figure 2-10: Cartoon summarizing structural development on the northwestern part of the study area starting from old at the bottom to young to the top. The stepwise structural reconstruction is based on observation and interpretation of seismic cross section and time slice maps.
Stratigraphic thickness maps (TWT) between horizon G and horizon H (Fig. 2-11a) and between horizon F and horizon G (Fig. 2-11b) suggest the initiation of fault F5 after the formation of Horizon G. This interpretation is supported by the observation of a shift of the primary depocentre from the hanging-wall of fault CRF (between horizons H and G; Fig. 2-11a) to the hanging-wall side of the fault F5 (between horizons G and F; Fig. 2-11b).

**Figure 2-11:** a) True stratigraphic thickness map between successive horizons G and H showing the thickest sediments on the hanging-wall of fault CRF, and b) true stratigraphic thickness map between successive horizons F and G that shows the thickest sediments now shifted basinward from hanging-wall of fault CRF to the hanging-wall of fault F5. The analysis of sediment thickness maps reveals the exact initiation time of fault F5. Thickness of sediments are measured and presented in this figure in two way travel time (ms).
The ongoing activity of fault F5 (Fig. 2-10e) finally controls the overall landward tilting of its hanging wall, which not only affects sedimentation but also the development of structures such as fault FY that is near vertical at the present day geometry (Figs. 2-3, 2-8b), being rotated to this position from an originally more gentle dip (Figs. 2-10c, d). The youngest faults that initiate in the NW part of study area are regional faults F4 and F1 located seaward of fault F5 (Figs. 2-10e and 2-11b).

**Structural evolution of the SE part of study area**

Figure 2-12 summarizes the fault development in the SE of the study area showing the development of a succession of laterally and vertically segmented and linked networks of faults. In the very SE edge of the study area, the initial fault FZ displaces sedimentary units older than basal horizon L towards the W; this fault orientation is in contrast to the general SW displacement direction observed across the remaining part of the survey area (Figs. 2-6, 2-9b, 2-12a). The geometry of the hanging-wall strata of deep-seated fault FZ is consistent with an interpretation of an original fault strike NE-SW displacing the sedimentary succession into a NW direction (Fig. 2-12a). An erosional surface affecting both hanging-wall and footwall of fault FZ is documented on the vertical seismic section of Figure 2-9b. This surface can be hardly recognized in inline direction (Fig. 2-9a), probably because of subsequent faulting and the stratal deformation above caused by younger faults. In the following, fault segment FX\textsubscript{se}, initiated on the hanging wall of fault FZ. Fault segment FX\textsubscript{se} strikes NW-SE, displacing sedimentary strata basinward towards the SW (Figs. 2-9, 2-12b and c). Younger sediments (horizons I, H and G) on the hanging-wall of fault segment FX\textsubscript{se} indicate the post-erosional initiation and activity of this fault segment. The lateral growth of fault segments FX\textsubscript{se} and FX\textsubscript{nw} approaching each other created the elongate, multisegmented fault FX in the centre of the study area.
Figure 2-12: Cartoon showing structural patterns on the southeastern part of the study area. The stepwise structural reconstruction is based on observation and interpretation of seismic cross section and time slice maps.

e) This cartoon shows the initiation of fault F7 on the footwall of fault F6. The structural development in the SE part of study area highlights the landward backstepping migration of faults.

d) Fault F6 is active on the footwall side of segment FXse in landward direction. Fault F6 is linked vertically to the segment FXse in some places. Fault FZ is reactivated also by fault F6.

c) Segment FXse is now active displacing hanging wall sediments of fault FZ in basinward direction. This segment strikes in NW-SE direction rather oblique to Fault FZ. Fault FZ is inactive at this time and buried under footwall sediments of segment FXse.

b) An erosional surface indicated the latest activity on fault FZ. In the northwestern edge, the location of segment FXse is indicated by dotted line.

a) Fault FZ strikes in NE-SW direction displacing sediments to northwest. Fault FZ is bifurcated in upward direction showing syn-sedimentary activities.
Immediately thereafter, the main fault activity in the SE part of the study area switched landwards to the initiation of the kilometer-scale normal fault F6 (Fig. 2-12d). Fault F6 developed a concave shape, striking in a NW-SE direction and displacing sedimentary units of a thickness of over 1000 ms (TWT) to the SW (Fig. 2-12d). During its development, fault F6 affects both fault FX and fault FZ by partly reactivating the root of a fault growing laterally into the basal section of former fault FZ (Figs. 2-12c, d). This period of intense fault growth and linkage is succeeded by the initiation of landward fault F7 in the footwall of fault F6 (Fig. 2-12e). Fault F7 is semi-parallel to the fault F6 displacing its hanging wall in a SW direction.

This landward fault migration is finally followed by a further backstepping of bounding faults during the initiation of fault F8 in the footwall of fault F7 (Fig. 2-12e). On the map view of Figure 1b, fault F8 links to fault F7 at its NW tip, bifurcating fault F7 in a landward direction. At depth, faults F6, F7 and F8 seem to join in one common, flat-lying root partly incorporating former deep-seated fault FZ, suggesting a downward growth and linkage of these backstepping overburden faults (Figs. 2-2, 2-3, 2-4, 2-5, 2-12d and e).

Discussion

In the study area, fault segments FX_{SE} and FX_{NW} are interpreted to have grown by tip propagation and lateral linkage (Mansfield and Cartwright, 2001, Young et al. 2001, Jackson et al. 2002, Childs et al. 2003) to initiate the elongate, multi-segmented fault FX. The two fault segments show in the early stages of development (horizon levels K and L) a non-uniform fault activity that is documented by a differential hanging-wall sedimentary record and stratal geometry (Figs. 2-8, 2-13 and 2-14). The sediments on the hanging-wall of segment FX_{NW} are rather planar, dip towards the fault surface and show only small thickness variations (about 60 ms TWT, Figure 2-13), suggesting the contemporaneous activity of fault FY on the hanging-wall side forming with
segment FX_{NW} a small half-graben depocentre. In contrast, the stratal architecture on the hanging-wall side of segment FX_{SE} shows a considerable bending creating an antiform geometry.

Figure 2-13: TWT thickness map perpendicular to successive horizons G and horizon K on the hanging wall side of fault FX. TWT thickness maps indicate dissimilar fault activity and hanging wall sedimentary record of two segments of a single fault after linkage (see the text for more details).

The associated reflector packages are wedge-shaped and thicken considerably into the fault plane (about 180 ms TWT of thickness difference, Figure 2-13).

At horizon level J, fault segments FX_{SE} and FX_{NW} linked and started to grow as a single fault, but both fault segments maintained some of their pre-linkage characteristics. Only after the cessation of all activity along fault FX (above horizon level G, younger faults (e.g. faults F5, F6, F7, F51,
F61 and F71) modified the pre-existing fault geometry and the hanging-wall sedimentary record (Fig. 2-14). Within the study area, fault F5 initiated after the deposition of horizon G on top of fault segment FX_{NW} (Figs. 2-10 and 2-11). However, Figures 2-7 and 2-8a indicate that it is difficult to define the exact location of the upper fault tip in seismic section. The analysis of the hanging-wall sedimentary thickness both before and after the initiation of fault F5 (Figs. 2-11, 2-13) suggests a contemporaneous fault activity on fault segment FX_{NW} and fault F5, and thus no quiescence on the fault segment FX_{NW} prior to the vertical linkage to fault F5.

Figure 2-14: Surface depth map of horizon K showing the different geometries of the hanging wall sedimentary units of segments FX_{NW} and FX_{SE} after linkage. Depth vs. geometry plots (across and parallel to the fault plane) illustrates how vertical linkage and reactivation modifies the geometry of hanging wall sediments (see the text for more details).

In the southeastern part of the study area, sediments on the hanging-wall of segment FX_{SE} are slightly bent creating an antiform geometry (Figs. 2-8, Fig. 2-13). Fault segment FX_{SE} is linked in a
topward direction to a series of basinward dipping normal faults. At the northwestern end of fault segment FX_{SE} close to the linkage point to segment FX_{NW}, at least four faults can be mapped on the upper tip of fault segment FX_{SE} (Fig. 2-15, seismic section B). The geometry of these faults suggests an upward bifurcation of fault segment FX_{SE} towards faults F6, F51, F5 and F7. In such locations it is rather difficult to distinguish which fault might have acted finally as the upward continuation of fault FX. Seismic section C of Figure 2-15 shows furthermore the initiation of fault branch F61 as a splay or possible bifurcation continuing from the upper tip of fault segment FX_{SE}, and the adjacent faults F6, F51 and F7 that are interpreted to have successively stepped back into the former footwall terrain of the deep-seated fault FX. Seismic sections D, E and F (Fig. 2-15), finally document the spatial arrangement and partial linkage of fault segment FX_{SE} with faults F6, F7, F8, F61 and F71. All of these faults are different in scale and their movement history, documenting that fault segment FX_{SE} is vertically attached and linked to more than one fault at different time steps. This spatial arrangement strongly contrasts that of the fault segment FX_{NW}. In addition, at the time of deposition of horizon G fault segment FX_{SE} seems to have been inactive. This is the opposite of the ongoing tectonic activity along fault segment FX_{NW}.

The detailed analysis of the diverse tectonic development of the faults above the NW and SE segments of deep-seated fault FX is important in that it influenced the geometry and internal architecture of the sedimentary succession stored in individual fault-controlled depocentres of the overburden: the reflectivity time-slices of figures 2-6, 2-7 and 2-8 show common concentric reflectivity signatures on the respective hanging-walls of faults CRF, F2, and fault segments FX_{NW} and FX_{SE}. This pattern witnesses a general younging of sediments towards the fault plane related to the development of synformal depressions on the hanging-wall side of these bounding faults.
Figure 2-15: Series of inline cross section through the study area (sections A to F) showing vertical linkage and reactivation of fault FZ, segment FXNW and segment FXSE. Reflectivity time-slice map illustrates studied fault FZ and both segments FXNW and FXSE on plan view. Note the dotted part on fault F6 is the projection of this fault on time-slice maps.
The pronounced curvature of reflections that starts at the fault tips and moves progressively towards the fault plane documents that the location of maximum displacement on the respective fault planes was at the center of the faults, defining the spot that accumulated the thickest sedimentary record (Fig. 2-13). This rather simple relationship between sedimentation and the early-stage movement of the deep-seated faults was subsequently modified by the later-stage deformation of the hanging-wall of fault FX, particularly by the initiation and activity of the faults F4, F5, F6 and F7. Figures 2-13 and 2-14 documents that the two deformation phases proposed, (1) the deformation related to the activity of fault FX and (2) the deformation linked to the development and growth of faults F5, F6 and F7 can be interpreted from thickness data between horizon K and horizon G. The depth map of horizon K (Fig. 2-14) finally highlights the structural diversity of the study area related to the modifications of the original hanging-wall geometry of fault segments FXNW and FXSE by the development of the younger faults F5, F6 and F7. The geometry of horizon K at segment FXNW documents the development of a classic synformal depocentre that preserved the original depositional geometry in this area. In contrast, above fault segment FXSE, particularly the younger faults F6, F7 and finally F8 (Fig. 2-14) have significantly modified the original synformal architecture of the fault-controlled depocentre to a later-stage antiformal structure; this observation emphasizes the pronounced lateral and temporal variability of faulting and depocentre development above a deep-seated, multi-segmented fault system that seems to transmit individual characteristics of its different segments to younger structures in the overburden.

**Conclusion**

The interpretation of three-dimensional seismic-reflection data from the western Niger Delta documents the initiation, growth and decay of synsedimentary deltaic faults at various depth levels. Differential fault activity during deltaic sedimentation is observed to create a maximum of
local accommodation that correlates with the location of maximum displacement in the central part of the faults, which decreases laterally towards the fault tips. The accommodation variation and the associated thickness of syn-tectonic delta sediments may vary depending on the fault activity by the evolution of local fault-controlled depocentres. The tectonic-stratigraphic analyses presented can be used in other deltaic settings to locate areas of maximum and minimum fault displacement.

A key observation of this study is that deep-seated, multi-segmented deltaic growth faults can link vertically to several faults of various scale through time. It is further documented that the growth and linkage history of two segments of one fault, even if temporarily acting as one multi-segment structure, may be very dissimilar. Seismic-reflection and isopach-map analysis show that at the time of initiation and vertical linkage of an overburden fault to a deep-seated fault, one fault segment was active whilst another was inactive. It can be furthermore documented that the formerly inactive segmented of the deep-seated fault was later reactivated and passively linked and re-used by at least three kilometer-scale overburden faults, each of them with a different initiation time. These observations indicate that although two segments of one fault grow laterally into another and act at certain times as one single fault, these segments may be linked, partly re-used or reactivated by different faults at different times preserving parts of their former independence.

The structural and stratigraphic interpretation results of this study finally document a correlation of the deltaic depositional pattern with the tectonic development by the fault-control of the location and persistence of individual deltaic depocentres. However, late-stage faulting in the deltaic overburden has a high potential to destroy the stratigraphic imprint of earlier, deeper seated faulting. The recognition of such a complex fault-stratigraphy relationship is particularly
important for estimating the influence of younger fault movement on hydrocarbon pathways or
the discovery of subtle fault-controlled hanging-wall reservoirs.

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Chapter 3: The influence of sedimentary loading on faulting and rollover development in deltas

Abstract

Three-dimensional seismic data and wireline logs from the western Niger Delta were analyzed to reveal the sedimentary and tectonic history of a major deltaic growth-fault depocenter comprising a kilometer-scale rollover anticline. The seismic units of the rollover show a non-uniform thickness distribution with their respective maximum near the main bounding growth-fault on the landward side of the system. This wedge-shaped sediment-storage architecture ultimately reflects the non-uniform creation of accommodation space in the study area that was controlled by 1) the differential compaction of the hanging-wall and footwall strata, 2) the lateral variation of fault-induced tectonic subsidence above the listric master fault, and possibly 3) local subsidence related to the subsurface movement of mobile shale reacting to loading and buoyancy. A sequential three-dimensional decompaction of the interpreted deltaic rollover units allowed to reconstruct and measure the compaction development of the rollover succession through time, documenting that sediment compaction contributed per depositional interval to between 25 and 35% of the generation of depositional space subsequently filled by deltaic sediments. The incremental decompaction of sedimentary units was further used to quantify the cumulative amount of accommodation space at and around the studied rollover that was created by fault movement, shale withdrawal, regional tectonic subsidence, isostasy and changes in sea level. If data on the regional subsidence and eustasy are available, the contribution of these basinwide controls to the generation of depositional space can be subtracted from the cumulative accommodation
balance, which ultimately quantifies the amount of space for sediments to accumulate created by fault movement or shale withdrawal. This observation is important in that it implies that background knowledge on subsidence, stratigraphic age and sea-level changes allows to reconstruct and quantify fault movement in syn-tectonic deltaic growth successions, and this solely based on hanging-wall isopach trends independent of footwall information.

**Keywords:** Sedimentary loading, differential compaction, rollover, Niger Delta

**Introduction**

The development of rollover anticlines is a common phenomenon on the hanging-wall side of kilometer-scale syn-sedimentary normal faults growth faults in deltas. The origin and the shape of rollover anticlines has been the subject of many previous investigations (e.g. Hamblin, 1965; Cloos, 1968; Bruce, 1973; Gibbs, 1983; Shelton, 1984; White et al., 1986; McClay, 1990; Dula, 1991; Xiao and Suppe, 1992; Withjack et al., 1995; Mauduit and Brun, 1998; McClay, 1998; Imber et al., 2003; Withjack and Schlische, 2006; Brun and Mauduit, 2008) that documented and analyzed the key controls for rollover development. These include e.g. the shape of the bounding fault (White et al., 1986; Groshong, 1989; Dula, 1991), the amount of syn- and post-depositional slip on the bounding fault (Xiao and Suppe, 1992), the respective hanging-wall and footwall deformation mechanism (Imber et al., 2003; Brun and Mauduit, 2008) and the rate of syn-tectonic sedimentation and compaction (Xiao and Suppe, 1992). However, since tectonic and sedimentary processes act contemporaneously during rollover formation it remains difficult to determine whether depositional or structural processes exert the primary influence on the development of rollover anticlines.
Figure 3-1: Sketch illustrating, A) wedge-shaped sediments on the hanging wall (HW) of a listric fault recording an accommodation maximum near the fault plane due to tectonic displacement, and B) the development of thicker hanging-wall deposits in the vicinity of the fault plane due to differential loading and compaction. FW: footwall.

Rollover anticlines in deltas most often form asymmetrical antiforms in which the thickness of sedimentary units increases towards a basinward-dipping (regional) or landward-dipping (counter-regional) master fault. This wedge-shaped stratal geometry reflects differential accommodation development and associated differential sediment accumulation on the hanging-wall of the bounding fault, with the maximum of accommodation creation and deposition in the immediate vicinity of the master fault (Fig. 3-1). Control on accommodation creation is provided by fault
growth and the tectonic displacement of pre- and syn-kinematic hanging-wall units (Fig. 3-1A); 
the typical stratigraphic response to this syn-sedimentary faulting is the accumulation of thicker 
beds or of additional layers in the immediate vicinity of the bounding growth fault (e.g. Hodgetts 
et al., 2001; Back et al., 2005, 2006). The differential thickness of the syn-kinematic strata on the 
flanks of rollover anticlines, in turn, causes differential loading of the underlying deltaic substratum, 
with the maximum of the sedimentary load (and therefore compaction below) associated with the 
thickness maximum of the hanging-wall fill (Fig. 3-1B). Such a loading effect must be considered to 
contribute to the differential subsidence of hanging-wall strata and therefore potentially to the 
bending of stratal surfaces, which is a gravity-driven sedimentary effect that has been rarely 
documented or analyzed. The key aim of this work is to quantify and discuss the contribution of 
sedimentary loading to accommodation creation on the flanks of deltaic rollover anticlines, which 
will be exemplarily demonstrated on 3D seismic-reflection data and well information of a kilometer-scale 
rollover system located in the subsurface of the Niger Delta, Nigeria (Fig. 3-2).

Figure 3-2: Approximate location of the study area in the swamp belt of the western Niger delta 
(Nigeria).
Subsurface geology, data and methodology

The Niger Delta is one of the World’s largest Tertiary delta systems, located on the West African continental margin at the apex of the Gulf of Guinea (Fig. 3-2). The delta succession comprises a highly progradational, generally upward-coarsening association of Tertiary clastics up to 12 km thick (Doust and Omatsola, 1989). The delta stratigraphy and structure are intimately related, with the development of each being dependent on the interplay between sediment supply and subsidence (Doust, 1990). The geological analyses presented in this study are based on the interpretation of a pre-stack time migrated 3D seismic-reflection volume of a ca. 400 km² survey area in the coastal-marine transition of the western Niger Delta (Fig. 3-2). The study area is located in the extensional, gravity-driven structural domain of the delta (Doust and Omatsola, 1989; Damuth, 1994; Hooper et al., 2002), in which the progradation of the deltaic sedimentary wedge over basal marine shales caused the formation of numerous kilometre-scale, gravity-driven, syn-sedimentary growth faults (Fig. 3-3; also see Thorsen, 1963; Bruce, 1973; McCulloh, 1988; Lundin, 1992; Cartwright et al., 1998). The northwestern part of the study area is marked by three large-scale, arcuate-shaped, seaward-dipping normal faults (faults 1, 2 and 3) that extend laterally over several kilometers (Fig. 3-3) and displace sedimentary units of Pliocene to recent age by several hundreds of milliseconds TWT (Fig. 3-4 section A). In contrast, the central and southeastern parts of the study area exhibit a structurally complex zone of deltaic rollover (Fig. 3-4 section B; Fig. 3-5 sections C and D) which is bound on its landward side by a series of large, subparallel, seaward-dipping, highly listric deltaic faults.

For a detailed structural interpretation, 3D coherency volumes were derived from the seismic reflectivity data using a semblance algorithm that highlights lateral amplitude variations between adjacent seismic traces.
Figure 3-3: Rollover anticlines I and II in the centre to southeast of the study area, bound on the seaward side by fault 1, in the northwest by listric normal fault 2, and in the east by faults 3 and 4. A) Depth map of Horizon D (overlain by coherency attribute) illustrating structural style and rollover geometry of the study area. Black dots indicate well locations used for the calculation of sand/shale ratios. B) Line drawing of large-scale bounding faults at the edges of study area and small-scale collapse faults formed at the crest of the studied rollover systems. Dashed lines indicate the locations of the vertical reflectivity sections of figures 3-4 and 3-5.
Figure 3-3 for example shows the coherency signature extracted from seismic marker horizon D, emphasising the lateral tectonic framework of the study area that exhibits the southern and central, kilometer-scale, NW-SE trending rollover zone bound by fault 1 on its seaward side, fault 2 in the northwest, and the listric, seaward-dipping normal faults 3 and 4 in the east. Deformation related to the activity of the respective bounding fault system led to the development of a large rollover affecting the central and southeastern study area (rollover anticline I), an older precursor of the main rollover located further to the SW (rollover anticline II). Rollover anticline I is characterized by numerous synthetic and antithetic normal faults that accommodated the collapse of the anticline crest, as is the older, buried rollover anticline II (Figs. 3-3, 3-4 and 3-5).

Figure 3-4: Vertical reflectivity sections and interpretative line drawings illustrating the structural and sedimentary pattern across the study area. The seismic data highlight the presence of listric, synsedimentary normal faults (growth faults) and syn-tectonic sediments (growth strata). Seismic marker horizons A to F and seismic units AB to EF indicated on the sections. Section A shows kilometer-scale growth faults displacing strata in the northwest of the study area. Section B illustrates multi-segmented fault 1 and the presence of a single rollover anticline (rollover I) on the hanging wall of fault 4. See figure 3-3 for the location of the reflectivity sections.
In the study area, syn-kinematic sedimentation during rollover formation resulted in the accumulation of a sedimentary succession characterized by highly variable thicknesses (Figs. 3-4 and 3-5); the observed lateral differences in unit thicknesses must have induced laterally heterogeneous compaction that likely affected the geometric development (i.e. bending) of the kilometre-scale rollover systems I and II. To analyze and quantify the impact of differential sedimentary loading and compaction on rollover development, unit thicknesses were calculated from a depth-converted, survey-wide seismic interpretation framework based on 6 laterally continuous marker horizons named F to A from old to young (Figs. 3-4 and 3-5).

**Figure 3-5:** Seismic reflectivity section C show documenting the existence of two generations of hanging-wall rollovers in the study area. Rollover anticline I is located immediately seaward of bounding fault 4, and relatively young in age as still (active after development of horizon A); rollover anticline II is older in age and ceased activity before the deposition of horizon B.
At well locations, these depth-converted marker horizons served as a reference level for integrating subsurface lithology information into the study (e.g. sand/shale prediction from GR data, see Fig. 3-6). In an initial stratigraphic restoration approach, all mapped sedimentary units were decompacted by removing the interpreted seismic units in incremental steps from top (young) to bottom (old), allowing the underlying rock to decompact stepwise. The 3D decompaction applied was *sensu* Sclater & Christie (1980) using an exponential decay of the porosity with increasing depth, and a porosity-depth coefficient (c-factor). Once the effect of sedimentary loading on the stratal column was corrected, the remnant bending of the respective rollovers at each decompacted target level revealed the effect of either fault-controlled tectonic subsidence or shale withdrawal on stratal bending.

**Seismic Interpretation**

The study area is characterized by four major syn-sedimentary, listric, seaward-dipping (regional) normal faults (faults 1 to 4) that trend from the NW to the SE (Figs. 3-3, 3-4 and 3-5), two kilometer-scale, NW-SE oriented rollover anticlines between faults 1 and 4 (Figs. 3-3 and 3-5) and numerous medium- to small-scale synthetic and antithetic normal faults with a maximum displacement of about 60-70 ms (TWT) in the collapsed crests of the rollovers (Figs. 3-4B and 3-5).

Fault 1 at the southwestern edge of the study area is formed by at least three individual fault segments (Fig. 3-4B) that joined through time to form one interconnected fault system (Fazli Khani and Back, 2012). The maximum displacement of fault 1 is ca. 500 ms (TWT). Fault 2 is an arcuate shaped growth fault on the footwall of fault 1 (Fig. 3-3). Its maximum displacement is around 450 ms (TWT). Fault 3 displaces strata on the footwall of fault 2 with a maximum offset of ca. 900 ms (TWT). Fault 4 is the main bounding fault of the rollover anticline of the central study area; stratal displacement along this fault is difficult to estimate due to data limitation on its
footwall side (Fig. 3-5). Figure 3-5 further documents the presence of two major rollover anticlines in the study area that are sub-parallel to bounding fault 4. The more basinward, SW rollover anticline II is stratigraphically older and ceased activity in the depositional interval between marker horizons D and C (Fig. 3-5).

Rollover anticline I that succeeds in the NE is younger and remained active until shortly after the development of marker horizon A (Fig. 3-4, section B; Fig. 3-5).

**Figure 3-6:** Gamma-ray log signature at selected wells used for the calculation of average sand/shale ratios for the sedimentary units of the study area. The sand/shale ratio presented on the right side column is the average value calculated for each unit. Note the presence of an overpressured basal interval in Well C. See figure 3-3 for the location of the wells.
In the crests of rollover anticlines I and II, arrays of numerous normal faults accommodated the extension associated with the stratal bending of the rollovers, following the general NW-SE anticline trend (Fig. 3-3). The activity of these faults seems to have migrated through time from a broad, outward position on the respective anticline limbs to a successively narrower position near the rollover crests.

Seismic horizons A to F (Figs. 3-4 and 3-5) were mapped on prominent reflections of high lateral continuity, including at faults cross-checks between horizon-slice interpretations (Fig. 3-3; also see Back et al., 2006) and wireline-log data (e.g. Fig. 3-6).

**Figure 3-7:** True stratigraphic thickness of sedimentary unit AB and BC at the compacted state (present day). The thicknesses of the sedimentary units were measured between successive horizon pairs (true stratigraphic thickness). The respective cut-off values for the minimum and maximum thickness of each sedimentary unit are indicated by a horizontal black line.
Subsequently, true stratigraphic thicknesses were measured vertically between successive horizon pairs (Fig. 3-7). To visualize the thickness variation in map view, isopach maps were generated (Fig. 3-8). The six sedimentary units associated were named unit EF, DE, CD, BC, AB and “above HA” from old to young (Figs. 3-4 and 3-5).

**Figure 3-8:** True stratigraphic thickness of the interpreted sedimentary units from old to young. The isopach maps highlight a maximum of sediment stored on the flanks of the studied rollovers I and II, while the record of sediment stored on top of the rollovers is much thinner. Note that the color scales vary between the isopach maps for an optimum thickness-range display.
Basal stratal unit EF shows considerable thickness variations across the study area, with the most prominent relative thickness maximum located on the hanging wall of fault 4 with around 800 meters, and a minimum thickness of 300 meters that is observed at the center of study area (Fig. 3-8). On average, unit EF consists of ca. 50 % sandstone and shale (Fig. 3-6), with a slight increase in the sandstone content in landward (northeastern) direction. The succeeding stratal unit DE stores its maximum of 500 meters of sediments further to the northeast; its minimum of 200 to 250 meters characterizes the central part of the study area (Fig 3-8). The gamma-ray signature of unit DE (Fig. 3-6) indicates almost 60 % sandstones in this unit across the study area. Sedimentary unit CD consists of approximately 60 % shale and 40 % sandstone, with a maximum thickness of around 600 meters in the northeastern study area. The thickness of sediments decreases towards the centre of study area to around 250-300 meters (Fig. 3-8). The isopach map of unit BC also shows a maximum of 500 meters of sediments in the north and northeastern parts of the study area, and a minimum of 250-300 meters of sediment in the center. Unit BC is characterized by an average sandstone content of around 60 %, with a clear basinward (westerly) decrease in sandstone content (Fig. 3-6). Depositional interval AB shows a thickness variation between a maximum of about 300 in the north and a minimum of about 200-225 meters in the central study area. This unit comprises up to 80% sandstone. At the top of the succession, the sediments above horizon A consist of up to 90% sandstone (Fig. 3-6), attaining a thickness of about 1200 m in the SW of the study area (Fig. 3-8).

Quantification of sedimentary loading and compaction

Table 1A documents the results of the stepwise decompaction of the studied deltaic rollover system. The incremental changes in the thickness of the sedimentary units during the decompaction using the porosity-depth relation of Sclater & Christie (1980) are plotted in six columns, starting on the left with the compacted, present-day state. The rows of Table 1A plot
per sedimentary unit the respective minimum and maximum unit thicknesses in meters measured before and after each decompaction step. I.e., the first decompaction step balanced the weight of the sedimentary column above surface A, a sedimentary interval mainly consisting of sandstones as recorded e.g. in wells A, E and F (Fig. 3-6). Decompaction due to the removal of this uppermost sedimentary interval resulted in a decompacted thickness of topmost unit AB ranging between 240 and 400 m (Table 1A), which equals a 40 m thickness increase in the thinnest part of the unit and an 80 m thickness increase in the thickest part (Table 1B). The effects of this first decompaction step on units BC, CD, DE and EF are also shown in Table 1B: here, initial unloading resulted in a thickness increase in the respective thinner parts of the units between 20 and 60 m, and in the thicker parts between 40 and 80 m. Consequently, the total thickness increase for all sedimentary units after the first decompaction step was between 200 and 320 m (Table 1B).

The second decompaction step balanced the weight of unloading the remaining sedimentary succession from unit AB (Table 1A). Decompaction due to the removal of unit AB resulted in a relatively uniform thickness increase of units BC, CD, DE and EF between 20 and 40 m, and the total thickness increase for all units after this decompaction was between 80 and 140 m (Table 1B). Decompaction step 3 balanced the removal of unit BC from the sedimentary column. This decompaction step resulted in a differential thickness increase of the remaining units CD, DE and EF between 20 and 120 m, and the total thickness increase for all units after the removal of interval BC was between 100 and 220 m (Table 1B).

Decompaction steps 4 and 5 finally balanced the weight of unloading the remaining succession from units CD and DE, respectively (Table 1A). Decompaction due to the removal of unit CD (step 4) resulted in a thickness increase of units DE and EF between 40 and 120 m, and the final unloading of unit DE (step 5) increased the thickness of the basal unit EF by 60 to 140 m. The total thickness increase for all units after decompaction step 4 was 100 to 200 m, and after decompaction step 5 between 60 and 140 m (Table 1B).
Table 1A: Rollover unit-thickness for the compacted state and after the incremental steps of decompaction. Decompaction 1 accounts for the removal of sediment above horizon A, decompaction 2 for the removal of unit AB, decompaction 3 for the removal of unit BC, decompaction 4 for the removal of unit CD and decompaction 5 for the removal of unit DE. Values range between respective minimum and maximum for each sedimentary unit after each decompaction step.

<table>
<thead>
<tr>
<th>Depositional unit</th>
<th>Unit thickness, compacted (m)</th>
<th>Decompacted unit thickness after decompaction 1 (m)</th>
<th>Decompacted unit thickness after decompaction 2 (m)</th>
<th>Decompacted unit thickness after decompaction 3 (m)</th>
<th>Decompacted unit thickness after decompaction 4 (m)</th>
<th>Decompacted unit thickness after decompaction 5 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment above A</td>
<td>900-1000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AB</td>
<td>200-320</td>
<td>240-400</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BC</td>
<td>280-500</td>
<td>340-580</td>
<td>360-620</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CD</td>
<td>260-580</td>
<td>300-640</td>
<td>320-600</td>
<td>380-800</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DE</td>
<td>200-500</td>
<td>220-540</td>
<td>240-560</td>
<td>260-620</td>
<td>320-740</td>
<td>-</td>
</tr>
<tr>
<td>EF</td>
<td>300-800</td>
<td>340-860</td>
<td>360-900</td>
<td>380-940</td>
<td>420-1020</td>
<td>480-1160</td>
</tr>
</tbody>
</table>

Table 1B: Incremental difference (Δ) between the respective decompaction result and that of the preceding decompaction, as provided by Table 1A. The total Δ-thickness values (m) equals the space generated in the underburden by balancing the removal of the respective top unit. This space is a minimum estimate for the accommodation provided by compaction due to the loading of the preceding delta units with a new top unit.

<table>
<thead>
<tr>
<th>Depositional unit</th>
<th>Δ thickness after decompaction 1 (m)</th>
<th>Δ thickness after decompaction 2 (m)</th>
<th>Δ thickness after decompaction 3 (m)</th>
<th>Δ thickness after decompaction 4 (m)</th>
<th>Δ thickness after decompaction 5 (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sediment above A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>AB</td>
<td>40-80</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BC</td>
<td>60-80</td>
<td>20-40</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CD</td>
<td>40-60</td>
<td>20-40</td>
<td>60-120</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>DE</td>
<td>20-40</td>
<td>20-20</td>
<td>20-60</td>
<td>60-120</td>
<td>-</td>
</tr>
<tr>
<td>EF</td>
<td>40-60</td>
<td>20-40</td>
<td>20-40</td>
<td>40-80</td>
<td>60-140</td>
</tr>
<tr>
<td>Total Δ thickness</td>
<td>200-320</td>
<td>80-140</td>
<td>100-220</td>
<td>100-200</td>
<td>60-140</td>
</tr>
</tbody>
</table>
Quantification of accommodation

Along continental margins, the development of the space that is made available for sediment to be deposited (accommodation) is controlled by regional, basin-scale parameters including thermal subsidence, isostatic subsidence due to sediment loading, and eustasy (e.g. Plint et al., 1992; Coe et al., 2003). In the study area, sediment compaction seems another important mechanism creating significant accommodation space on a local scale by reducing the volume of the underlying sediment (Fig. 3-9).

Figure 3-9: Results of the incremental backstripping (decompaction and isostatic correction) of the sedimentary succession of the study area illustrating the effect of sedimentary loading on rollover development on each horizon surfaces. Ca. 75% of the average dip on horizons A, B and C, approximately 70% of the average dip on horizons D and E, and around 60% on horizon F is induced by sedimentary loading of the underlying sedimentary units (uncertainty of +/- 5%).
An additional control on the creation of local accommodation was very likely syndepositional faulting (see faults on Figs. 3-3 to 3-5, Fig. 3-7), and possibly the subsurface movement of a mobile shale substratum (Fazli Khani and Back, 2012).

The regional, margin-scale controls on accommodation can be considered to have influenced the western Niger Delta including the study area in a uniform way. With respect to the individual structural environments documented, the influence of eustasy and basinwide subsidence can be estimated as laterally equal throughout the studied survey, irrespective whether measured on footwall or hanging wall, along the rollover flanks or at the crest of the rollovers. In contrast, compaction as a local accommodation control could have considerably varied across the study area. A similar lateral variability probably applies for fault-controlled subsidence that should have developed respective subsidence maxima on the hanging walls of major bounding faults near the fault plane. In comparison to faulting and compaction, the prediction of potential accommodation creation by subsurface shale movement is less clear. Bulges of potentially mobile shales seem to preferentially form within the cores of rollover anticlines and behind the fault planes of major bounding faults (e.g. Doust and Omatsola, 1989); areas of potential shale withdrawal might be located inbetween, but inferences about possible shale-movement directions remain on the studied 3d seismic data ambiguous.

The incremental decompaction of the studied rollover system yet quantified the compaction of the studied deltaic succession to 60-140 m when depositing sedimentary unit DE, to 100-200 m by accumulating unit CD, to 100-220 m during the formation of unit BC, to 80-140m when depositing unit AB and to 200-320 m during the accumulation of the strata above horizon A (Table 1B; Fig. 3-9). However, a comparison of the isopach data of this study with the decompaction results (Table 2) also shows that e.g. between the development of horizons E and D, a package of 320-740m of uncompacted sediment accumulated, leaving after a subtraction of the accommodation provided by compaction an unbalanced surplus of 260-600 m sediment.
**Table 2:** Summary of key parameters used for the 3D decompaction of sedimentary units of the Niger Delta rollover, and decompaction results set in relation to accommodation development.

<table>
<thead>
<tr>
<th>Depositional unit</th>
<th>Unit thickness, compacted (m)</th>
<th>δ-depth coefficient* (1/km)</th>
<th>Average surface porosity*</th>
<th>Unit thickness, entirely uncompacted (m)</th>
<th>Δ-thickness between compacted and fully uncompacted state (m)</th>
<th>Accommodation (m) generated by compaction of the underburden due to loading with respective top unit†</th>
<th>Accommodation provided by eustasy, thermal subsidence, isostasy, fault movement and shale withdrawal§ (m)</th>
<th>Accommodation created by fault movement and/or shale withdrawal* (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>200-320</td>
<td>0.27</td>
<td>0.49</td>
<td>240-400</td>
<td>40-80</td>
<td>80 - 140</td>
<td>160-260</td>
<td>100</td>
</tr>
<tr>
<td>BC</td>
<td>280-500</td>
<td>0.39</td>
<td>0.56</td>
<td>360-620</td>
<td>80-120</td>
<td>100 - 220</td>
<td>260-400</td>
<td>140</td>
</tr>
<tr>
<td>CD</td>
<td>260-580</td>
<td>0.39</td>
<td>0.56</td>
<td>380-800</td>
<td>120-220</td>
<td>100 - 200</td>
<td>280-600</td>
<td>320</td>
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<tr>
<td>DE</td>
<td>200-500</td>
<td>0.39</td>
<td>0.56</td>
<td>320-740</td>
<td>120-240</td>
<td>60 - 140</td>
<td>260-600</td>
<td>340</td>
</tr>
<tr>
<td>EF</td>
<td>300-800</td>
<td>0.39</td>
<td>0.56</td>
<td>480-1180</td>
<td>160-380</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Sensu Sclater & Christie (1980); †See bottom row of Table 1B; §Values calculated from difference between decompacted unit thickness (column 5) and accommodation generated by compaction (column 7); *Difference between maximum and minimum accommodation of column 8.
A similar difference characterizes the balance between compaction and the unit thicknesses of all succeeding intervals (Table 2). The constant surplus on the side of the unit thicknesses must reflect a control for accommodation creation different from compaction, which, following the line of arguments from above, should either be related to eustasy, regional (isostatic) subsidence, faulting and/or subsurface shale movement (Table 2, column 8).

A comparison between the remaining regional and local controls on accommodation development suggests that the respective surplus minima of each unit (ranging between 160 and 280 m; Table 2, column 8) might be used as a first-pass approximation of a regional accommodation trend controlled by global sea-level change and continental basinwide isostatic subsidence; the differences between the respective surplus maxima and minima between the rollover crest and flanks (Table 2, column 9), in contrast, must be locally controlled since strongly varying across the study area. This difference in accommodation development within one sedimentary unit is therefore very likely related either to synsedimentary deltaic faulting or the subsurface movement of mobile shale. If measured from old to young, this lateral variation is up to 340 m for unit DE, 320 m for unit CD, 140 m for unit BC and 100 m for unit AB (Table 2). Through time, accommodation provided by faulting and/or shale movement seems thus generally waning, which suggests a decreasing importance of faulting and/or shale movement for the late-stage rollover development.
Discussion

The results of the horizon interpretations and isopach analyses of the studied Niger Delta rollover document that all sedimentary units are characterized by a non-uniform thickness pattern with the respective maximum located on the landward rollover flank near the main bounding growth fault (e.g. Figs. 3-4 and 3-5). This wedge-shaped sediment-storage architecture led to the differential loading of the underlying strata which, in turn, influenced the geometric development of the studied rollover. The stepwise decompaction of the sedimentary units within the rollover anticline shows that compaction exerted an important control for the development of accommodation space around the studied rollover anticline, contributing particularly during the late stage development of the studied rollover system (i.e. during the accumulation of units BC and AB) to up to 35% of the generation of depositional space and thus stratal bending on the rollover flanks. If compared to the amount of accommodation likely created by fault movement and/or shale withdrawal in the study area (Table 2, column 9), the influence of compaction on the creation of depositional space (Table 2, column 7) seems initially relatively low (intervals DE and CD), but equals and even partly exceeds the fault- or mobile-shale-driven values during the deposition of sedimentary units BC and AB.

The decompaction of the sedimentary record of the rollover by backstripping comprised a series of successive interpretation steps, each of which introduced uncertainties into the quantitative reconstruction. The first uncertainty affecting the above calculations was the interpretation accuracy. As all seismic interpretations were carried out on state-of-the-art 3D-seismic reflection data above 3s (TWT) depth (Figs. 3-4 and 3-5), the horizon-picking uncertainty was estimated at +/-10 ms (TWT). The results of the subsequent depth conversion of the marker horizons were then compared to well tops mapped in depth (e.g. Fig. 3-6), constraining horizon-to-well mismatches after depth conversion to less than +/- 40 m (maximum at the basal horizon F).
Figure 3-10: Sketch highlighting the relative importance of the parameters controlling accommodation creation on both hanging wall and footwall sides of a listric synsedimentary normal fault associated with a hanging-wall rollover. The cartoon on the left side of the figure illustrates a growth fault/rollover system influenced in its development by compaction, loading, regional tectonic subsidence, eustasy and fault-related subsidence. The cartoon on the right side shows the same system after decompaction and isostatic correction (unloading). Plotted are the vertical distances between successive horizon pairs after backstripping, which provides a measurement for the amount of accommodation generated by regional tectonic subsidence, eustasy and fault-related hanging-wall subsidence. If background information on regional tectonic subsidence and eustasy is available, hanging-wall subsidence by faulting can be readily calculated, even in the case that footwall data is lacking. Note that paleobathymetric differences might have existed between the footwall and hanging-wall sides; in the studied system, these differences are be estimated to be at maximum in the order of a few meters.
The error concerning the relative unit thicknesses in the 3D model between the individual unit bases and the tops thus remained relatively low, which was an important pre-condition for the validity of the subsequent decompaction and isostatic correction. Uncertainties entering the model during decompaction included the range of values for initial porosities (see e.g. Waltham et al., 2000), and errors in the assumed average porosities (e.g. by an omission of lateral porosity change, see Fig. 3-6).

Figure 3-10 illustrates that the decompaction of a deltaic rollover system can be used to quantify the amount of hanging-wall accommodation created by 1) local fault-induced (tectonic) hanging-wall subsidence, 2) shale withdrawal, 3) thermal subsidence and isostasy as well as 4) changes in sea-level through time, but that the individual contribution of each of these factors remains unspecified. Table 2 shows that in the studied example the sum of these factors is in the order of a few hundreds of metres. Figure 3-1A indicates that the minimum contribution of fault movement and/or shale withdrawal to the creation of hanging-wall accommodation space can be approximated by subtracting the remnant accommodation at the rollover crest from the respective maximum at the bounding fault, which equals after decompaction the difference between the respective maximum and minimum of the accommodation provided by eustasy, thermal subsidence, isostasy, fault movement and shale withdrawal (Table 2, column 8). Important in this context is that there is no indication in the studied data for any significant submarine topography development (e.g. slumped units on the rollover flanks) influencing the palaeobathymetry; the above accommodation estimation is therefore in line with classical across-fault kinematic analyses such as throw vs. depth plots (Barnett et al., 1987; Cartwright, 1998; McLeod et al., 2000; Childs et al., 2003; Castelltort et al., 2004) or the calculation of growth indices (Bischke, 1994; Cartwright, 1998; Taylor et al., 2008), as the basinwide parameters thermal subsidence, isostasy and eustasy should be equal throughout the studied growth-fault/rollover system. If viewed solely from the hanging-wall (rollover) side of the studied system, it can be in
turn postulated that knowledge on the regional pattern of thermal subsidence and isostasy combined with a detailed eustatic record and geological age information can be alternatively used to calculate faulting-induced hanging-wall subsidence. This observation is important in that it implies that background knowledge on regional basin subsidence, stratigraphic age and sea-level changes can be used to reconstruct and quantify fault movement in deltaic growth successions, and this solely based on hanging-wall isopach trends independent of any footwall information. Such an approach will analyze and quantify fault movement purely by an accommodation analysis of the hanging-wall succession balanced for regional tectonic subsidence trends and sea-level change, a method that can be readily applied in any deltaic growth-fault/rollover setting.

**Conclusions**

(1) Detailed 3D structural and stratigraphic analysis of a kilometer-scale deltaic rollover system of the Niger Delta documents that all studied rollover units exhibit a non-uniform isopach pattern with their respective thickness maximum located near the main bounding fault on the landward side of the system. This wedge-shaped sediment-storage architecture prevailed for considerable time and led to a differential loading of the underlying strata which, in turn, influenced the geometric development of the studied rollover.

(2) Incremental decompaction of the rollover units documented that compaction exerted an important control for the development of accommodation on both sides of the rollover anticline. This loading-driven process contributed in the late-stage development of the studied rollover more to the stratal bending and generation of depositional space on the rollover flanks than tectonic displacement along the main bounding fault. However, faulting (and possibly subsurface shale movement) seem to have acted as the main control for accommodation development during the early development of the rollover system.
The results of this study document that the decompaction of sedimentary units can be used in growth-fault and rollover settings to estimate the respective amount of accommodation created by fault movement (and/or shale withdrawal), regional tectonic subsidence and changes in sea-level; however, the individual contribution of each of these processes and particularly the contribution of a potentially mobile substratum to the creation of hanging-wall space might remain unclear. Yet, if data on the footwall sedimentary record across the bounding fault is available, fault-induced hanging-wall subsidence can be measured by classic fault-kinematic analysis-techniques. An alternative approach can be used when such footwall data is lacking: the analysis and quantification of fault movement then requires background knowledge on the regional subsidence, the age of the studied succession and the record of sea-level during deposition. Subtraction of the regional subsidence and the effects of sea-level changes from the total hanging-wall accommodation will then reveal the amount of pure fault-induced hanging-wall subsidence, enabling the quantification of synsedimentary fault movement without using footwall data.

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References


Executive summary

The interaction between sedimentation and faulting is a complex issue in deltaic settings. In such regions, rapid sedimentation and the progradation of sandstones and shales commonly causes the generation of normal listric growth-faults, a mechanism of faulting drive by gravity (gravity driven tectonics). An understanding of the parameters controlling the interrelation between sedimentation and faulting is an important issue since deltas are among the most prolific hydrocarbon provinces in the world.

In this thesis, three-dimensional seismic and well data from the western Niger Delta were investigated to study the initiation, lateral growth and retreat, quiescence and decay of faulting, and to evaluate the interaction between faults and fault segments in lateral and vertical linkage and reactivation. In the course of this work the effects of fault activity on the hanging-wall side deformation and development of folding related to the fault activities was highlighted. Finally, this study attempted to put an insight into the parameters controlling the development of rollover anticlines and accommodation creations in Delta settings.

In this work it was shown that a considerable lateral variability can occur regarding the style of syn-sedimentary normal faults and associated syn-kinematic strata within one tightly defined deltaic depocenter. The temporal variation in fault-length development and stratal displacement are documented to occur primarily during the early growth phase of the studied faults. It was further shown that although on a large scale an apparent correlation with sediment loading exists, deltaic fault growth remains a process that may act out of sequence, irrespective of the regional sedimentary trend. The awareness of such a potentially complex history of deltaic faults is e.g. important for fluid migration studies that rely on accurate fault-movement predictions and facies juxtaposition analyses.
This thesis also revealed that growth fault characteristics such as the initiation time, fault segmentation and lateral linkage, temporal and spatial growth, displacement along the fault plane and location of the maximum displacement, vertical linkage, quiescence and fault reactivation can be studied by analyzing the syn-kinematic sedimentary units located on the hanging-wall of deltaic normal faults. The study showed that each fault-segment may maintain pre-linkage characteristics even after lateral linkage. In the study area vertical fault linkage occurred by two different processes; (1) vertical linkage contemporaneous to the fault activity and (2) vertical linkage after decay of fault segment. Each linkage process may have acted differently depending on the local sedimentary pattern and the associated hanging-wall deformation.

The work presented in this thesis finally delineated the relative importance of parameters controlling local accommodation creation in delta setting. Dissimilar fault activity across the study area created at various times a non-uniform accommodation distribution as revealed by wedge-shaped sediments to the fault plane. Non-uniform sedimentation ultimately led to differential loading and differential compaction on the downthrown side of the studied growth faults, which can be regarded as an important factor contributing to the creation of depositional space in deltas.
Zusammenfassung

Das Zusammenwirken zwischen Störungsprozessen und Sedimentablagerungen in deltaischen Systemen ist ein komplizierter Sachverhalt. In solchen Regionen sorgen eine schnelle Ablagerung und die Progradation von Sandsteinen, Siltsteinen und Tonen für die Bildung von listrischen Abschiebungen, die durch die Schwerkraft bedingt werden. Das Verständnis der einzelnen Parameter, die die Beziehung zwischen Ablagerung und Störungsprozessen beschreiben, ist ein wichtiger Kernpunkt, da Deltas zu den kohlenwasserstoffreichsten Gebieten der Welt gehören.

In dieser Arbeit wurden dreidimensionale Seismik und Bohrdaten aus dem westlichen Nigerdelta verwendet, um den Auslöser, das Wachstum und den Rückgang, die Inaktivität und den Zerfall von Brüchen zu untersuchen, sowie die Beziehung und Reaktivierung zwischen Störungen und Störungssegmenten in lateralen und vertikalen Verbänden zu beurteilen. Im Rahmen dieser Arbeit wurden die Auswirkungen von Störungsaktivitäten auf die Deformation der Hangendscholle, und die Entwicklung von Faltenstrukturen, die durch Störungsaktivitäten bedingt wurden, untersucht. Abschließend beabsichtigt diese Arbeit einen Einblick in die Parameter zu geben, die die Entwicklung von Überroll-Antiklinalen und die Raumgewinnung für Sedimentablagerungen in Deltas kontrollieren.

In dieser Arbeit wurde dargelegt, dass es zu erheblichen lateralen Unterschieden in der Form von syn-sedimentären Abschiebungen und den damit syn-kinematisch verbundenen Schichten in einem klar definierten deltaischen Ablagerungsraum kommen kann. Die zeitlich bedingten Unterschiede in der Entwicklung der Störungslänge und des stratigraphischen Versatzes wurden insbesondere innerhalb der frühen Wachstumsphase der untersuchten Störungen dokumentiert. Darüber hinaus wurde gezeigt, dass trotz der im großen Maßstab deutlich existierenden Korrelation zur Sedimentauflast, das Störungswachstum innerhalb eines Deltas ein unabhängiger


Diese Arbeit beschreibt schließlich die relative Bedeutung der Parameter, die die lokale Akkommodationsentwicklung in der Deltaeinstellung kontrollieren. Unterschiedliche Störungsaktivität innerhalb des Untersuchungsbereiches hat beispielsweise mehrmals eine lateral uneinheitliche Sedimentverteilung (z.B. keilförmige Sedimente) geschaffen. Diese uneinheitliche Sedimentation führte u.a. zu differenzieller Belastung und kompaktion im Hangendblock der
untersuchten Störungen; diese Kompaktion muss als ein bedeutender Einflussfaktor zur Akkommodationsentwicklung in Deltas berücksichtigt werden.
Curriculum Vitae

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Nationality: Iranian
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January 2009 – Decembre 2012
PhD Student at the Department of Geosciences, Energy & Mineral Resources Group (EMR), RWTH Aachen University, Germany
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Professional Appointments

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Research interests

My research focuses mainly on the interaction of tectonic and sedimentation along the continental margins, rifted basins and gravity-driven regions. I integrate three dimensional seismic and well data with palinspastic reconstruction and basin analysis to understand the initiation, growth and linkage, decay and reactivation of normal faults. I am also interested on the interrelation between faults and development of associated hanging wall deformation.