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The Rovuma Delta deep-water fold-and-thrust belt, offshore Mozambique

Estevão Stefane Mahanjane [a,*], Dieter Franke [b]

[a] Instituto Nacional de Petróleo (INP), Av. Fernão Magalhaes N. 34 - 2° Andar, PO. Box 4724, Maputo, Moçambique
[b] Bundesanstalt Für Geowissenschaften Und Rohstoffe (BGR), Geozentrum Hannover, Stilleweg 2, 30655 Hannover, Germany

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ABSTRACT

We interpret two-dimensional seismic reflection data from the Rovuma Delta basin deep-water fold-and-thrust belts. Two major arcuate complexes with different architecture and extent are identified. While in the northern Palma arcuate complex a multitude of steep, east-dipping thrust-related fold anticlines formed above a single main detachment, in the southern Mocimboa arcuate complex multiple detachments resulted in the formation of thrust duplexes. In between the two arcuate domains, only few thrust-related fold anticlines developed.

Our interpretation of the Rovuma basin is a linked system of up-dip extension and down-dip compression that is mainly driven by gravity tectonics. Sediment loading and a hinterland uplift due to the development of the East African Rift System since the Oligocene is proposed as origin of the delta.

It is shown that the main, seaward-dipping detachment in Early Cenozoic strata is likely under-compacted and overpressured shale. Conversely, shale diapirism is questionable since the shape and location of such structures in the fold-and-thrust-belts appear simply indicating steeply dipping imbricated folds, rooted by a near vertical thrust.

We suggest that mainly a different rheology and thickness and thus efficiency of the shale detachment across the delta resulted in different morphologies and geometries of the deep-water fold-and-thrust-belts.

1. Introduction

Despite the long-standing academic interest in deep-water fold-and-thrust belts (DWFTBs), little has been published about the Rovuma Delta basin offshore NE Mozambique. The Rovuma Delta basin (Fig. 1) has a proven prolific hydrocarbon fairway in NE Mozambique's offshore deep-water. Different sources report discovered in-place natural gas resources that may reach 100 Trillion Cubic Feet (e.g. Ledesma, 2013). The discoveries are trapped in complex tectonic structures in a system of extensional faults and compressional DWFTBs, and in deep-water submarine fans.

Deep-water fold-and-thrust belts develop at both active and passive continental margins. At passive continental margins, gravity-driven systems prevail that are triggered by the rigid translation of a rock mass down the slope (Ramberg, 1981). Gravity gliding is usually associated with linkage of up-dip extension with a down-dip contractional toe region via a detachment zone (Morley et al., 2011). Thus, typically not the complete sedimentary section is affected but deformation is often limited to a mobile zone (usually either overpressured, under-compacted shale or salt) at the base of the gravity-driven system. The general principles of dominant controlling factor of gravity detachment systems are the (1) initial deposition of salt or massive shales to form an efficient regional detachment, and (2) progradation of a large delta or group of deltas which introduce massive volumes of clastic sediments into the basin (Morley et al., 2011). The mechanism of shale deformation differs from those for salt deformation due to their different rheologies (Morley and Guerin, 1996). Salt is a viscous material whose rheology is independent of temperature, burial or strain, resulting in continuous deformation until it becomes isolated into pods. In contrast, shale deforms primarily as the result of internal shear strength being reduced by overpressuring and dewatering of shales will stop their mobility (Weimer and Slatt, 2004). As a consequence of the detachment rheology, the structural styles between shale and salt gravity-driven systems differ (Sapin et al., 2012). Morley (2003a) showed the main difference is that, in the case of shales, the weak mechanic behaviour is not confined to a specific stratigraphic unit. Counter-regional normal faults, major listric faults that dip landward, have been described in both *shale-* and *salt-detachment*. However, according to Sapin et al. (2012), the counter-regional shale systems show an important amount of extension, in contrast to salt tectonics.

With this paper we aim at a better understanding of the tectonic setting along the Rovuma Delta basin. The main basis of the study was the structural mapping of approximately 1500 line km of 2D multi-channel seismic data (filtered & scaled migration), transecting the Rovuma Delta DWFTB system (Fig. 1). The dataset comprises two surveys: Lonropet (LRP-98) and Western Geophysical (MBRWG-00), collected in water

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* Corresponding author.
E-mail addresses: estevao.stefane@inp.gov.mz, stefane.ac@gmail.com (E.S. Mahanjane).

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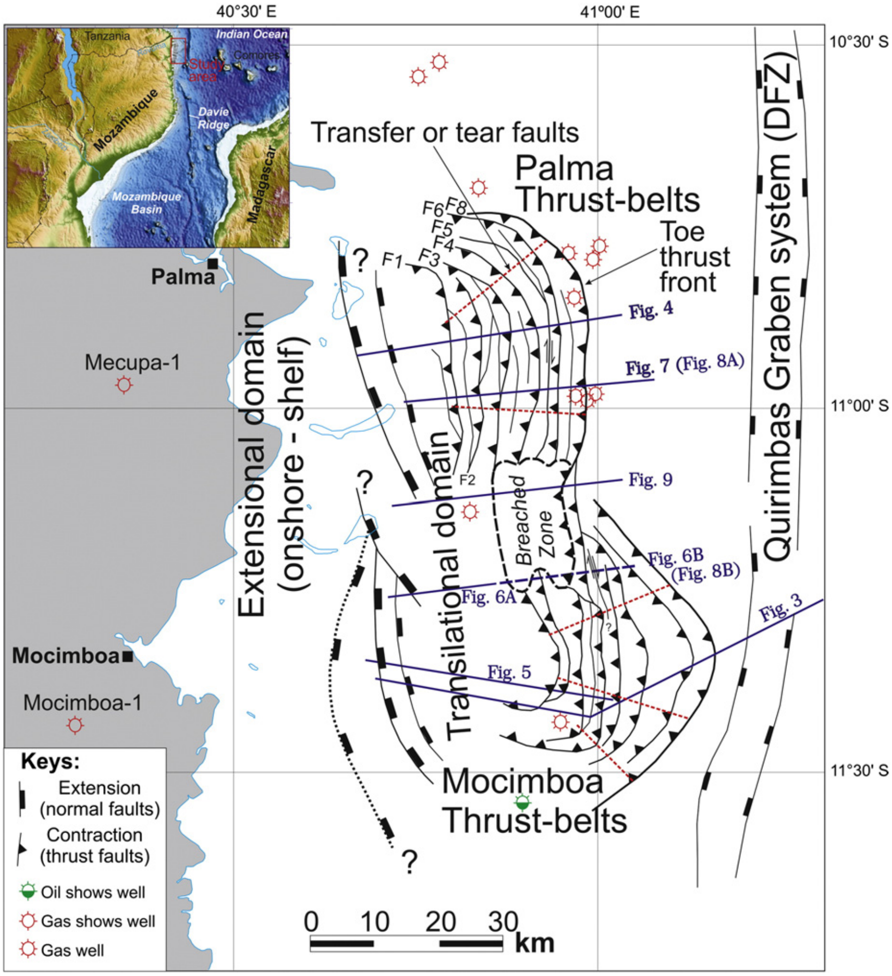

Fig. 1. Major structural elements of the offshore Rovuma Delta and the Quirimbas graben of the Davie Fracture Zone. The thrust-and-fold belts show a general E–W trend and are located in deep-water, between 1000 and 2000 m. Two major arcuate complexes developed to the south of the Rovuma River estuary: The northern Palma thrust belts and the southern Mocimboa thrust-belts. The location of the seismic example lines is indicated (dark blue).

depths between 500 and 2500 m (Fig. 1). The seismic data were interpreted both in paper-record form and using workstation installed integrated Seismic Micro-Technology KINGDOM™ software. We provide a detailed description of the general appearance of deformational tectonic mechanisms along the deltaic system. Our interpretation classifies the Rovuma Delta DWFTB as a gravity gliding system where the downdip fold-and-thrust belt is linked to updip extension via a detachment. The latter is suggested to be made up of overpressured shales.

1.1. Geological background

1.1.1. Tectonic evolution

Mozambique's passive continental margin originates from the breakup of Gondwana. According to Rabinowitz et al. (1983) the Africa–Madagascar breakup took place around 165 Ma, in the Middle Jurassic, followed by the southward motion of Madagascar and this is believed to have ended by the early Aptian (c. 121 Ma) (Rabinowitz et al., 1983) or middle Aptian (c. 118 Ma) (Bassias, 1992). Thermochronological and structural data from basement rocks proximal to the Rovuma basin margin indicate that only a narrow zone was affected by rifting (e.g. Daszinnies et al., 2009; Emmel et al., 2011), typical for a transtensional rift basin.

The NNW–SSE oriented Davie Fracture Zone controlled the southerly motion of Madagascar (Bird, 2001; Scrutton, 1978) along a dextral strike–slip system during Late Jurassic and Early Cretaceous times (Bassias, 1992). Several depressions formed along the Davie Fracture Zone, including the Rovuma basin during the time of the main movement (Mahanjane, submitted for publication). Northern Mozambique lies within a major N–S trending orogenic belt and the basement is made up of Late Proterozoic rocks of the Mozambique metamorphic belt (Salman and Abdula, 1995). In mid-Jurassic time a rapid denudation episode affected the Rovuma rifted margin, associated onshore with an erosional response along the major dextral strike–slip fault (Emmel et al., 2011; Roberts et al., 2012). From the Early Cretaceous on, the Davie Fracture Zone off Mozambique became inactive (Coffin and Rabinowitz, 1987, 1992) and the western margin of the Rovuma basin then became part of the passive margin. The onshore sedimentary sequence in the Rovuma basin is bound to the west and south by gneisses, granulites and migmatites of the Mozambique Belt (Pinna, 1995), and to the east by the Indian Ocean (Hancox et al., 2002).

1.1.2. Stratigraphy

Sedimentary successions up to 10 km thick of the Rovuma basin widely resemble the tectonic evolution. The lithostratigraphy of the onshore Rovuma basin is described in detail by Key et al. (2008) and Smelror et al. (2008) while the offshore was addressed by Salman and Abdula (1995) and Emmel et al. (2011).

A summary of lithostratigraphy of the northern offshore Rovuma basin in Mozambique is presented in Fig. 2. Sedimentary deposits comprise Middle Jurassic to Cenozoic strata (Salman and Abdula, 1995). It is an open question if there are Early Permian to Middle Jurassic Karoo age sediments below, as inferred by Salman and Abdula (1995) based on seismic correlations with the Tanzanian Selous basin. In fact, when reconstructing Madagascar back to its pre-breakup position the modern

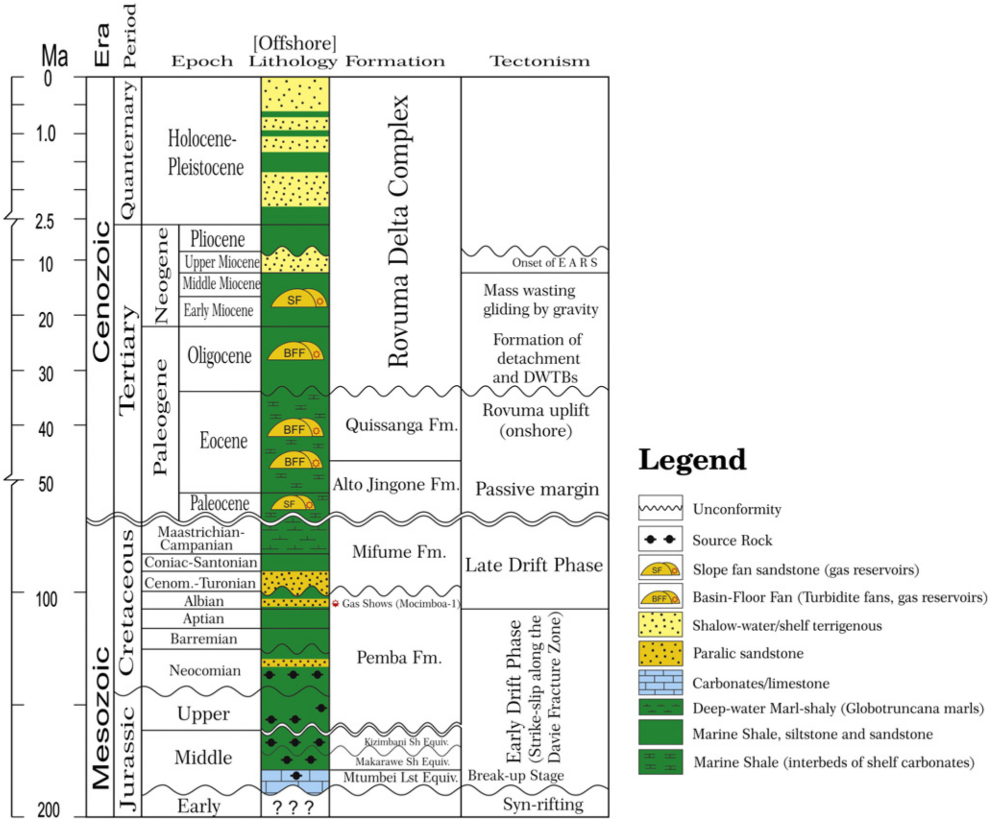

Fig. 2. Simplified stratigraphy of the northern offshore Rovuma basin based on ECL & ENH, 2000; Key et al., 2008; Salman and Abdula, 1995.

Rovuma basin is situated in between the Karoo basins Selous (Tanzania), Duruma (Kenya), and Morondava (Madagascar) (Catuneanu et al., 2005) and the pre-drift sediments show general good correlation between these basins (Hankel, 1994). The main question is about extensive uplift and erosion resulting in a regional Early to Middle Triassic hiatus (Hankel, 1994) that may have caused the absence of Karoo sediments before sedimentation was resumed in the Ladinian in the Rovuma basin. However, the quality of the deep portions of the seismic reflection data at hand makes it impossible to definitely judge on the presence or absence of Karoo sediments in the Rovuma basin. If present in our interpretation such sediments would be found in what we indicate as basement.

The Jurassic–Cretaceous successions of the Rovuma basin are related to the progressive break-up of south-eastern Gondwana. A Late Jurassic regional unconformity reflects a change to transform-controlled passive margin conditions as Madagascar moved southwards relative to mainland Africa (Raillard, 1990). Onshore the coarse basin margin sediments above the unconformity are referred to as the Macomia Formation and the marine sediments are referred to as the Pemba Formation (Key et al., 2008).

A Late Cretaceous marine transgression is proposed as the origin of the Mifume Formation, which comprises several thousands of meters of predominantly grey marls or mudstones and calcareous sandstones (Key et al., 2008). Onshore it consists of thin layers (up to 70 cm) of interbedded sandstones which become coarser upwards (Key et al., 2008), where they grade into limestones.

During the Early Cenozoic the region still was affected by a transgression which reached a maximum in the Eocene, with regression setting in during the Late Eocene (Nairn et al., 1991). The Mocimboa-1 Borehole shows the rapid eastward increase in thickness of the post-Mifume Formation sediments from less than a few hundred metres to about 3000 m. The Paleocene–Eocene sediments encountered in the well are deep-water carbonate shales with a thickness of 130 m (Salman and Abdula, 1995). Paleocene–Eocene successions occur offshore as shelf carbonates with interbeds of calcareous sandstone and marls (Key et al., 2008; Smelror et al., 2008). In central to south Tanzania the accumulation of a thick, outer shelf, clay-dominated succession (the Kilwa Group) was deposited during Upper Cretaceous to Lower Miocene. Late Campanian to Middle Eocene aged clays are overlain with marked angular unconformity by Lower Miocene clays that are probably locally reworked and re-deposited earlier clays (Nicholas et al., 2006). Based on ECL and ENH (2000) and Salman and Abdula (1995) it is proposed here that such clay-dominated Paleocene–Eocene successions are widespread in the offshore Rovuma Delta.

The Rovuma deltaic complex consists of a thick, eastward prograding wedge of Cenozoic fluvial deltaic deposits (continental and paralic clasts) to shallow-water marine and deep-marine strata that overlie unconformably the interface of Palaeocene–Eocene successions (Key et al., 2008; Salman and Abdula, 1995). The offshore delta complex is characterized by sequences of marine shale, siltstone and sandstone which grade to paralic and continental clastics towards the onshore.

The origin of the delta formation is likely a regional uplift of eastern Africa, potentially linked to a doming in the Oligocene (Key et al., 2008) or at the earlier stage in the Lutetian (Roberts et al., 2012), prior to the formation of the East African Rift. Roberts et al. (2012) claim that this uplift modified continental drainage patterns and directions for major large river systems including the Nile, Congo, Zambezi and Rovuma (?) systems. A Miocene transgression led to shallow water marine sedimentation during progradation of the Rovuma delta contemporaneous with rift-related onshore sedimentation in the East African Rift System (Key et al., 2008).

Significant uplift and erosion occurred in southern Tanzania after the Late Miocene and likely also extended to the Rovuma basin. The coastal zone was effectively blanketed by fluvial and shallow marine sands and grits that are of Pliocene or younger age. This sequence suggests the denudation of a significant source region inland, possibly the basement of the Masasi spur to the west. If this were the case, then it would be contemporaneous with thermal doming and tilting which occurred across the Tanzanian craton(s) immediately prior to modern rift initiation in the north (Nicholas et al., 2007).

2. Interpretation of the 2D reflection seismic data

In the following the linked system of upslope extension, a transitional domain and the down-slope compressional domain (fold-and-thrust-belt) is described. The entire Rovuma Delta is located to the south of the present-day Rovuma River (Fig. 1).

2.1. Extensional domain

The extensional domain comprises both an onshore and an offshore area. In the onshore area it extends about 50 km inland where elongated listric normal faults ramp down to a common detachment (Law, 2011). This domain continues for another 30 km in the offshore region, where again regional listric normal faults sole out at a major, seaward dipping detachment. The extensional deformation resulted in the formation of rollover structures, hanging-wall crest collapse grabens and counter-regional normal faults (Fig. 3).

The structural style of the northern offshore extensional zone, which is linked to the Palma thrust-belt, is characterized by parallel to sub-parallel normal faults that strike NNW and dip to the ENE (~60°). The individual faults may align along the shelf for up to 45 km (Fig. 1). Towards the east, the fault angle diminishes gradually from ~60° in planar rotational extensional faults to ~40° in listric normal faults. Consecutive pairs of listric normal faults deform most of the Cenozoic successions, resulting occasionally in sequences of half-graben structures (e.g. Figs. 6A, 7).

The southern extensional zone (*Mocimboa*) is made up of a set of normal faults, striking more or less north-south, which are less steep (~45°) than in the northern domain. Here the normal faults extend for up to 50 km across the shelf.

At the seaward limit of the extensional domain, series of synthetic and antithetic faults and crest collapse structures are present (Fig. 7).

2.2. Translational domain

The translational domain is a relatively undeformed area between the extensional and the compressional domain. The length of the translational area in the *Mocimboa Complex* is relatively larger than that of the *Palma Complex*. This domain is typically less than 20 km wide (e.g. Fig. 8) and occasionally the extensional domain is directly adjacent to the contractional domain.

2.3. Compressional domain

Mapping of thrust faults segments resulted in two morphologically prominent arcuate regions, the northern *Palma* and the southern *Mocimboa thrust-belts*. The width of the compressional area of the Rovuma DWFTB varies from ~18 km within the *Palma thrust-belts* to ~25 km at the SE portion of *Mocimboa thrust-belts* (Fig. 1). The *Palma thrust-belts* cover an area of approximately 900 km^2 while the *Mocimboa thrust-belts* cover a smaller area, approximately 750 km^2.

Both arcuate regions show similar deformation styles with asymmetric imbricate fans and ramp-flat geometries. The DWFTBs are predominately offshore verging folds with some break-thrusts at their forelimbs. A series of splay faults branching off and ramping sequentially out of the main detachment results in imbricate fans separated with an average distance of 1.0 to 3.5 km between them (Figs. 3, 4, 7).

The splay faults are convex upward with gentle dips at the surface. The most widespread geometry is that of blind thrusts terminating upward (ramp-up section) into markedly asymmetric fault-propagation folds. All thrust faults sole into a seaward dipping detachment that is imaged at between 3.2 s TWT to about 4.5 s [TWT] (Fig. 6A, B). The about 2.0 km [1.8 s TWT] thick deformed sediments have been buried by the most recent sediment wedge of Pliocene–Pleistocene age levelling the continental slope at the seafloor. The detachment is buried between 4.0 km (3 s TWT) to 4.5 km (4 s TWT) (Figs. 4, 7, 8A).

In both domains there are up to eight major successive thrust-related fold anticlines (F1 to F8; see Figs. 1, 4, 7). We observe a general steepening of the forelimbs in landward direction from about

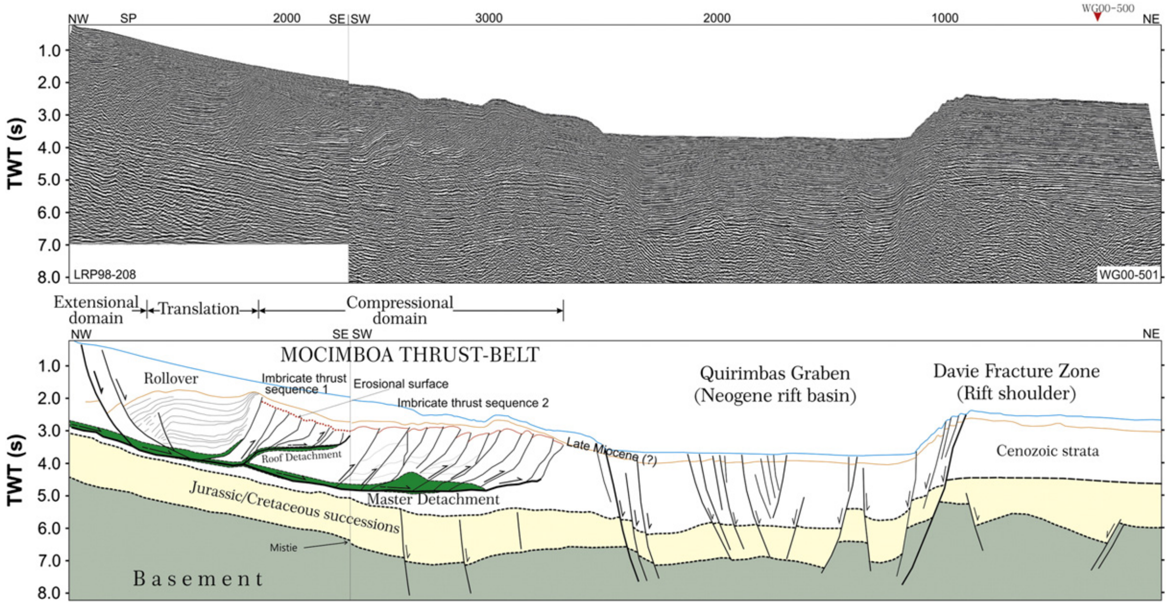

Fig. 3. Top: Composite reflection seismic lines showing the general architecture of the southern Rovuma deltaic system (Mocimboa). Bottom: Interpretation of extensional and compressional structures at the continental slope. The extensional zone is dominated by normal faulting resulting in rollover structures. Two prominent imbricate thrust sequences (toe thrusts) are extending towards the deep water area. Further seaward, rift-related extension is manifest in the Quirimbas Graben within the Davie Fracture zone. See Fig. 1 for location.

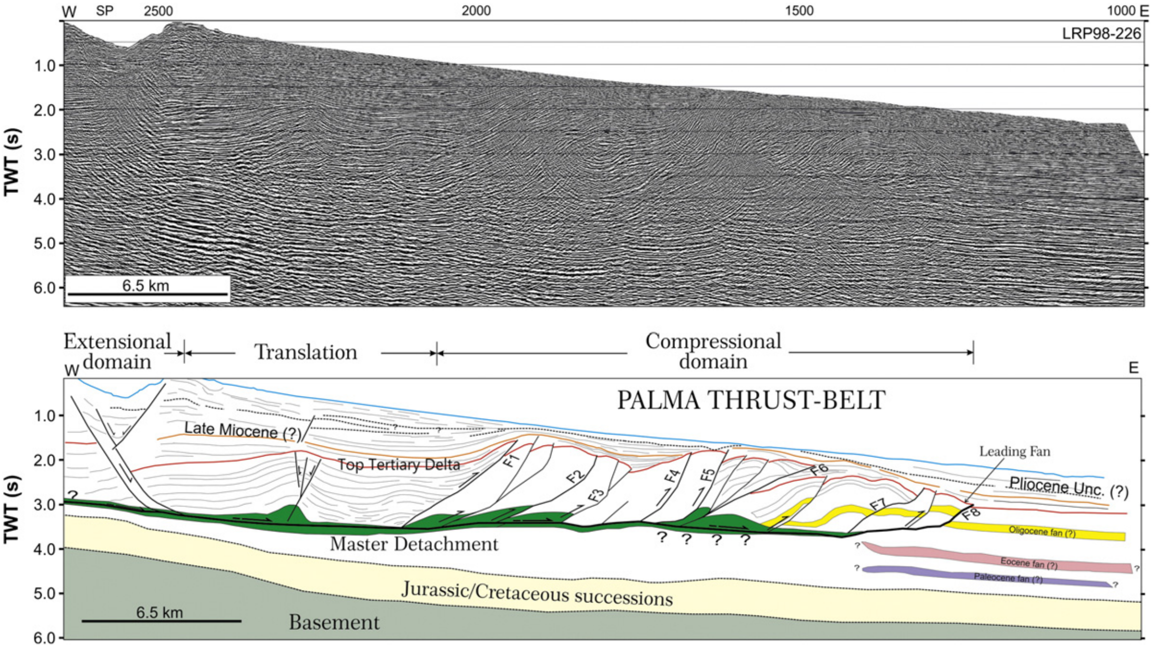

Fig. 4. Top: Reflection seismic lines showing the general architecture of the northern Rovuma deltaic system from the translation to the contractional domains of the Palma Arcuate Complex. Bottom: Structural and stratigraphic interpretation showing basinward-dipping listric extensional faults in the west and an evolving counter-regional normal fault towards the contractional domain. Here a complex system of DWTFBs developed. See Fig. 1 for location.

20° at the frontal anticline to a near vertical structure at the most landward anticline *F1* (~70°, e.g. Fig. 4). The well-developed imbricate thrust faults and associated folds gradually die out to the east to form the forelimb imbrications in a narrow triangular sliver of rock which defines the front-toe thrust-belts before reaching the Neogene Davie rift grabens (Figs. 1, 3).

A couple of thrust duplexes are distinct in our data in the southern *Mocimboa thrust-belts* (Figs. 5, 6B). Here an upper imbricate-sequence is underlain by a second detachment. The top of the upper imbricate-sequence is strongly eroded, eliminating completely the shape of toe-thrusts (Figs. 3, 5).

In general, the thrust-belts appear to be inactive since the Pliocene–Pleistocene except in the zone of steep breached imbricates located between the *Palma* and *Mocimboa thrust-belts*. In this area less thrust-related fold anticlines developed, the folds did reach the seafloor and subsequently were eroded (Fig. 9). Forelimb imbrications resulted in a narrow triangular sliver which broadens upward and terminates at the synclinal axis, separating the branching imbricates.

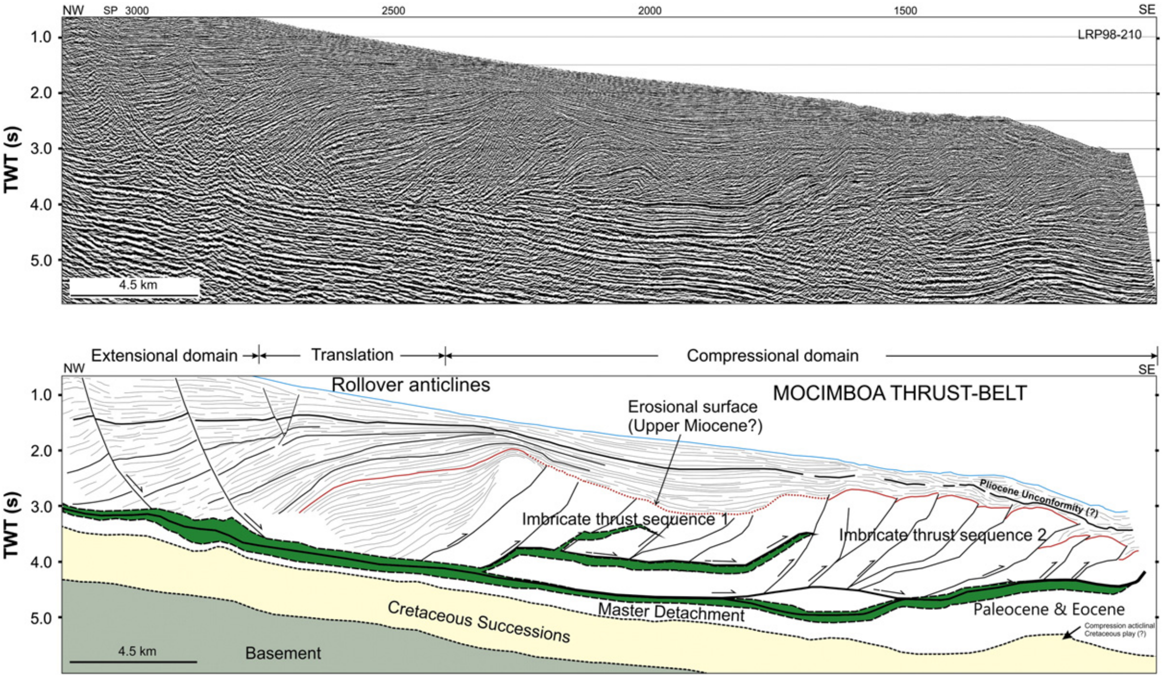

Fig. 5. Top: Reflection seismic lines showing the general architecture of the southern Rovuma deltaic system from the translation to the contractional domains of the Mocimboa Arcuate Complex. Bottom: Structural and stratigraphic interpretation showing basinward-dipping listric extensional faults with rollover anticlines in the translational zone. The contractional region is dominated by DWTFBs with partly dual detachment surfaces resulting in thrust duplexes.

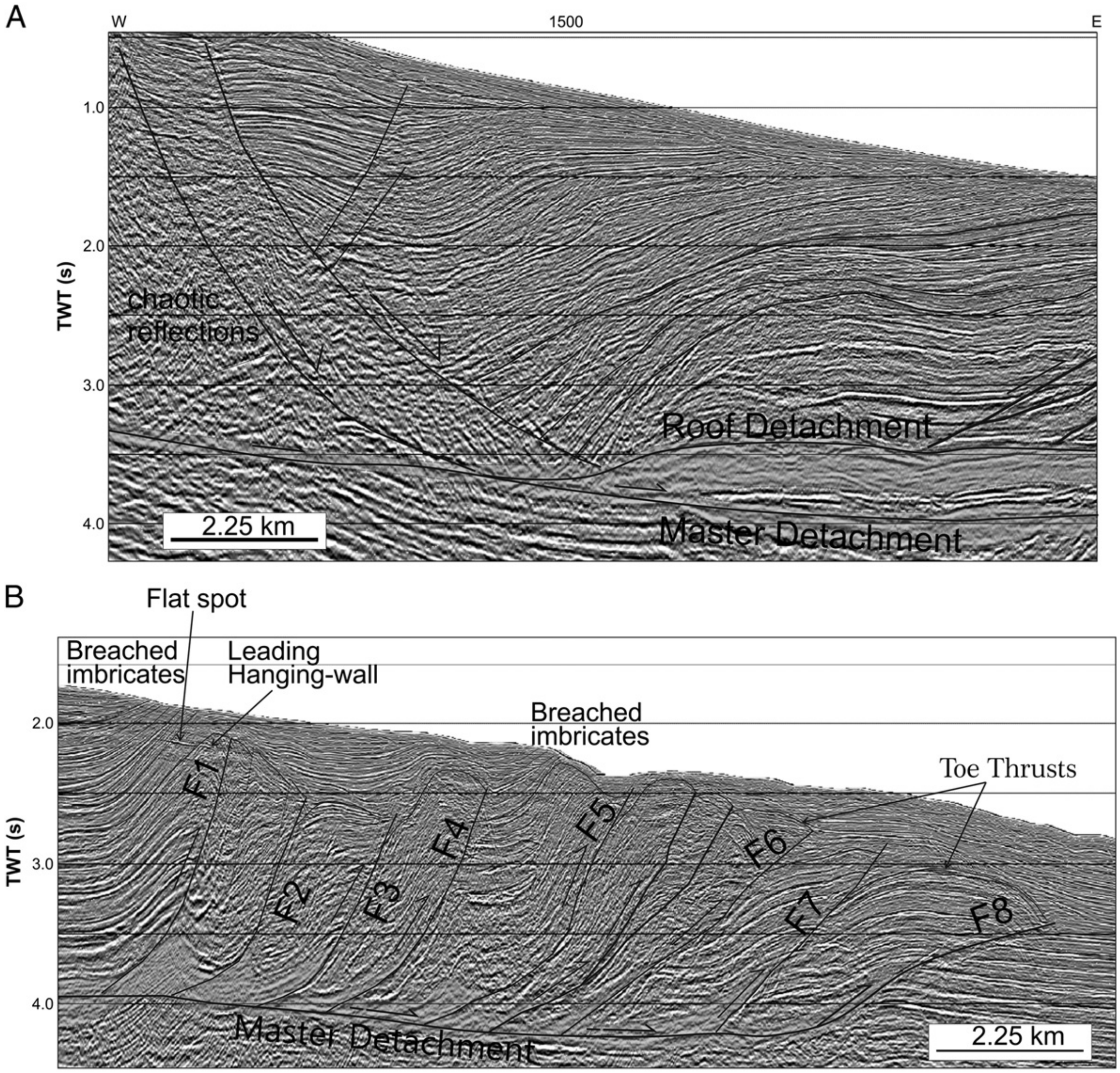

Fig. 6. Example seismic section (Profile LRP98-212) showing regional listric normal faults (A), that sole out at a major detachment fault in the southern (Mocimboa) extensional domain. The deformation resulted in the formation of rollover structures in the translational zone and two detachments in the east. (B) Shows the corresponding compressional structures that developed above a single master detachment. The grey area indicates mobile strata.

3. Discussion

3.1. Formation of the Rovuma Delta deep-water-fold-belt

The architecture of the Rovuma Delta is basically that of an up-dip extensional region which is linked to a down-dip arcuate region with asymmetric imbricate fans and ramp-flat geometries. This fits quite well the model of gravity gliding down an inclined slope on a thin detachment sensu Morley et al. (2011). The Rovuma DWFTBs are dominated by imbricate thrusts underlain by a seaward-dipping detachment, whilst up-dip extensional province, strongly segmented by listric faults dominates the onshore and shelfal areas (Figs. 1, 3).

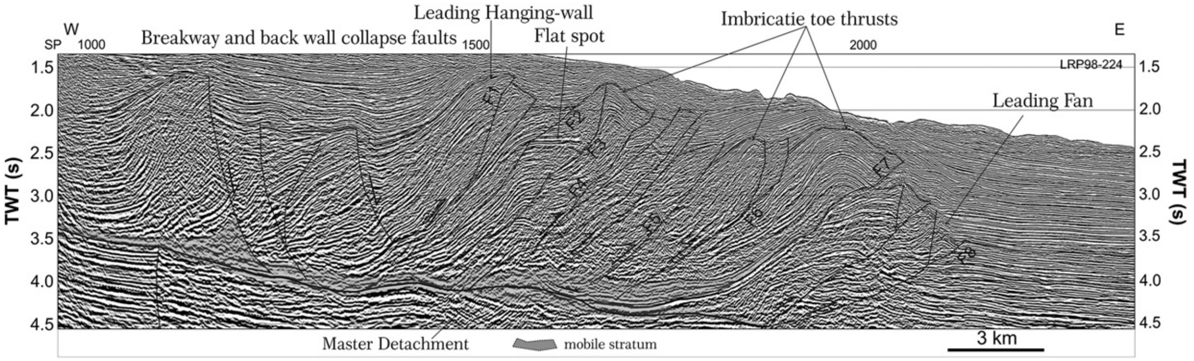

Fig. 7. Dip-line across the northern DWFTB complex of the Rovuma Delta. The eight major stacked imbricates are indicated as F1 to F8. See Fig. 1 for location. The extensional and contractional domains are located close together.

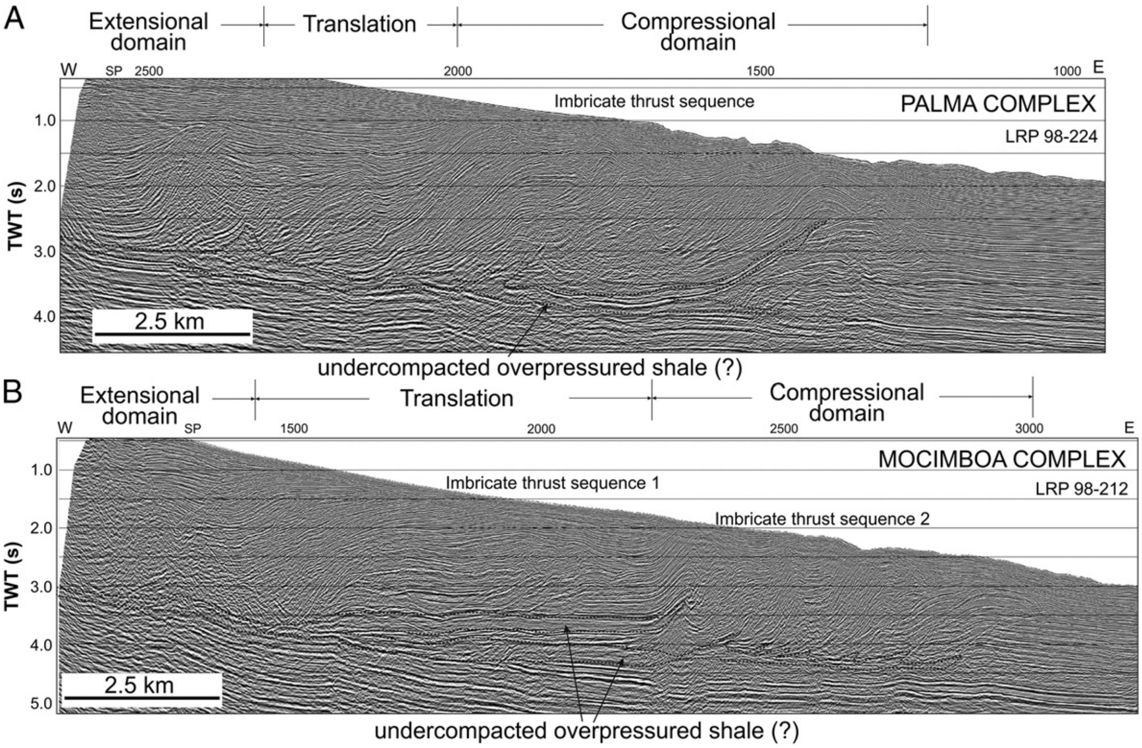

Fig. 8. Reflection seismic lines showing the structure and architecture of the mobile layers, forming the detachment in the northern Palma (A) and southern Mocimboa (B) complexes. Dome (or diapir geometries are often observed in the Palma Complex (A), while in the Mocimboa Complex duplicated detachments occur, with the formation of thrust-duplexes (B).

The linked system stretches for about 130 km from the onshore coastal area over the offshore area as far east as the present location of the DFZ.

The fold belt probably developed at the toe of the slope mainly during the Oligocene and Miocene. Mass-transport occurs along a mobile layer of Paleocene/Eocene age, dipping seawards and serving as a basal detachment. On top of the fold belt an erosional unconformity of inferred Middle–Late Miocene age marks the termination of folding.

The regional Oligocene–Miocene deltaic system is underlain by a detachment which follows the general east–west trend of deformational settings (Fig. 1). Modern rifting along the Rovuma basin is manifest by half-grabens that developed in the sedimentary strata with the controlling faults dipping and displacing eastwards (e.g. Fig. 3).

There are in principal two scenarios that have caused the formation of the Rovuma deep-water fold-and thrust-belt: (i) Progradation of a

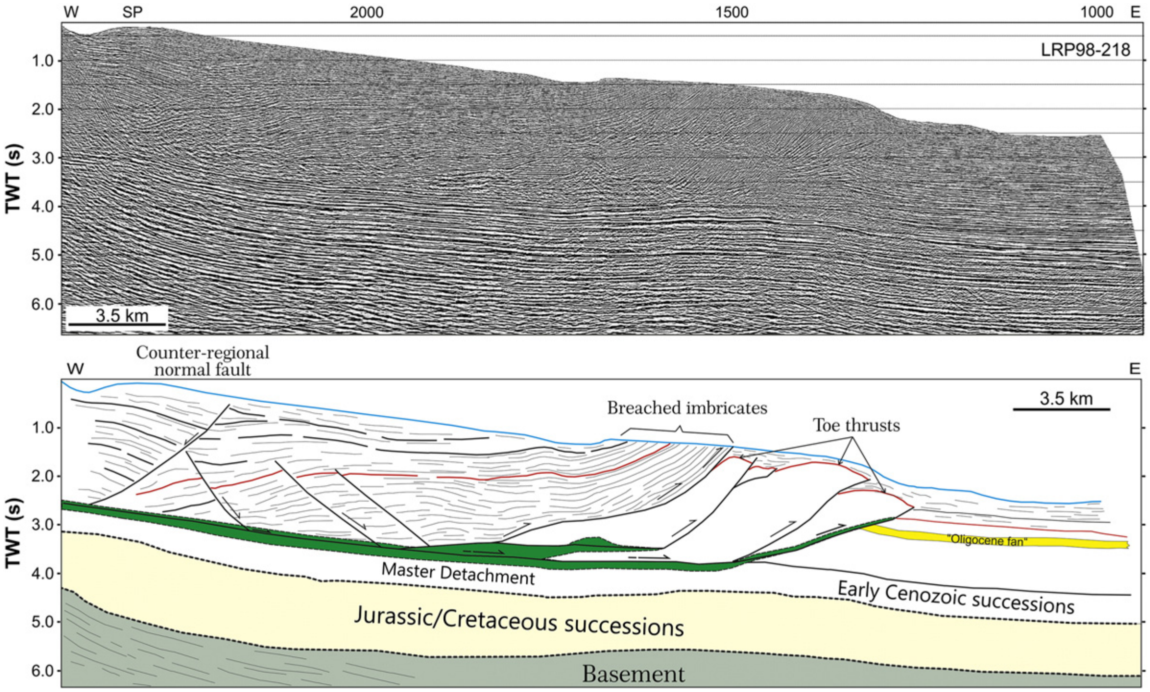

Fig. 9. Reflection seismic section transecting the breached area between the Palma and the Mocimboa thrust-belts. The breached imbricates reach the seafloor. In this region DWTFBs are less developed with few thrust sequences.

large delta or group of deltas which introduced massive volumes of clastic sediments into the basin, (ii) uplift of the hinterland, or a combination of both.

From the timing of formation of the deep-water fold and thrust belts there is a link to hinterland uplift in any case. Even if we assume that perturbation of forward propagation of the sedimentary wedge or presence of significant differential loading and gravity sliding did impose the offshore progradation and propagation of folds and thrusts (Hesse et al., 2009; Morley et al., 2011), the high deposition rate was controlled by river-transported sedimentation due to doming and erosion of eastern Africa associated with the development of the East African Rift System since the Oligocene (Chorowicz, 2005; Key et al., 2008).

Thus, the genesis of the Rovuma DWFTBs is likely linked to an uplift of the Rovuma hinterland, which triggers enhanced sedimentation and forced progradation of a delta lobe into the deep-water.

The Rovuma Delta shares many structural similarities with what is encountered in large deltas elsewhere, controlled by linked extensional and contractional gravity tectonic environments on passive-margins as the McKenzie, Gulf of Mexico, Amazon, Nile, Niger, NW Borneo, and Bight basin deltas (e.g. Morley et al., 2011).

3.2. Evidence for a mobile shale-detachment

The similarities between structures resulting from *shale* and *salt detachments* are unquestionable. Diapiric-like structures are indeed widespread in the Rovuma basin and may point towards an interpretation of a thick salt detachment. Such "diapirs" or dome structures occur at a particular startigraphic level below the imbricate thrust-and-fold-belts (Figs. 8A,B). Salman and Abdula (1995) suggested the presence of Middle and Lower Jurassic salt diapirs and salt ridges along the Rovuma basin coastline. Halogenetic deposits were suggested to extend from the Tanzania portion of the Rovuma basin into the northern Mozambique Rovuma basin.

However, the stratigraphic level of the detachment that is distinct in all seismic images is a major argument against a salt origin. Both extensional and compressional faults sole out above the Mesozoic successions and likely occur on a Late Eocene succession. This clearly postdates any potential salt layer which would be Jurassic in age. While salt typically leads to symmetric detachment folds, in the case of shale, contractional thrust and fold belts are dominated by asymmetric, basinward verging thrust imbricates and multiple detachment levels (Briggs et al., 2006). Moreover, variations in the efficiency of the detachment and major asymmetries are distinct throughout the Rovuma Delta. Development of thrust duplexes may have resulted from the efficiency of mobility along a *shale-detachment* in the basin, i.e., the southern part produced at least two prominent sequences of imbricate thrusts in the *Mocimboa thrust-belt* (Figs. 3, 5, 6B, 8B). The stratigraphic sequence is duplicated here, which the older strata in the hanging-wall is thrust over the younger strata in the foot-wall. In contrast, in the *Palma thrust-belt* a single basal detachment with a single imbricate thrust sequence is dominant. The thickness of the mobile layer here is nearly uniform with a maximum of about 500 ms (TWT) (Fig. 8A). The formation of counter-regional listric normal faults with large displacement is another argument for a shale detachment. Numerical modelling of *shale-detachment* structures like the Baram Deltaic Province and the Niger Delta indicates that a thick mobile shale section is required to generate the counter-regional fault province while a thin detachment does not produce counter-regional faults (Morley et al., 2011).

Analogous with the Niger Delta (Morley and Guerin, 1996) the under-compacted shale is assumed to contain overpressured fluids. A similar interpretation of thick mobile shales, forming a basal detachment, was presented earlier by Law (2011) for the Rovuma Delta. Such a layer was penetrated by the Mocimboa-1 and M'Nazi Bay-1 wells, close to the present day coastline of northern Mozambique and southern Tanzania (Salman and Abdula, 1995).

3.3. Shale diapirism?

Although the widespread dome structures in the Cenozoic sedimentary successions might be interpreted as shale diapirs (e.g. in the western portion of Fig. 6B) the origin is difficult to deduce due to limited seismic resolution in imaging at the anticline cores and crests of shale structures. Such structures may be interpreted either as steeply dipping imbricated folds, rooted by a near vertical thrust or as diapiric bodies piercing the overburden. Sapin et al (2012) based on high-quality seismic data generally question the actual role of shale tectonics in shale-dominated deltas and so far only mud volcanoes (similar with description by Flowler et al., 2000) and small scale shale injections (Morley, 2003b) are known in the field. Morley et al. (2011), in contrast, argue for the presence of thick mobile shale sections underlying at least the extensional domain in the Niger Delta.

In case of the Rovuma Delta, the relative location of the "diapiric bodies" in the fold-and-thrust-belt may guide our interpretation. The well-developed imbricate thrust faults and associated folds gradually die out in the seaward direction and the frontal anticlines typically dip at moderate angles of about 20°. In the landward direction there is a general steepening of the forelimbs from moderate to near vertical structures at the most landward anticline *F1* (~70°, e.g. Fig. 4). At this position the "diapirs" are found. This implies in our view a thrust fault origin for these structures. We suggest that the dome structures initially developed as gently dipping anticlines that steepened during further deformation. At the moment, limited reflection-seismic imaging of steep structures hinders a definite interpretation.

3.4. Origin of the two arcuate DWFTBs

There are two distinct and separated *arcuate DWFTBs* in the Rovuma Delta. The question is what may have caused such differences. The general tectonic process resulting in the formation of the DWFTB is certainly the same in both regions.

Our preferred interpretation is that the nature of the detachment differs across the basin. The tectonic deformation may have occurred along a detachment with a different rheology and/or thickness in the two domains, resulting in difference of morphology and geometry of the structures. Variations in the efficiency of the detachment are distinct throughout the Rovuma Delta. For example the formation of thrust duplexes likely is related to the efficiency of the *shale-detachment* in the basin. The compressional faults in the northern domain are generally much steeper (~60° dips) than in the southern domain, where fault dips are about ~45°. This resembles the dip trends in the corresponding extensional domains. Another structural difference is the width of the translational zone. The southern domain has a wide translational zone, whilst in the north a narrow translational zone with well-developed rollover anticline structures predominates.

The thickness of the ductile layer, as interpreted in the reflection seismic data, varies considerably from thin detachment zones to massive chaotic zones, some 2500 ms TWT thick. These massive zones are characterized by elongate, narrow sub-vertical steep-sided zones with mainly chaotic reflections (Fig. 8A). The impact of detachment layer thickness on thin-skinned fault geometry has been shown by Stewart (1999). In the case of a *shale detachment* not only the thickness of the shales but also the internal shear strength must be considered. This means the important factor here is the thickness of the mobile portions of the ductile layer that depends on the magnitude of fluid overpressures.

At basin scale, the front of the overpressured domain migrated basinward as sediments prograded seaward. Only in the zone of steep breached imbricates located between the *Palma* and *Mocimboa thrust-belts* was the basinward limit of this deformation not only controlled by the sedimentary wedge but likely also by the nature of the detachment. The mobile layer forming the detachment is not completely absent in this region (Fig. 9). It might be speculated that variations in

Eocene deposition resulted in higher sand content in this region lowering the efficiency of the detachment.

4. Summary and conclusions

Two prominent arcuate deep-water fold-and-thrust belts (*Palma* and *Mocimboa arcuate*) formed in the Rovuma basin. The *Mocimboa arcuate complex* occupies a greater area than the *Palma complex*. Its compressional domain shows thrust duplexes with broad translation zone and well imaged rollover structures. In contrast in the *Palma arcuate complex* a single main detachment resulted in the formation of a multitude of steep, east-dipping thrust-related fold anticlines, of which the youngest, most eastward-located anticlines exhibits the shallowest dip. In between both arcuate domains only few thrust-related fold anticlines developed, the folds did reach the seafloor and subsequently were eroded.

The architecture of the Rovuma Delta is basically a classic up-dip extensional region, which is linked to a down-dip arcuate region with asymmetric imbricate fans and ramp-flat geometries.

The system is gravity-driven and formed in response to up-dip sediment loading and regional tilting above a main detachment which is located in Early Cenozoic strata. Probably an under-compacted and overpressured *shale detachment* surface served to ramp-up the gliding sediments by gravity-driven deformation to form deep-water fold-and-thrust-belts. Conversely, shale diapirism is questionable since their shape and location in the fold-and-thrust-belts appears simply to indicate steeply-dipping imbricated folds, rooted by a near vertical thrust.

We suggest that mainly a different rheology and thickness and thus efficiency of the *shale detachment* resulted in different morphologies and geometries of the Rovuma Delta deep-water fold-and-thrust-belts.

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