Structural styles in the deep-water fold and thrust belts of the Niger Delta

Freddy Corredor, John H. Shaw, and Frank Bilotti

ABSTRACT

The deep-water Niger Delta includes two large fold and thrust belts, products of contraction caused by gravity-driven extension on the shelf that exhibit complex styles of thrusting. These contractional structures formed above multiple detachment levels in the overpressured shales of the Akata Formation. Using the patterns of growth sedimentation, fold shapes, fault-plane seismic reflections, and combined conventional and shear fault-bend folding theories, we describe and model the structural styles and kinematics of the fault-related folds and imbricate thrust systems that compose these belts. Individual fault-related folds, involving both forethrusts and backthrusts, are characterized by long planar backlimbs that dip less than the associated fault ramps, with upward shallowing of dips in growth strata above the backlimbs suggesting components of progressive limb rotation. Forelimbs are short compared to backlimbs, but growth strata show more consistent dips that suggest a component of folding by kink-band migration. Thus, we employ a combination of classic and shear fault-bend fold theories to describe these structures, including the influence of a weak basal detachment zone in the overpressured shales. We expand upon these theories to model the kinematics of imbricate thrust systems, which display a complex history of thrusting related to spatial and temporal variations in deposition across the delta. Regional patterns of folded growth strata are used to define break-forward, break-backward, and coeval thrusting involving single and multiple detachment levels. We define two main types of imbricate thrust systems: type I system with a single basal detachment level and type II imbricate system with multiple basal detachment levels, which cause massive structural thickening of the Akata Formation and refolding of shallow thrust sheets. Through the sequential restoration of two regional cross sections across these systems, we resolve the structural styles, the timing and sequences of thrusting, as well as the regional amounts of shortening, all of which have important implications for hydrocarbon maturation and charge in the deep-water Niger Delta.

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DATASHARE 20

Figure 16 is accessible as an oversized image on the AAPG Web site as Datashare 20 (www.aapg.org/datashare/index.html).

INTRODUCTION

The Niger Delta is located in the Gulf of Guinea, central west Africa, at the southern culmination of the Benue trough. The delta is considered one of the most prolific hydrocarbon provinces in the world, and recent giant oil discoveries in the deep-water areas suggest that this region will remain a focus of exploration activities. The deep-water Niger Delta contains two fold and thrust belts that accommodate updip, gravity-driven extension on the continental shelf. These fold and thrust belts initiated during the early Tertiary, and parts of them remain active today. Contraction and extension are linked by multiple detachment levels that are located in thick, early to middle Tertiary overpressured marine shales that underlie the deltaic deposits. As summarized in Wu and Bally (2000), differential loading caused by rapidly deposited sediments caused gravitational collapse of the continental shelf and formed a large growth normal fault that bound local depocenters. At depth, these normal faults sole onto the basal detachments, which extend downdip beneath the continental slope and emerge as thrust faults in deep water. Shale ridges, mud diapirs, and interdiapir depocenters characterize the outer continental slope between the extensional province on the shelf and the contractional fold and thrust belts in deep water.

The Niger Delta fold and thrust belts contain a wide variety of thin-skinned structural styles, including fault-bend, fault-propagation, and detachment folds, as well as complex imbricate thrust systems. The deep-water Niger Delta offers a unique opportunity to study these systems because the structures (1) are extremely well imaged at deep levels in seismic reflection profiles and (2) include syntectonic (growth) strata that record fold kinematics (Suppe et al., 1992; Zapata and Allmendinger, 1996; Casas-Sainz et al., 2002). In contrast, most onshore fold belts are difficult to image properly with standard seismic reflection techniques and are deeply eroded and, thus, generally lack syntectonic deposits.

The aim of this article is to describe the styles of thrusting and associated fault-related folding in the deep-water Niger Delta using balanced kinematic models to guide the structural interpretations of high-quality seismic reflection data. We also document the progressive development of the fold and thrust belts, and measure shortening, with sequential restorations of regional cross sections. Individual toe-thrust structures are interpreted using a combination of conventional and shear fault-bend fold theories (Suppe, 1983; Shaw et al., 2004; Suppe et al., 2004) that effectively describe the imaged fold and fault shapes, as well as the patterns of growth strata. Imbricate structures are interpreted by extensions of these methods to describe their structural geometries and infer the sequences of thrusting. The techniques and results presented in this manuscript have direct applications for petroleum exploration and production, in that the geometry and kinematics of these thrust systems dictate the size and complexity of the structural traps. Moreover, tectonic loading that results from the growth of these

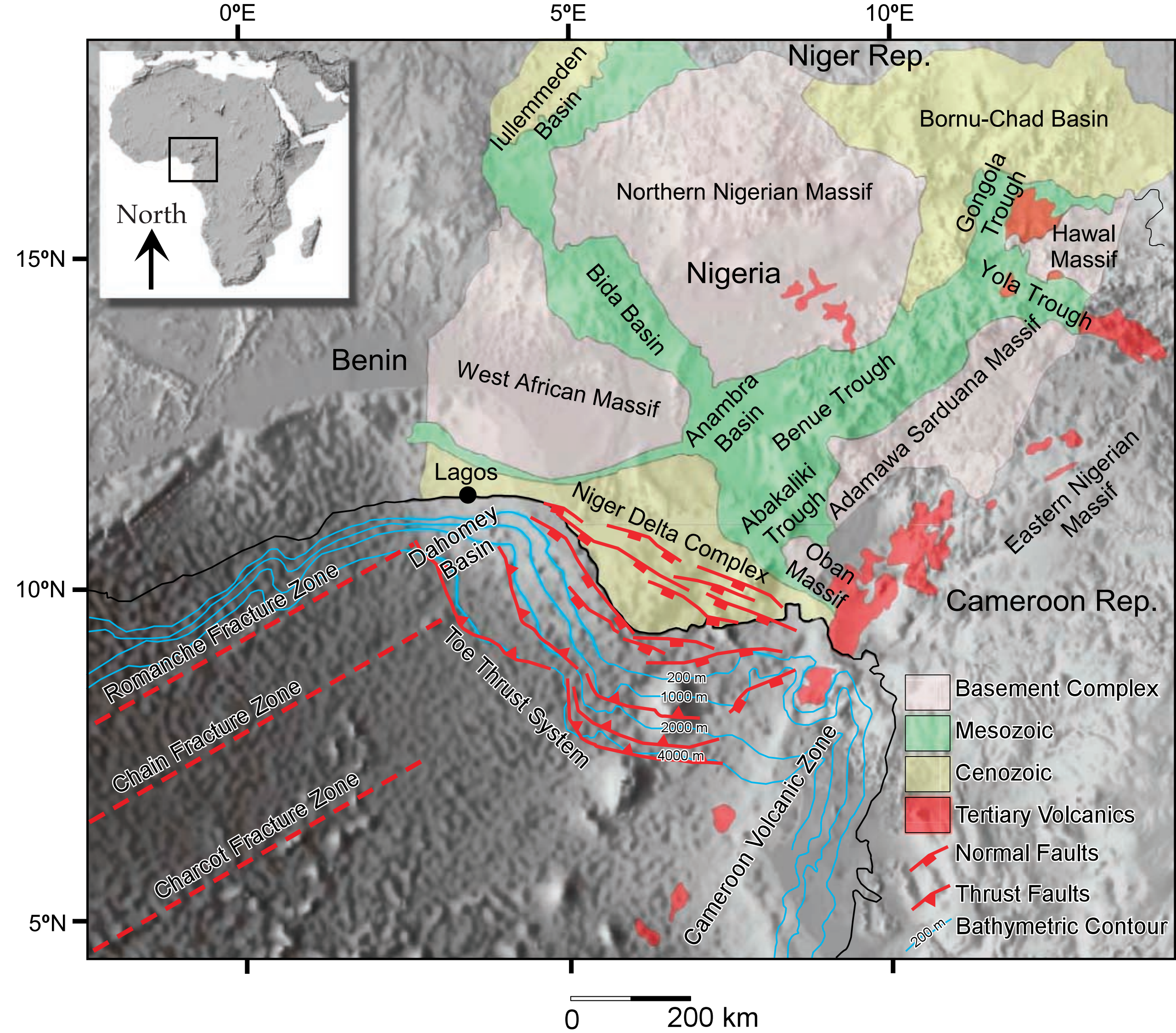


Figure 1. Location map of the Niger Delta region showing the main sedimentary basins and tectonic features. The delta is bounded by the Cameroon volcanic zone, the Dahomey basin, and the 4000-m (13,100-ft) bathymetric contour. The regional geology is modified from Onuoha (1999). Topography and bathymetry are shown as a shaded relief gray-scale image.

structures and their controls on deposition may also have important implications for hydrocarbon maturation and charge.

REGIONAL GEOLOGIC SETTING OF THE DEEP-WATER NIGER DELTA

The Niger Delta is located in the Gulf of Guinea on the margin of west Africa (Figure 1). It is one of the largest regressive deltas in the world (Doust and Omatsola, 1990) and is considered a classical shale tectonic province (Wu and Bally, 2000). The boundaries of the Niger Delta are defined by the Cameroon volcanic line to the east, the Dahomey basin to the west, and the 4000-m (13,100-ft) bathymetric contour (Figure 1). The shape and internal structure of the Niger Delta are also controlled by fracture zones along the oceanic crust, such as the Charcot fracture zone (Figure 1), expressed as trenches and ridges that formed during the opening of the South Atlantic in the Early Jurassic–Cretaceous. The Niger Delta sits at the southern end of the Benue trough, which corresponds to a failed arm of a rift triple

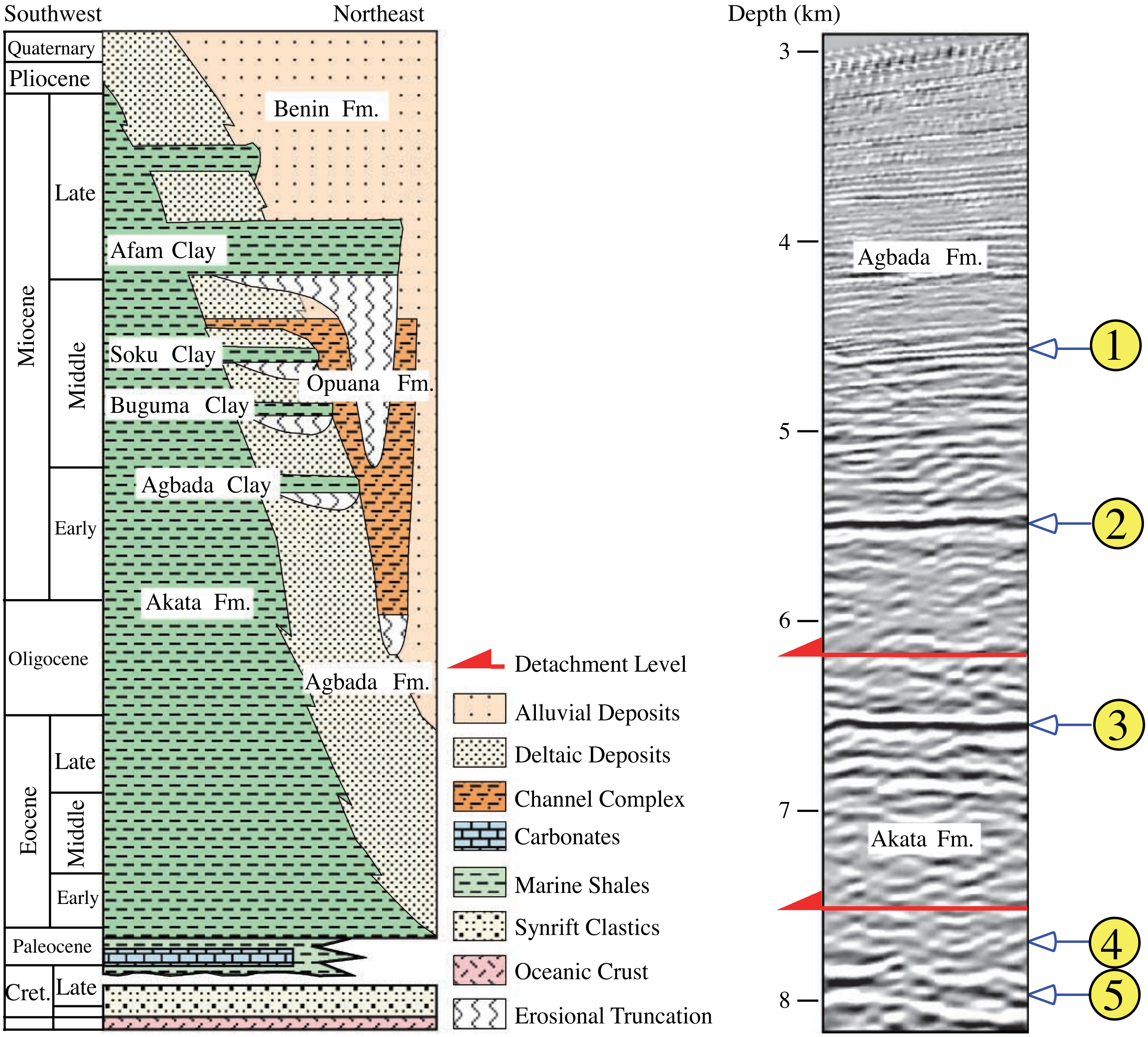


Figure 2. Schematic diagram of the regional stratigraphy of the Niger Delta and variable density seismic display of the main stratigraphic units in the outer fold and thrust belt and main reflectors, including (1) top of the Agbada Formation, (2) top of the Akata Formation, (3) mid-Akata reflection, (4) speculated top of the synrift clastic deposits, and (5) top of the oceanic crust. Main detachment levels are highlighted with red arrows. Stratigraphic section is modified from Lawrence et al. (2002).

junction, in which the rifting ceased in the Late Cretaceous (Lehner and De Ruiter, 1977). Margin failure after the cessation of rifting is caused by gravity gliding above basinward-dipping detachments and gravity spreading of a sedimentary wedge with a seaward-dipping bathymetric surface. Continued deformation is driven primarily by shelf and upper slope deposition, which maintains the bathymetric slope and the resulting gravity potential. Motion on the detachment is consumed downdip by toe-thrust systems on the outboard part of the slope.

Stratigraphy

The Niger Delta basin consists of Cretaceous to Holocene marine clastic strata that overlie oceanic and fragments of continental crust (Figure 2). The Cretaceous section has not been penetrated beneath the Niger Delta basin, and thus, Cretaceous lithologies can only be extrapolated from the exposed sections in the next basin to the northeast, the Anambra basin. In this basin, Cretaceous marine clastics consist mainly of Albian–Maastrichtian shallow-marine clastic deposits

(Nwachukwu, 1972; Reijers et al., 1997). The precise distribution and nature of correlative Cretaceous deposits beneath the offshore Niger Delta is unknown. From the Campanian to the Paleocene, both tide-dominated and river-dominated deltaic sediments were deposited during transgressive and regressive cycles, respectively (Reijers et al., 1997). In the Paleocene, a major transgression, referred to as the Sokoto (Reijers et al., 1997), initiated deposition of the Imo shale in the Anambra basin and the Akata shale in the Niger Delta basin. During the Eocene, the sedimentation changed to being wave dominated (Reijers et al., 1997). At this time, deposition of paralic sediments began in the Niger Delta basin, and as the sediments prograded south, the coastline became progressively more convex seaward. Today, delta sedimentation remains wave dominated (Burke, 1972; Doust and Omatsola, 1990).

The Tertiary section of the Niger Delta is divided into three formations, representing prograding depositional environments. The type sections of these formations are described in Short and Stäublee (1965) and summarized in a many other papers (i.e., Avbovbo, 1978; Evamy et al., 1978; Doust and Omatsola, 1990; Kulke, 1995). The Akata Formation at the base of the delta is of marine origin, and its thickness ranges from 2000 m (6600 ft) at the most distal part of the delta to 7000 m (23,000 ft) thick beneath the continental shelf (Doust and Omatsola, 1990). In the deep-water fold and thrust belts, the Akata Formation is up to 5000 m (16,400 ft) thick because of structural repetitions by thrust ramps described in this study and in the core of large detachment anticlines (Bilotti et al., 2005). The Akata Formation is composed of thick shale sequences that are believed to contain source rocks and may contain some turbidite sands (potential reservoirs in deep-water environments). On seismic sections, the Akata Formation is generally devoid of internal reflections (Figure 2), with the exception of a strong, high-amplitude reflection that is locally present in the middle of the formation. This mid-Akata reflection serves as an important structural marker for defining detachment levels. The Akata exhibits low P-wave seismic velocities ($\approx$2000 m/s; $\approx$6600 ft/s) that may reflect regional fluid overpressures (Bilotti and Shaw, 2001).

Deposition of the overlying Agbada Formation, the major petroleum-bearing unit in the Niger Delta, began in the Eocene and continues into the present. The Agbada Formation consists of paralic siliciclastics more than 3500 m (11,500 ft) thick and represents the actual deltaic portion of the sequence. This clastic sequence was accumulated in delta-front, delta-topset, and fluviodeltaic environments. Channel and basin-floor fan deposits in the Agbada Formation form the primary reservoirs in the Niger Delta. Onshore and in some coastal regions, the Agbada Formation is overlain by the Benin Formation, which is composed of late Eocene to Holocene continental deposits, including alluvial and upper coastal-plain deposits that are up to 2000 m (6600 ft) thick (Avbovbo, 1978).

Structure

The Niger Delta was originally divided into three structural zones (Damuth, 1994): an extensional zone I beneath the outer continental shelf and upper slope; an intermediate translational zone II beneath the continental slope; and a compressional zone III beneath the lower continental slope and uppermost rise. After Connors et al. (1998), we further subdivide the Niger Delta into five major structural provinces or zones based on structural styles imaged in seismic data and high-resolution bathymetry. These structural zones (Figure 3) include (1) an extensional province beneath the continental shelf that is characterized by both basinward-dipping (Roho-type) and counterregional growth normal faults and associated rollovers and depocenters; (2) a mud-diapir zone located beneath the upper continental slope, which is characterized by passive, active, and reactive mud diapirs (Morley and Guerin, 1996), including shale ridges and massifs, shale overhangs, vertical mud diapirs that form mud volcanoes at the seafloor (Graue, 2000), and interdiapir depocenters; (3) the inner fold and thrust belt, which is characterized by basinward-verging thrust faults (typically imbricated) and associated folds, including some detachment folds; (4) a transitional detachment fold zone beneath the lower continental slope that is characterized by large areas of little or no deformation interspersed with large, broad detachment folds above structurally thickened Akata Formation; and (5) the outer fold and thrust belt characterized by both basinward- and hinterland-verging thrust faults and associated folds. Deformation across these structural provinces is active today, resulting in pronounced bathymetry expressions of structures that are not buried by recent sediments, as illustrated in Figure 3. The inner and outer fold and thrust belts are most evident in the bathymetry, where ridges represent the crests of fault-related folds, and low regions correspond to piggyback basins formed above the backlimbs of fault imbricates.

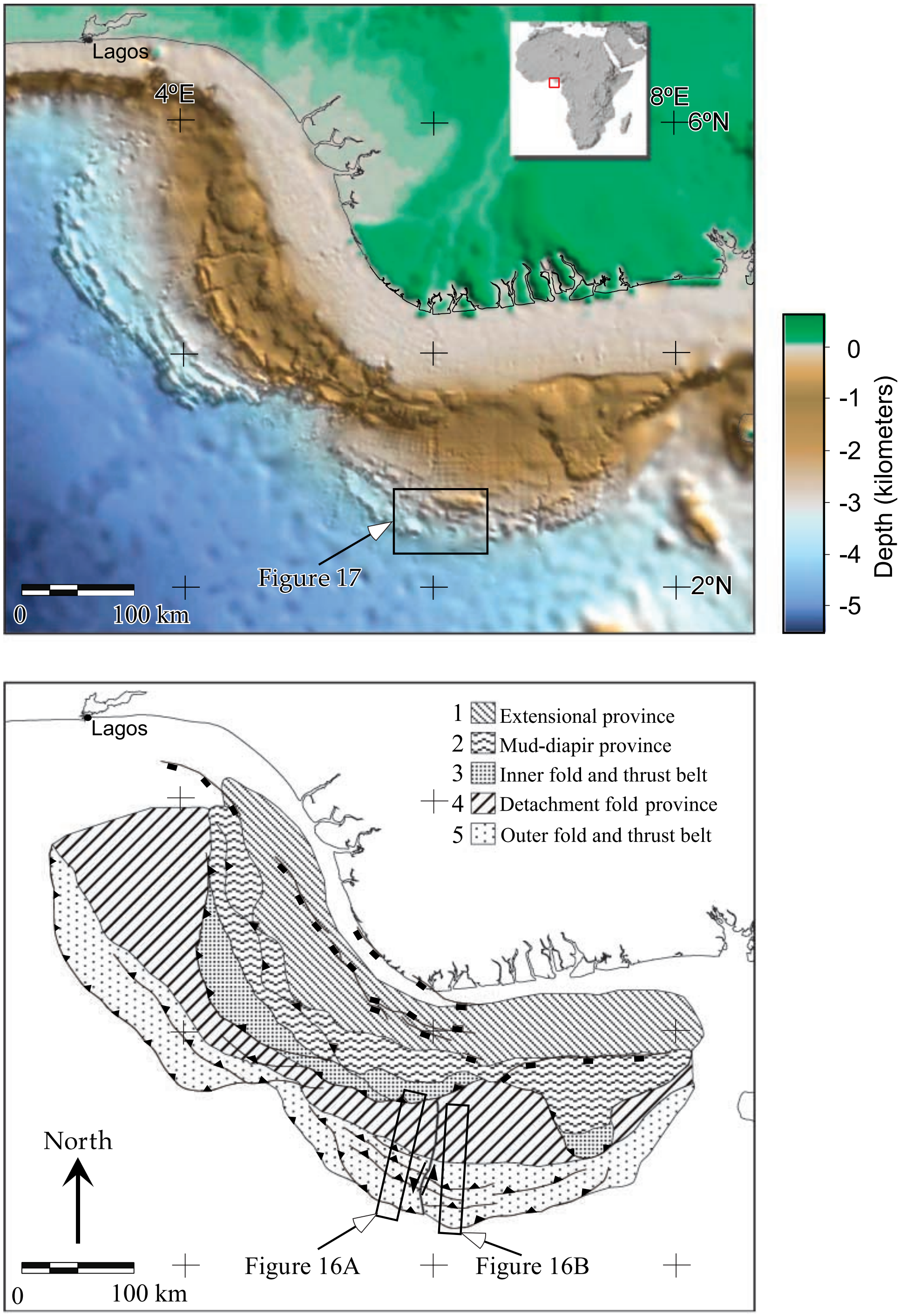


Figure 3. High-resolution bathymetric image of the Niger Delta obtained from a dense grid of two-dimensional seismic reflection profiles and the global bathymetric database (Smith and Sandwell, 1997), showing the main structural domains, including (1) an extensional province beneath the continental shelf, (2) a mud-diapir belt located beneath the upper continental slope, (3) the inner fold and thrust belt, (4) a transition zone beneath the lower continental slope, and (5) the outer fold and thrust belt.

The inner fold and thrust belt extends in an arcuate path across the center of the offshore delta, whereas the outer fold and thrust belt consists of northern and southern sections that define two outboard lobes of the delta. These two lobes, and their associated fold belts, are separated by a major rise in the basement topography that corresponds to the northern culmination of the Charcot fracture zone (Figures 1, 3). The break between the northern and southern sections of the outer fold and thrust belt results from thrust sheets being stacked in a narrow zone above and behind this major basement uplift (Connors et al., 1998; Wu and Bally, 2000).

To illustrate the deformation styles of the different structural provinces in the Niger Delta, we present a regional cross section (Figure 4) that is based on a

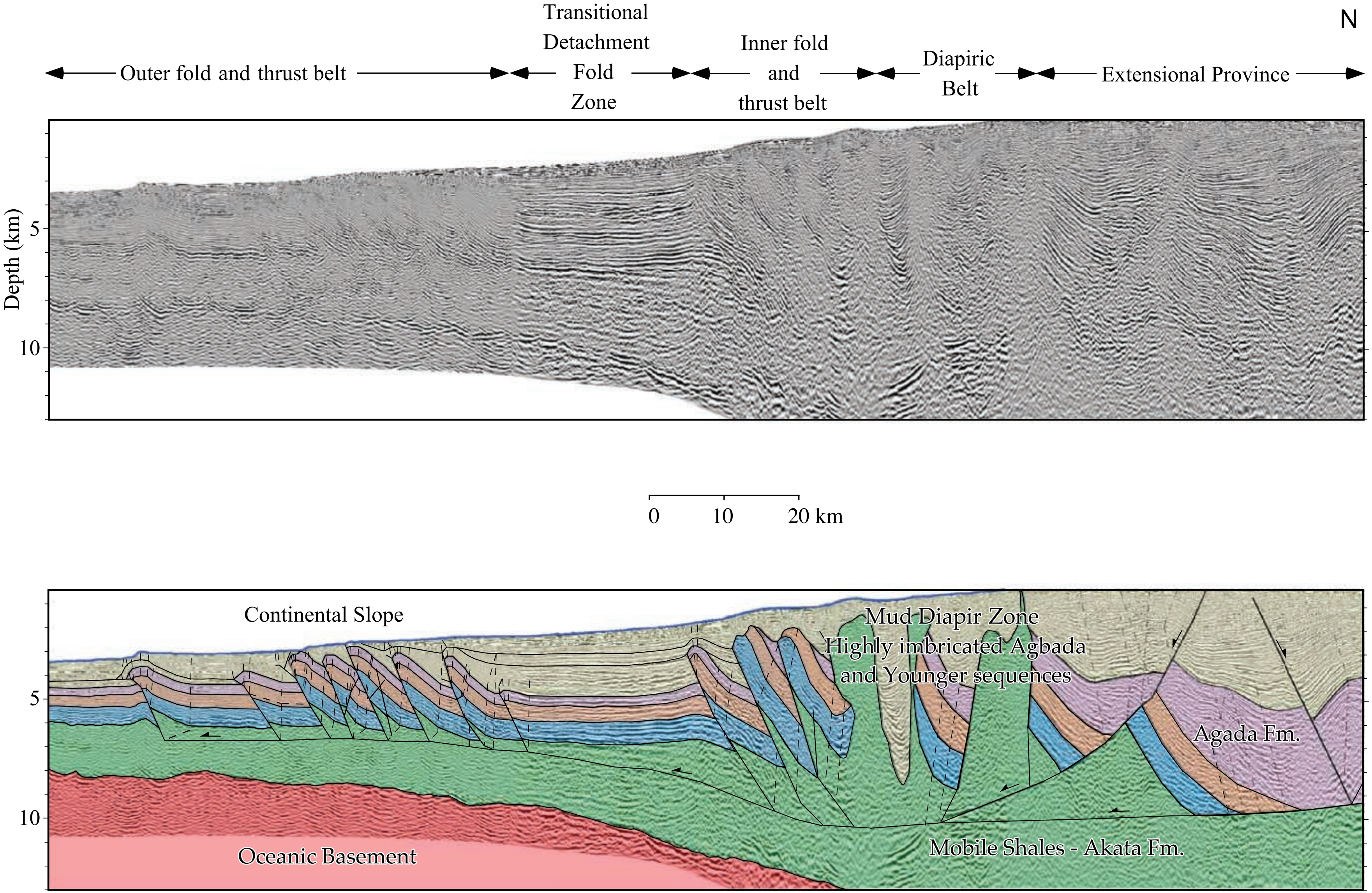


Figure 4. Uninterpreted and interpreted regional seismic profile across the Niger Delta showing the link between the extensional province on the shelf and the contraction in the toe-thrust systems in the deep water, as well as the main structural domains. Both regional and counterregional normal faults are present in the extensional province. Slip on these faults soles onto one or a series of basal detachments and extends across a diapiric zone into the deep-water fold and thrust belts. The inner and outer fold and thrust belts are separated by a zone of little or no deformation. Along strike, this transitional zone is characterized by detachment folds. Seismic section is poststack migrated and depth converted (data courtesy of Mabon Ltd.).

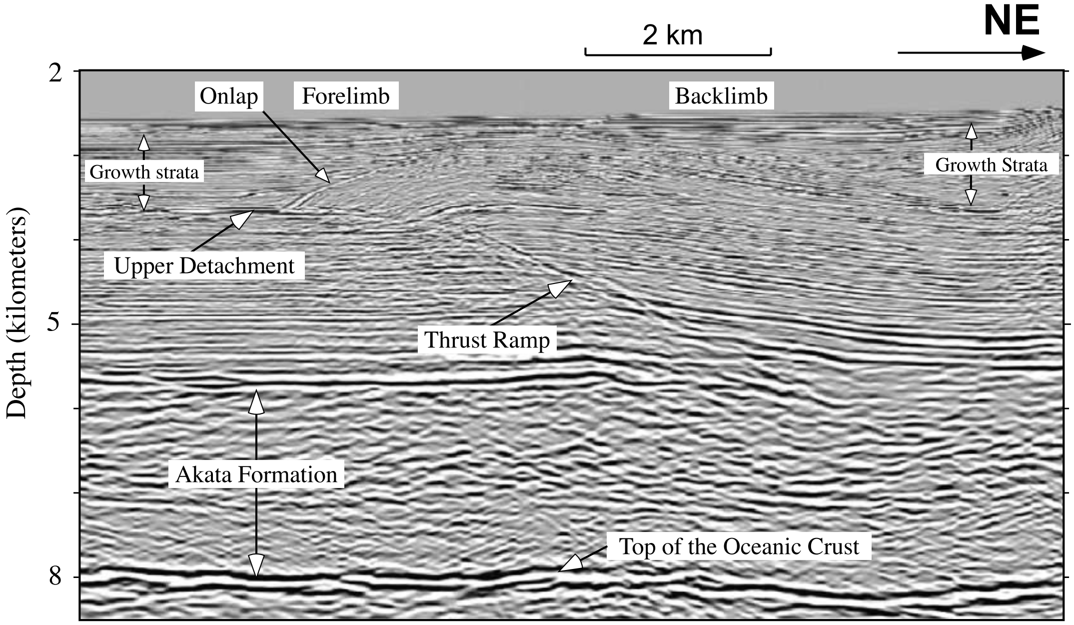


Figure 5. Seismic section across a typical toe-thrust structure in the deep-water Niger Delta with some important structural characteristics, including a relatively planar thrust ramp, a broad backlimb that dips less than the underlying thrust, and a narrow forelimb situated above the top of the thrust ramp. Upward-decreasing dips in the growth strata over the backlimb suggest folding with a component of limb rotation. Growth strata onlapping the forelimb suggest that the upper detachment was the seafloor at the beginning of thrusting, and that the structure grew with low to equal sedimentation rates compared with structural uplift rates. The top of the oceanic crust reflector is clearly illuminated. Seismic section is poststack migrated and depth converted.

poststack-migrated and depth-converted seismic section across the southern delta. The position of the regional structural cross section is similar to the section presented by Hooper et al. (2002). On the north side of the section, both basinward-dipping and counterregional growth normal faults are present in the extensional province beneath the continental shelf. Counterregional normal fault systems consist of upper Miocene to lower Pliocene prograding sequences, whereas down-to-basin growth fault systems contain upper Pliocene and Pleistocene distal prograding units with shingled toe turbidities (Mitchum et al., 2000). A major detachment zone in the Akata Formation links the extensional province across the mud-diapir zone to the contractional fold-thrust belts in the lower slope. Highly imbricated thrust sheets containing Tertiary to Holocene delta-front to deep-marine sediments form the inner and outer fold and thrust belts. The two fold belts are clearly separated by a zone of little deformation (Figure 4), which, along strike, is characterized by large detachment folds. Most thrust faults in these systems, with exceptions in the northern and central parts of the delta, verge toward the deep ocean and sole to detachment levels located inside the Akata Formation.

STYLES OF THRUSTING AND FAULT-RELATED FOLDING

Thrust faults in the deep-water Niger Delta are generally discrete, planar surfaces with continuity along the strike for several tens of kilometers. Fault ramps are typically defined by prominent fault-plane reflections (Figure 5) and sole to several different detachments in the Akata Formation. Fault-related folds above these thrusts are generally characterized by long planar backlimbs that dip substantially less than the underlying fault ramps. An upward shallowing of dips in growth strata above these backlimbs suggests a component of progressive limb rotation (Hardy and Poblet, 1994; Novoa et al., 2000; Shaw et al., 2004; Suppe et al., 2004) (Figure 5). Forelimbs are short compared to backlimbs and generally dip more steeply. Forelimb growth structures show more consistent dips that suggest a component of folding by kink-band migration, perhaps with lesser amounts of limb rotation. Steeper forelimbs are typically underlain by thrust tips similar to fault-propagation folds; however, most forelimbs that dip gently are underlain by shallow detachments, which, in many cases, occur at the paleoseafloor (Figure 5). In general, growth sedimentation rates are low compared

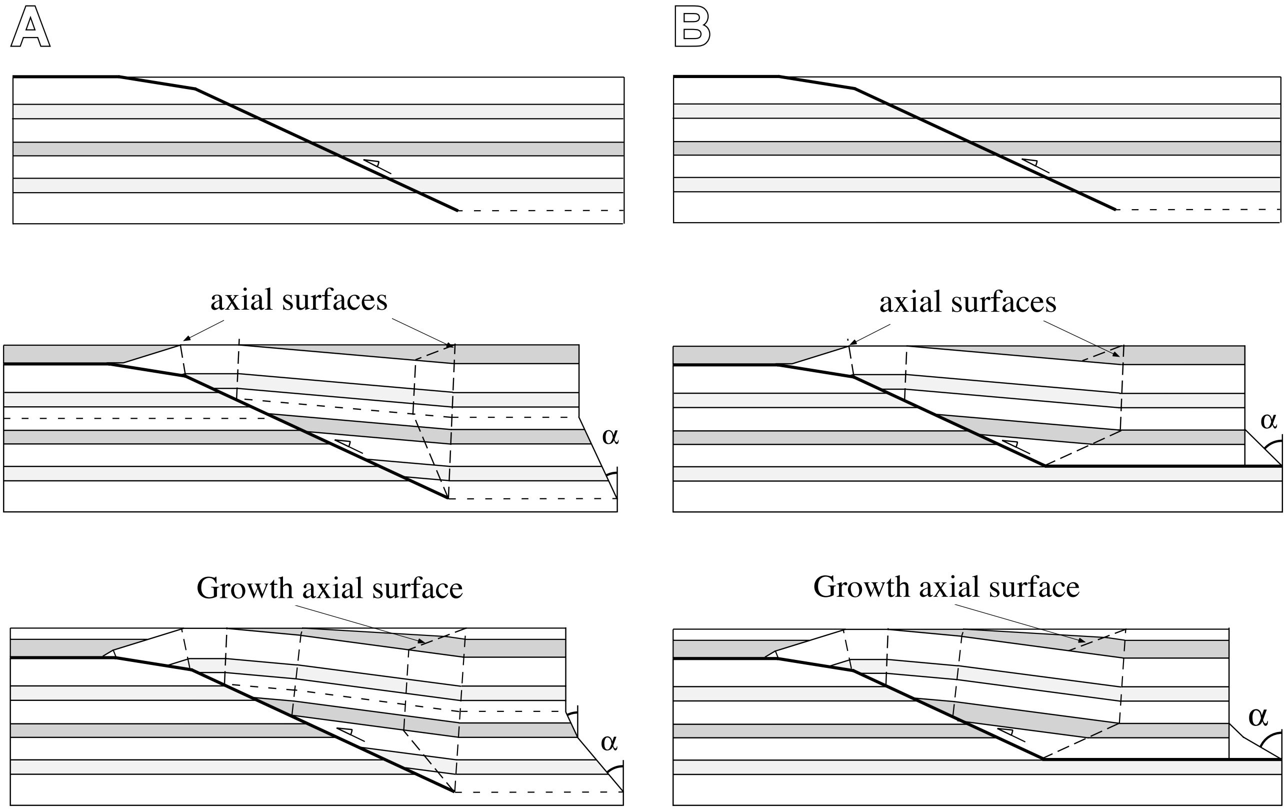


Figure 6. Sequential forward models of (A) simple- and (B) pure-shear fault-bend folds (Suppe et al., 2004), where the long, planar backlimbs dip less than the associated fault ramps. Patterns of growth sedimentation, where the uplift rates along the fault ramp are equal to the rates of growth sedimentation, indicate fold growth by combined limb rotation and kink-band migration. Growth strata onlapping the forelimb suggest that the upper detachment was the top of the pregrowth section at the beginning of thrusting. In simple-shear fault-bend folding, there is no slip required along the detachment level, and the decollement layer undergoes an externally imposed bedding-parallel simple shear. In pure-shear fault-bend folds, there is slip along the detachment level, and the decollement layer shortens and thickens above the fault ramp.

to fold and fault uplift rates, resulting in patterns of onlap above fold limbs and the emergence of the fold crest at the seafloor (Figure 5).

A combination of kink-band migration and limb rotation fold kinematics is invoked to model these deep-water Niger Delta fault-related folds, based on the characteristic geometries of growth strata described in the previous paragraph. Suppe (1999) and Suppe et al. (2004), following Jordan and Noack (1992), presented a theory to describe a new type of fault-bend fold (simple- and pure-shear fault-bend folds) that employ such hybrid kinematics (Figure 6) and has been shown to successfully describe Niger Delta toe-thrust structures (Corredor et al., 2005). These structures form by an externally imposed shear over a weak decollement layer of finite thickness at the base of fault ramps with, or without, basal fault slip. The geometry of shear-fault-bend folds is a function of both underlying fault geometry and shear magnitude. These structures are readily distinguished from classic fault-bend folds (Suppe, 1983) because their backlimbs (1) dip significantly less than underlying fault ramps; (2) are much wider than slip along the ramp; and (3) grow with a component of limb rotation, which is generally reflected in the growth strata (Shaw et al., 2004; Suppe et al., 2004).

We present an example of a single-shear fault-bend fold in the outer fold and thrust belt of the deep-water Niger Delta in Figure 7. This structure is interpreted as a pure-shear fault-bend fold (Suppe et al., 2004; Corredor et al., 2005), where the deformation of a weak decollement layer (Akata Formation) is locally confined to the rock volume in the immediate vicinity of the bottom of the fault ramp. Notice how the reflections at the bottom of the seismic section in Figure 7 are not deformed or offset by any faults, indicating that the basal detachment lies above the oceanic crust. An upper detachment is also observed below the forelimb,

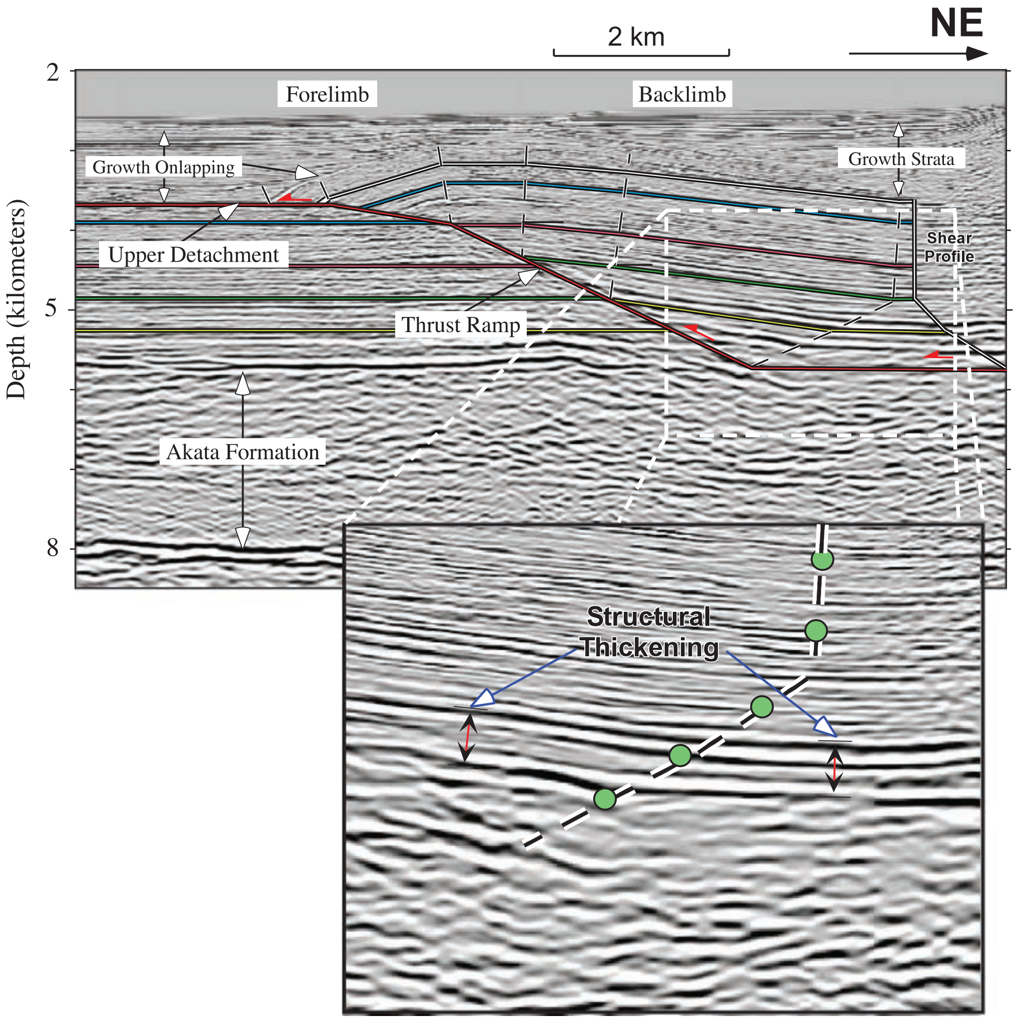


Figure 7. Seismic interpretation of a pure-shear fault-bend fold (Corredor et al., 2005). See Figure 5 for uninterpreted seismic section. The interpretation reflects some important characteristics of the structure, including the fold and fault shapes and the onlaps and fanning of limb dips in growth strata. Notice how the backlimb of the fold dips much less than the fault ramp, reflecting distributed shear in the lowermost deltaic and uppermost Akata section. Decreasing dips upward in growth strata over the backlimb of the fault-related fold suggest folding by limb rotation. The synclinal axial surface is not the angle bisector across the bottom of the deformed section. Green dots represent points of change of dip. The forelimb is modeled with the classic fault-bend folding theory (Suppe, 1983; Corredor et al., 2005).

which is interpreted as a simple fault bend that developed as it slipped past the ramp onto this upper detachment. The upper detachment corresponds to the seafloor at the time of formation of this structure, as it is immediately overlain by growth strata in the syncline adjacent to the forelimb. These growth strata onlap the forelimb, suggesting a low sedimentation rate compared to the uplift rate in the structure.

In the backlimb, the lack of any dip panels that are parallel to the underlying fault ramp, as well as the limb rotation recorded in the growth strata, suggests that shear is an important process in the formation of this structure. We interpret this structure as a pure-shear fault-bend fold (Figure 7), where the transfer of slip from the basal detachment to the fault ramp is accommodated by shortening and thickening of the overlying weak decollement layer. Notice in the model (Figure 6) and seismic example (Figure 7) how the backlimb synclinal axial surface, near the bottom of the fault ramp, is not the angle bisector across the ductile decollement layer where the shear is occurring, whereas the same axial surface is the angle bisector across the stratigraphic sequence above the ductile layer. This change in the inclination of the synclinal axial surface reflects the change in thickness of the ductile decollement layer above the bottom of the fault ramp that results from the pure shear (Suppe et al., 2004). The backlimb of this pure-shear fault-bend fold grows by components of limb rotation and kink-band migration, as recorded by the patterns of growth strata, whereas the forelimb grows exclusively by kink-band migration as a classic fault-bend fold.

We also recognize structures in the deep-water Niger Delta that are best described as simple-shear fault-bend folds (Figure 8). Like pure-shear fault-bend folds, simple-shear fault-bend folds are characterized by long planar backlimbs that dip less, typically much less, than the underlying fault ramps, with upward-shallowing dips

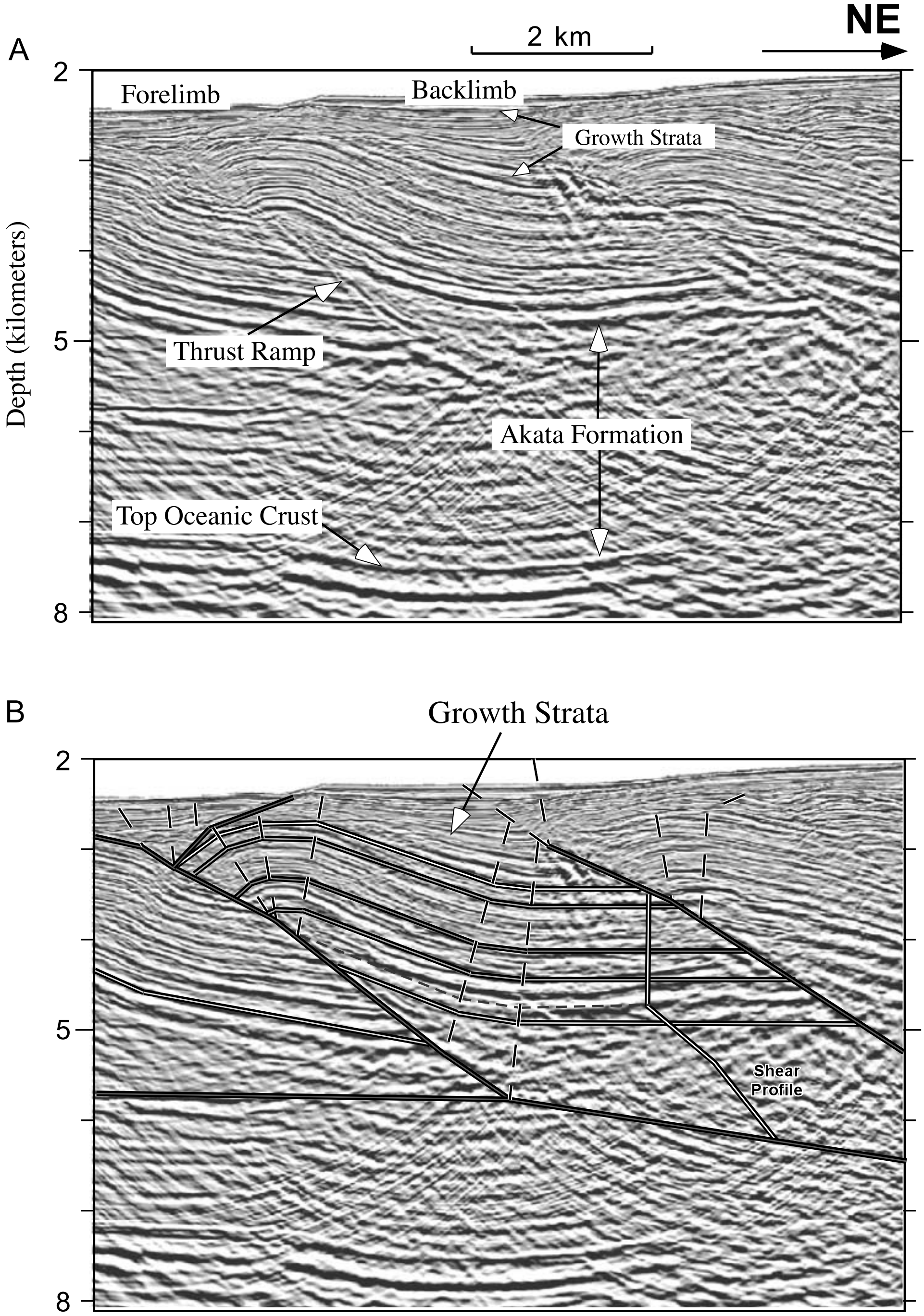


Figure 8. (A) Uninterpreted and (B) interpreted two-dimensional poststack-migrated and depth-converted seismic section through a simple-shear fault-bend fold (Suppe et al., 2004). The interpretation reflects some important characteristics of the structure, including the fold and fault shapes and the onlaps and fanning of limb dips in growth strata. Notice how the backlimb dips much less than the fault ramp. Decreasing dips upward in growth strata above the backlimb suggest folding by limb rotation. Growth strata onlap above the forelimb, suggesting low to equal growth sedimentation rates compared with structural uplift rates. This simple-shear fault-bend fold has a planar backlimb synclinal axial surface. This serves as the primary means of distinguishing this type of structure from pure-shear fault-bend folds.

in growth strata suggesting a component of progressive limb rotation. This type of fault-bend fold forms as a decollement layer of finite thickness undergoes externally imposed homogenous simple shear (Suppe et al., 2004), with no requirement of slip along a discrete basal detachment surface. Slip along the fault ramp increases from zero at the bottom of the ramp to a maximum at the intersection of the ramp with the top of the decollement layer that undergoes shear. As described by Suppe et al. (2004), simple-shear fault-bend folds grow by a component of limb rotation and a component of kink-band migration (Figure 6), resulting in patterns of growth strata that show upward shallowing of dips. Simple-shear fault-bend folds have planar backlimb synclinal axial surfaces, unlike pure-shear structures. This serves as the primary means of distinguishing these types of structures. In Figure 8, we contend that a planar backlimb syncline is most

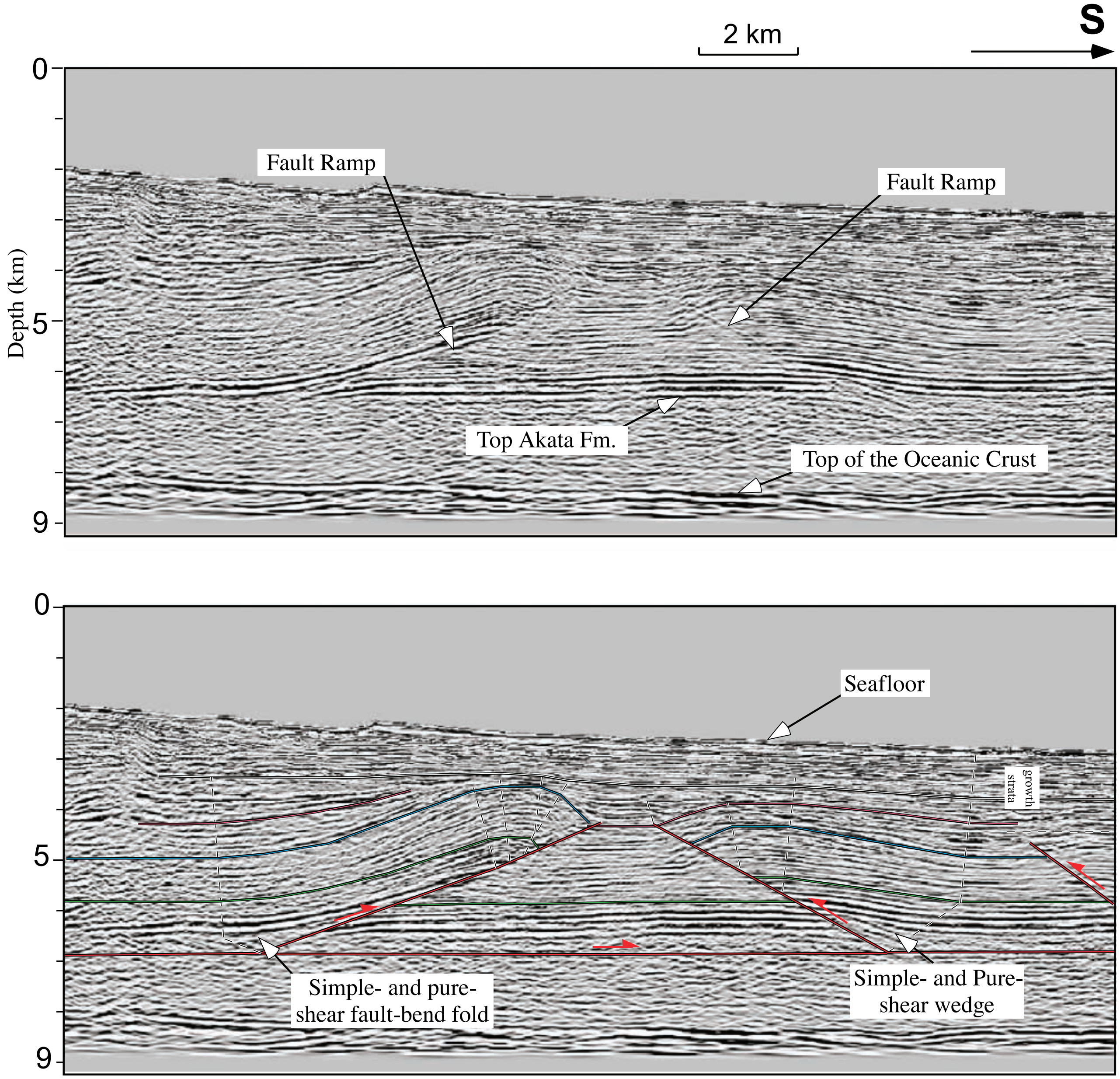


Figure 9. Uninterpreted and interpreted seismic profile showing a simple-shear fault-bend fold and a pure-shear wedge in the leading edge culmination of the outer fold belt. Note the common detachment level for both the forethrust and backthrust near the top of the Akata Formation (seismic data courtesy of Mabon Ltd.).

consistent with the imaged fold shape and inferred depth of the basal detachment, and thus, it is the basis for interpreting this structure as a simple-shear fault-bend fold.

In the central and northern delta, the outer fold and thrust commonly includes backthrusts and tectonic wedges (Figure 9). These backthrusts typically occur in places where the bathymetric slope, basal detachment, and maximum horizontal stress directions are essentially parallel to one another, yielding an equal preference for fore- and backthrusts (Bilotti and Shaw, 2001). The geometry and kinematics of these wedge structures are also effectively described by shear fault-bend theory (Suppe et al., 2004). Most wedges, and especially those that occur at the outboard toes of the fold belt, are best described by pure-shear theory because it is unlikely that externally imposed simple shear would extend from the foreland beyond the deformation front. The structures imaged in Figure 9 demonstrate that pure- and simple-shear fault-bend folds can occur in close proximity to one another and share common basal detachments.

In general, we assess that pure-shear fault-bend folds are more common than simple-shear folds in the deep-water fold and thrust belts of the Niger Delta. This implies that the deformation in the Akata Formation, which encompasses the weak decollement layer, is more typically confined to the rock volume in the immediate vicinity of the fault ramps. Perhaps this is caused by stress concentrations localizing deformation or the fact that the Akata in places is highly dissected by imbricate thrust structures, making it difficult to transfer simple shear over large distances. In the next section, we explore these imbricate structures, further developing the concepts of shear fault-bend folding described and applied here.

Several considerations are observed in applying shear fault-bend fold methods to interpret structures in the deep-water Niger Delta and similar structural provinces. Foremost is that the method of distinguishing between simple- and pure-shear fault-bend fold end members relies heavily on identifying the patterns of axial surfaces. The ability to do this depends, of course, on the quality of the imaging and accuracy of depth migrations or conversions, especially in synclines near the bottom of fault ramps. Differences between simple- and pure-shear solutions impact the predicted depth of the detachment, and so, it is critical to use the best available tools to help constrain these interpretations. Given that the decollement layer is weak, it is possible, if not likely, that both pure- and simple-shear processes are active together in folds. In other words, there is both simple shear in the weak layer and local thickening caused by complex small-scale deformation. Nevertheless, we argue that many of the structures can be successfully modeled as approximating pure- or simple-shear end members, and that sufficient imaging quality does exist in many cases to distinguish these two types of structures. Furthermore, the predicted basal detachment levels can be evaluated in relation to nearby structures or other regional considerations, further helping to distinguish pure- from simple-shear fault-bend folds.

IMBRICATE THRUST SYSTEMS IN THE DEEP-WATER NIGER DELTA

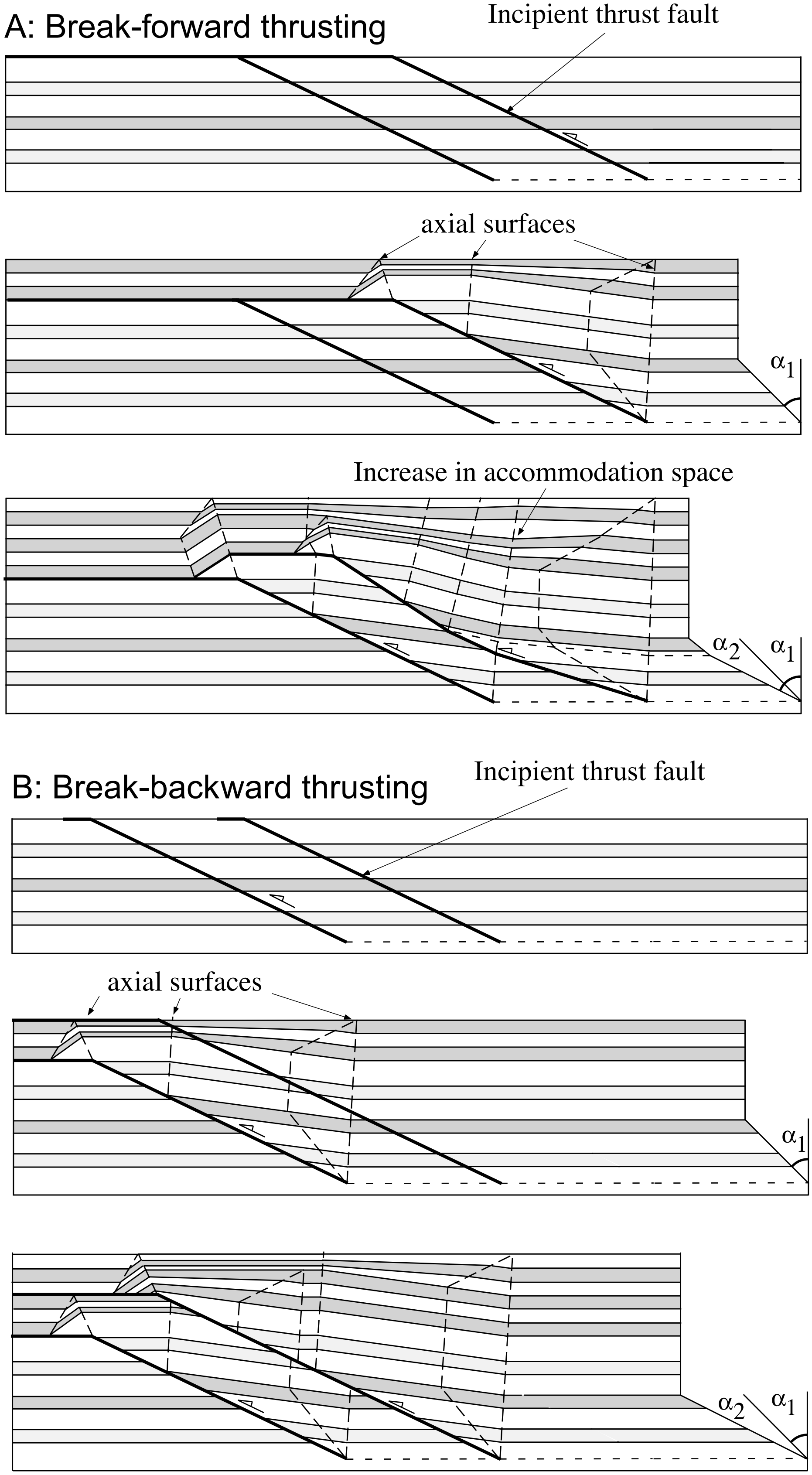
The Niger Delta offers a unique opportunity to study complex imbricate thrust systems because these structures are essentially unmodified by erosion and are extremely well imaged in seismic reflection data (Figures 4, 5). Imbricate systems occur in the deep-water Niger Delta in both the inner and outer fold and thrust belts in a range of styles with varying magnitude of shortening. Some structures appear to conform with common duplex and break-forward imbricate thrust models (Dahlstrom, 1969; Suppe, 1983; Moen-Maurel et al., 1999), whereas other systems exhibit more complex patterns that are consistent with multiple detachment levels and out-of-sequence (break-backward) thrusting (Shaw et al., 1999). The style, size, fault spacing, and thrusting sequence of these systems appear to vary with respect to the thickness of the sedimentary pile (depth of detachment), sedimentary and detachment slopes, and the nature and internal structure of the sedimentary pile and detachment unit. Hence, variations in these parameters that result from the complex stratigraphic and structural framework of the Niger Delta produce a wide variety of imbricate structures. Moreover, variations in regional sedimentation, including switching of deposition among various delta lobes, have led to a complex history of thrusting.

In this study, we emphasize three major structural elements that influence the most common styles of imbricate thrust systems in the Niger Delta, namely, (1) the mode of shear transfer between thrust sheets, (2) the thrusting sequence, and (3) the number and depth of basal detachments. The following sections address each of these elements and the influences on styles of imbrication.

Imbricate-Shear Fault-Bend Folding

To model the imbricate systems in the deep-water Niger Delta, we expanded on shear fault-bend folding theory and developed forward models for both break-forward and break-backward imbricate systems. Imbricate-shear fault-bend fold systems are characterized by the transfer of shear both forward and backward across fault imbricates with or without displacement along detachment levels. Shear can be transferred across individual fault imbricates in several ways, reflecting the styles of shear fault-bend folding in individual thrust sheets and their thrusting sequences (Corredor et al., 2001, 2005; Suppe et al., 2004). Figure 10 illustrates two end-member modes of shear transfer in imbricate systems. In break-forward imbricate systems involving simple-shear fault-bend folds, shear can be transmitted forward across the imbricate thrust stack into new thrust sheets, with or without further slip on the preexisting faults, and with or without slip along a basal detachment. This tends to result in a decrease

Figure 10. Sequential forward models for two end-member modes of imbricate-shear fault-bend folds with patterns of growth sedimentation, including (A) break-forward imbrication with distributed transfer of shear and (B) break-backward imbrication with no transfer of shear (redrawn from Corredor et al., 2001).



of the ramp and bed dips in hinterland thrust sheets (Figure 10A). This shallowing of imbricated thrust ramps is in direct contrast to conventional break-forward imbricate systems (Suppe, 1983), where imbrication causes a steepening of overlying thrust sheets. Rotation of these hinterland thrust sheets by simple shear also typically refolds and shallows parts of the overlying fold limbs, yielding fold limbs with multiple dip domains. This refolding, and the decrease in ramp dip, effectively produces an increase in accommodation space for growth sedimentation. This can result in minibasins developing above the refolded limbs, with structural downlap and other distinctive stratigraphic patterns in growth strata. The hinterland thrust sheets also decrease their structural relief.

In break-backward imbricate systems involving shear fault-bend folds, shear is transmitted toward the hinterland with or without additional deformation occurring in the older, foreland thrust sheet (Figure 10B). The development of multiple dip domains in the younger, hinterland structure results from its thrust fault displacing and refolding parts of the older frontal thrust sheets. Patterns of truncated and offset axial surfaces make these break-backward imbricate structures distinct from their break-forward counterparts. In the following section, we apply these end-member models to interpret imbricate structures based on their thrusting sequence.

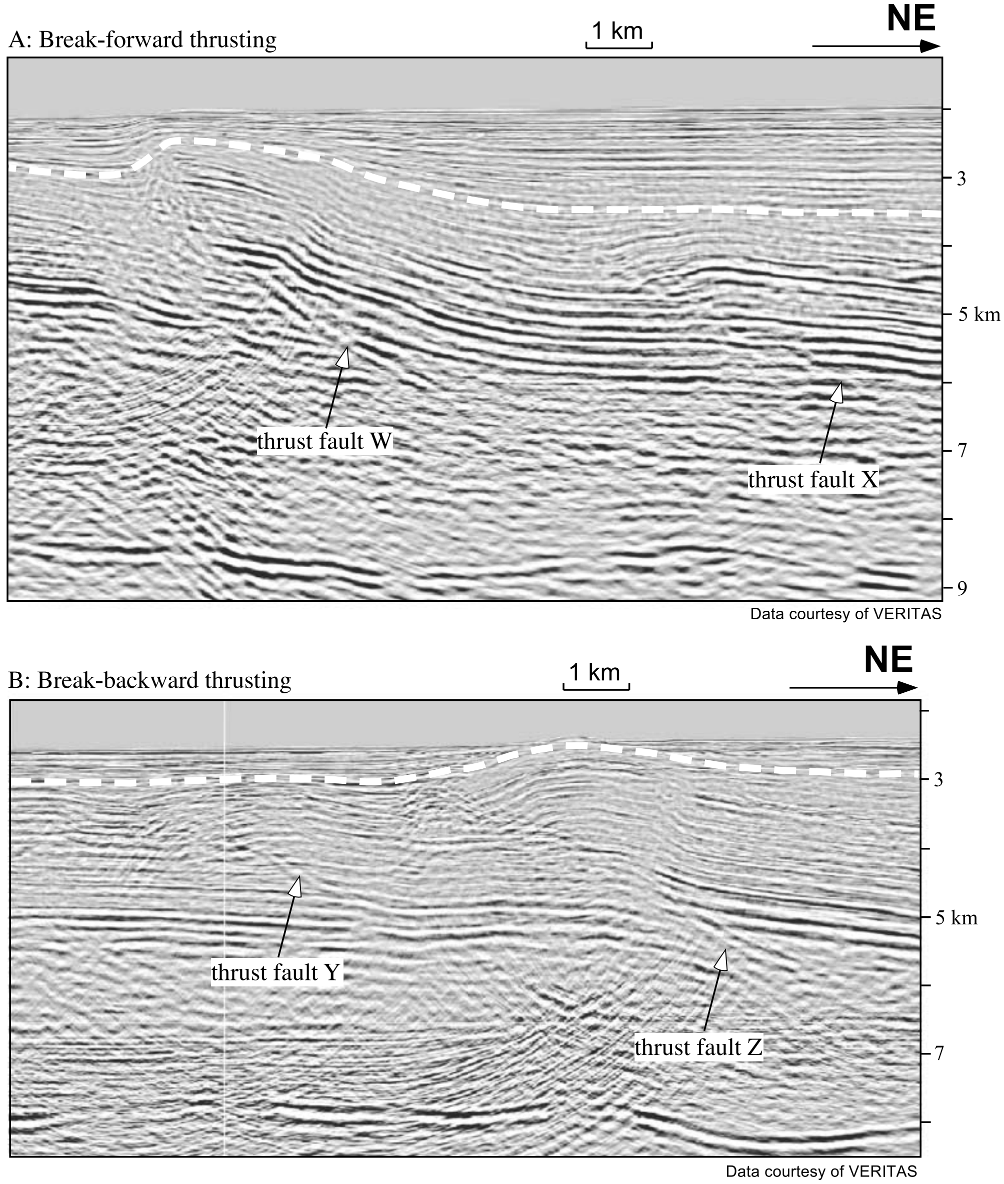
Thrusting Sequence Resolved by Growth Strata

Spatial and temporal variations in deposition across the delta have led to a complex history of thrusting. In particular, the age of thrusting in the Niger Delta does not simply propagate toward the foreland or hinterland. Instead, local thrust systems exhibit components of both break-forward and break-backward thrusting. Moreover, the complex geometries that result from the imbricate-shear fault-bend folding described in the previous section make it challenging to define the sequence of imbrication from classic geometric relationships between dip panels (Suppe, 1983; Shaw et al., 1999). Thus, in many cases, it is necessary to use patterns of growth strata and unconformities to establish the sequences of imbrication in deep-water Niger Delta structures. In general, the rates of sedimentation to uplift in these structures are low, yielding patterns of onlap above forelimbs and backlimbs, folded growth strata above backlimbs, and in some cases, exposed fold crests. As illustrated by the models presented in the previous section, these patterns of growth sedimentation are diagnostic of thrusting sequences for imbricate-shear fault-bend folds (Figure 10). Figure 11A is an example of a break-forward sequence of imbrication that results from new thrust faults being developed in the footwall of what was previously the active thrust imbricate (Butler, 1982). Folded growth strata over the leading thrust sheet are younger than those folded in the trailing thrust sheet. In contrast, Figure 11B shows a break-backward sequence of imbrication, where thrusting has propagated from foreland to hinterland. Growth strata over the trailing thrust sheet are younger than those folded over the leading thrust sheet.

Guided by the patterns of growth strata illustrated in these models, we identify both break-forward and break-backward imbricate systems in the inner and outer fold and thrust belts of the Niger Delta (Figures 12, 13). The example presented in Figure 12 corresponds to a break-forward shear imbricate system in the outer fold and thrust belt, where the shear has been transferred forward into a new foreland thrust sheet. We interpret that at the time of initial formation of these structures, the thrust faults emerged to the seafloor. The foreland-directed simple shear has folded the preexisting imbricate toward the hinterland similar to the model in Figure 11A. Notice how the angle of the hinterland fault ramp, as well as the associated backlimb dips, changes from higher values in the upper part of the ramp to lower dips in the lower part of the ramp. The inflection point between these two dip segments at the fault ramp, from which a hanging-wall axial plane emanates, corresponds to the top of the weak decollement layer that undergoes shear in the frontal imbricate. This relationship suggests that the reduction of dips toward the hinterland is produced by the shear that has been transferred forward into the younger imbricate. The patterns of growth strata are also consistent with this general thrusting sequence because they indicate an initial phase of deformation of the hinterland thrust sheet that predates the foreland structure. During the latter phase of foreland thrusting, it appears that the hinterland thrust sheet also moved. This period of coeval foreland and hinterland thrusting is compatible with the structural patterns induced by the initial break-forward component of thrusting (Shaw et al., 1999).

To further test our interpretation of break-forward thrusting in Figure 12, we use the folding vector method (Shaw et al., 1999). Notice how the vector U, which measures the deflection from the horizontal of bedding in a dipping panel above the frontal imbricate, is equivalent to the vector U′, which measures the deflection of the thrust ramp of the trailing imbricate. This relationship shows that the deflection of the trailing

Figure 11. Seismic sections imaging two fault sets (W, X and Y, Z) showing different sequences of thrusting. In (A), the fold associated with fault X does not deform and, thus, predates the annotated yellow horizon. The fold related to fault W clearly deforms and, thus, postdates this horizon, reflecting a break-forward thrusting sequence. In (B), the fold associated with fault Y does not deform and, thus, predates the annotated yellow horizon. The fold related to fault Z clearly deforms and, thus, postdates this horizon, reflecting a break-backward thrusting sequence.



thrust sheet is caused by folding related to the frontal imbricate.

In contrast, Figure 13 illustrates three thrust sheets with a break-backward sequence of imbrication as interpreted from the patterns of growth sedimentation, where increasingly younger growth strata are folded toward the hinterland. A constant dip value for each of the three backlimbs is observed, suggesting that no refolding by break-forward imbrication has occurred. Additionally, it can be observed how folds and axial surfaces of foreland structures are truncated by hinterland thrust ramps.

The break-backward imbricate system shown in Figure 13 is located in the outer fold belt of the deep-water Niger Delta, along the same two-dimensional seismic section and behind the break-forward thrust system presented in Figure 12. This suggests a complex internal sequence of imbrication for Niger Delta fold belts, which will be also documented in our restorations of regional structural sections. This observation of complex sequences of imbrication is similar to results obtained in analog models for fold and thrust belts above weak decollements (Costa and Vendeville, 2002).

Role of Basal Detachment Levels in Styles of Imbricate Systems

Two major, regional basal detachment levels are common in the Niger Delta thrust belts: one near the top of the Akata Formation and the other near the bottom

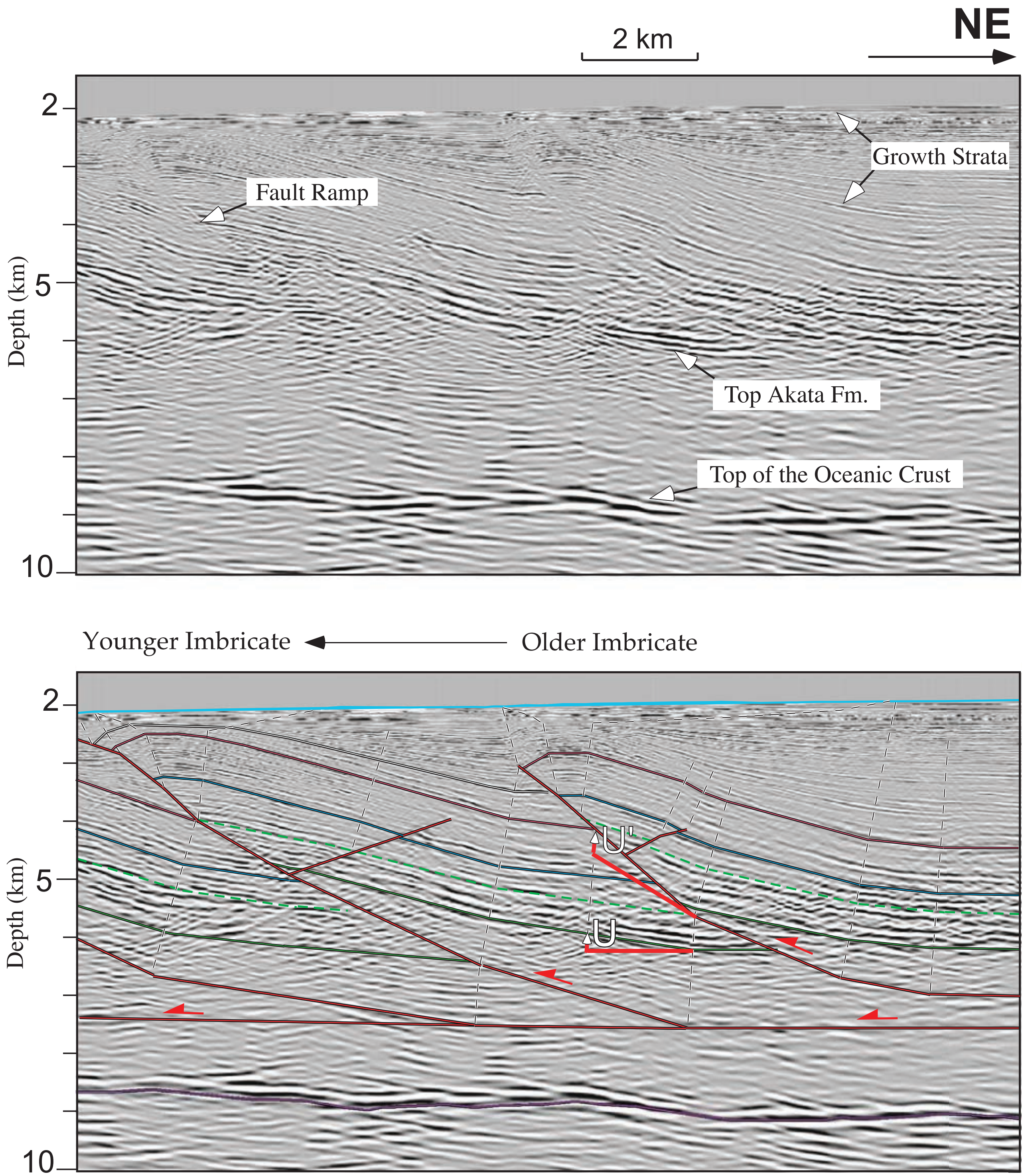


Figure 12. Uninterpreted and interpreted seismic section across a break-forward imbricate system with forward distributed transfer of shear, showing the patterns of growth sedimentation (compare with model in Figure 10A). Folding vectors used to test the sequence of imbrication: Vector U represents the amount of shear required to fold the green layer in the footwall, which is equal to vector U′ that represents the amount of folding of the overlying fault ramp. This relationship between folding vectors is indicative of a break-forward sequence of imbrication (Shaw et al., 1999). Individual thrust sheets are interpreted as multibend simple shear fault-bend folds (Suppe et al., 2004), similar to the model shown in Figure 10.

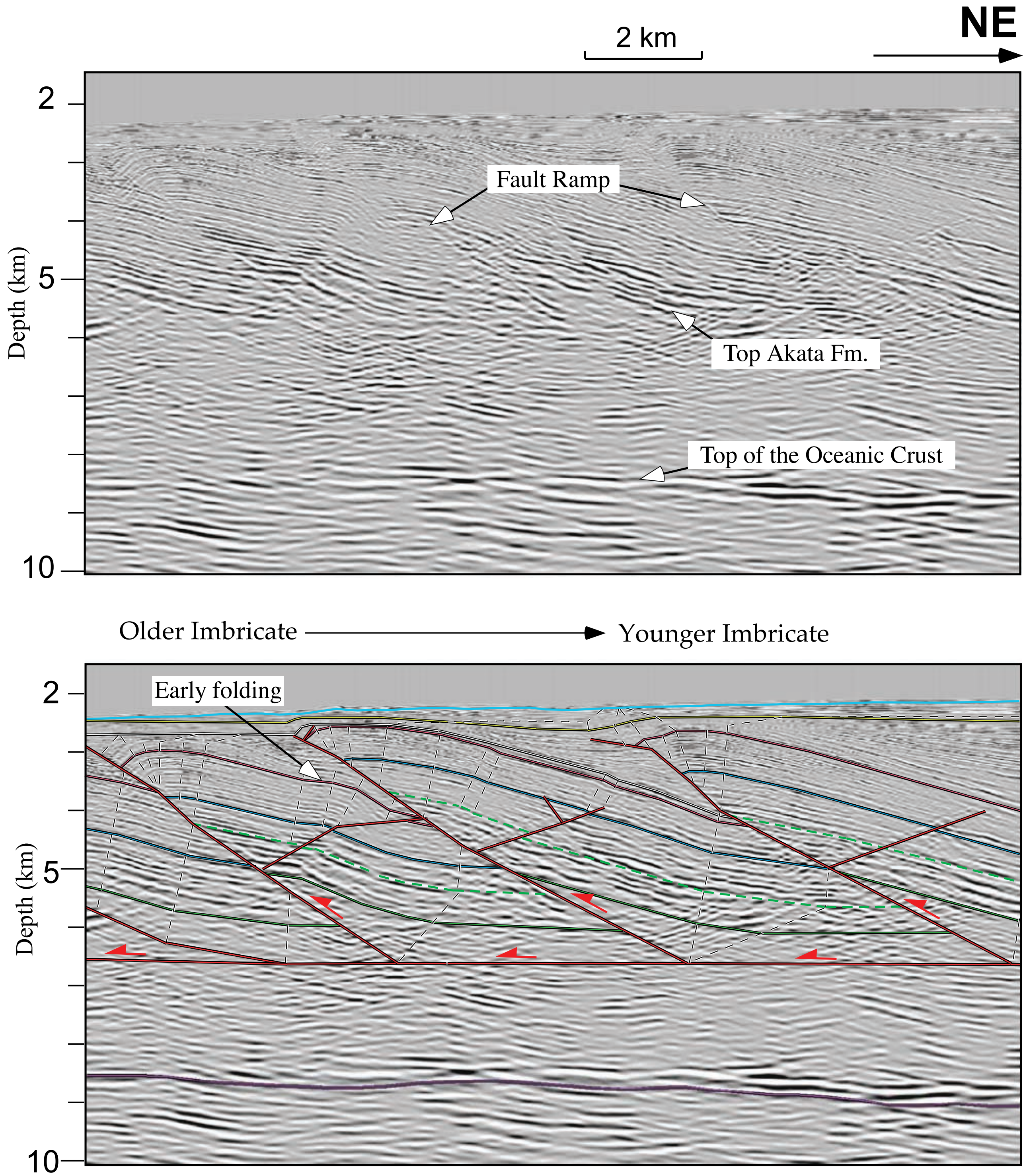


Figure 13. Uninterpreted and interpreted seismic profile across a break-backward imbricate system with no distributed transfer of shear, showing the patterns of growth sedimentation. Individual thrust sheets are interpreted as multibend simple and pure shear fault-bend folds (Suppe et al., 2004), similar to the model shown in Figures 10 and 11.

of the same formation near the top of the oceanic basement (Figure 14). The presence of one (Figure 14) or both detachment levels (Figure 14) in different parts of the thrust belts strongly influences the style of thrusting and imbrication and serves as the basis for our definition of two end-member styles of imbricate systems. Type I imbricate systems consist of several thrust sheets, typically with a complex internal sequence of

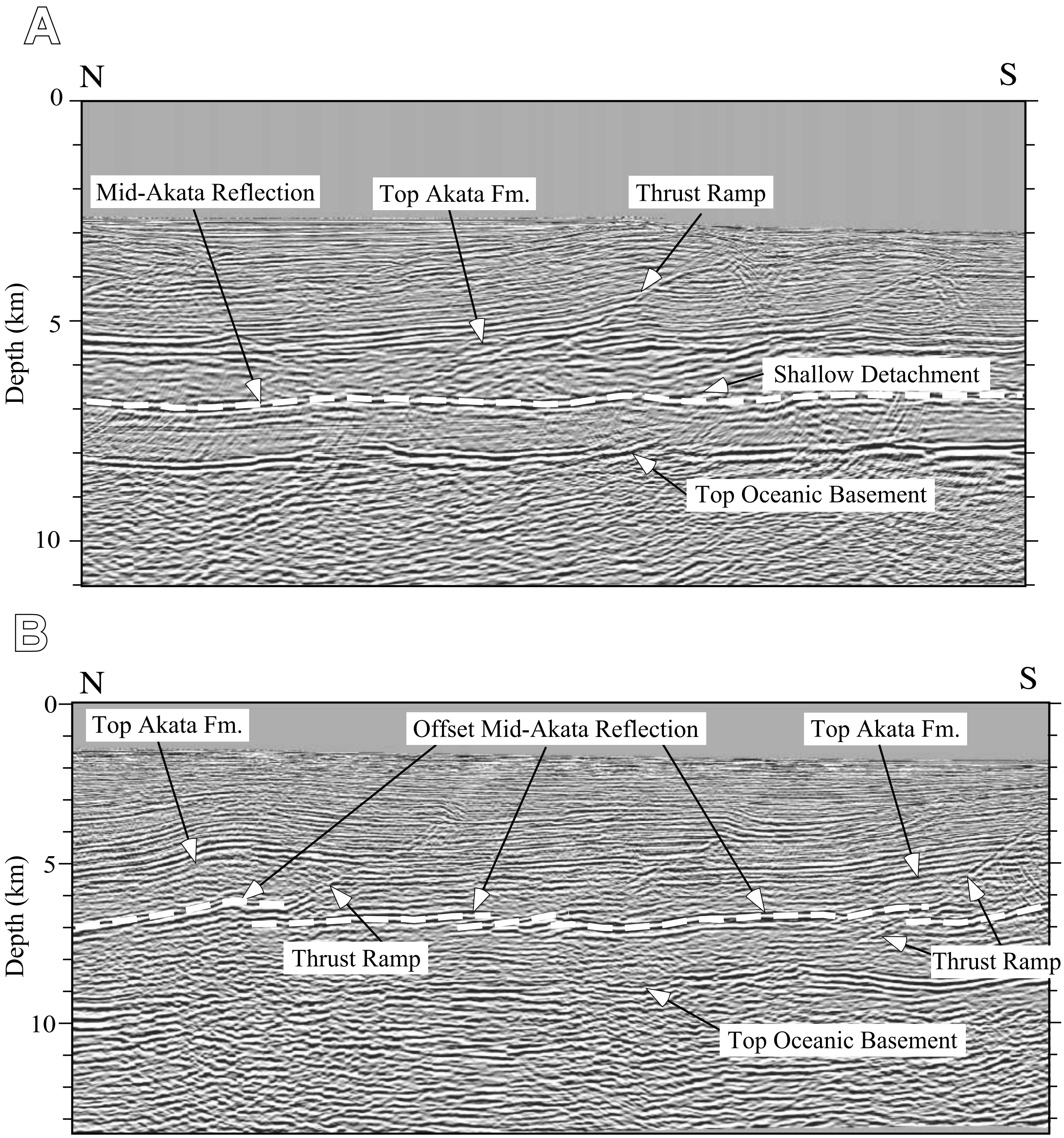


Figure 14. Depth-converted seismic sections showing a comparison between a system with a shallow detachment and a system with multiple detachment levels in the deep-water fold and thrust systems of the Niger Delta. Both the top of the Akata Formation and the top of the oceanic crust are shown in both sections. (A) Shallow detachment level near the top of the Akata Formation. (B) System with multiple detachment levels. A shallow detachment is observed near the top of the Akata Formation, and a deep detachment is observed near the top of the oceanic crust. The two detachment levels are connected by fault ramps that cut through the Akata Formation that causes the structural repetition of this formation.

imbrication, above a single detachment level in the Akata Formation (Figure 15A). They are comparable to many classic thin-skinned thrust belts (Price, 1981, 2001; Shaw et al., 1999) but, nevertheless, have distinct styles of internal thrusting, reflecting the complex thrusting sequences and imbricate-shear fault-bend folding mechanisms that we have used to describe them. Type II imbricate systems also consist of multiple thrust

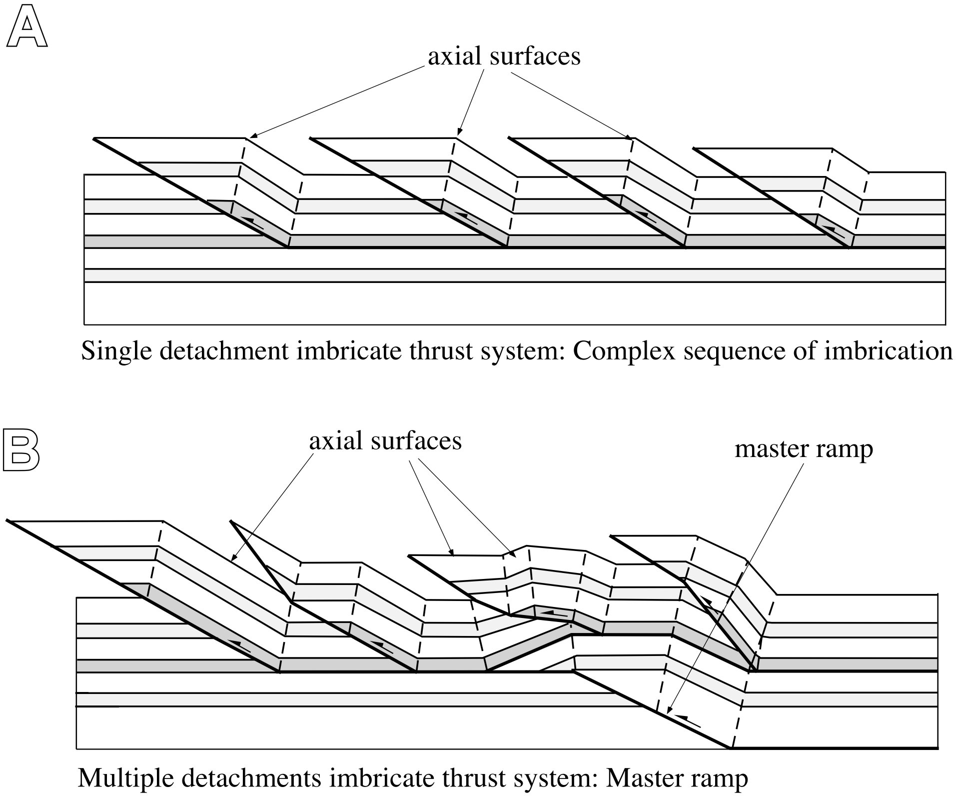


Figure 15. Schematic models of two main types of imbricate thrust systems in the deep-water Niger Delta. (A) Single detachment imbricate thrust system. The variable geometry in thrust imbricates suggests a complex sequence of imbrication. (B) Multiple detachment imbricate thrust system. A master ramp connecting the upper and lower basal detachments refolds the overlying thrust sheets. A folded upper detachment is suggested over the trailing lower detachment thrust imbricate.

sheets typically with complex sequences of imbrication; however, they involve slip on two separate basal detachment levels, generally corresponding to the regional upper and lower Akata detachment zones. In cases where the two detachment levels in type II imbricate systems are linked by a master ramp (Figure 15B), the Akata Formation becomes highly thickened, and large anticlinoria form.

Figure 16 shows uninterpreted seismic sections across both types I and II imbricate systems in the outer fold and thrust belt of the deep-water Niger Delta. The section in Figure 16A corresponds to a seismic profile across a type I imbricate system where multiple basin-verging fault imbricates can be observed. A single detachment for this imbricate system is interpreted near the top of the Akata Formation. Notice the lateral continuity of the top of the oceanic crust reflection, which is not involved in the deformation of this imbricate system. All of the fault-related folds in the various thrust sheets have similar amplitudes, and the depths of stratigraphic units are similar in their backlimb synclines. These patterns are consistent with thin-skinned thrusting above a common detachment level. A detailed interpretation of this type I imbricate system, using both conventional and shear fault-bend fold kinematic theories (Suppe, 1983; Suppe et al., 2004), is presented in Figure 16A. Both simple-shear and pure-shear fault-bend folds are interpreted based on distinguishing characteristics described in Figure 6. The oldest thrust sheet in this system corresponds to the one located on the northern (hinterland) side of the section toward the shelf. The youngest thrust sheet is on the south side of the section, at the leading edge of the imbricate system. The relative ages of these two thrust sheets suggest a regional break-forward sequence of imbrication. However, a complex internal sequence of imbrication is interpreted for this system based on the observed patterns of growth sedimentation. For instance, fault imbricate E is older than fault imbricate F (Figure 16A), suggesting a break-forward sequence of imbrication, but fault imbricate E is also older than fault imbricate D, suggesting a break-backward sequence of imbrication. A fuller description for the sequences of imbrication for this type I imbricate system is presented through a sequential restoration in the following section.

Figure 16B corresponds to a seismic section across a type II imbricate system that is also located in the outer fold and thrust belt. As in type I imbricate systems, the imbricate system presented in Figure 16B is characterized by multiple basin-verging thrust faults with overlying fault-related folds of similar amplitudes.

The fault ramps in this system, however, sole to two different detachment levels. Thrust faults on the south side of the system sole to a detachment near the top of the Akata Formation, whereas thrusts on the north side of the system sole to a detachment near the bottom of the Akata, just above the oceanic crust. A broad anticline present in the center of the system, between the two sets of thrust sheets, is cored by a thick layer of Akata Formation. We interpret that this broad anticline is cored by a fault ramp that duplicates the Akata Formation and connects the upper and lower basal detachment levels (Figure 16B). This deep master ramp explains the large forelimb that is present on the south side of the broad anticline and contributes to the large amount of displacement required on the upper Akata basal detachment present to the south of the structures. Note that the growth sedimentation above the backlimb of this broad anticline suggests fold growth with a component of limb rotation, which is not consistent with simple fault-bend fold kinematics for the deformation above the deep master ramp. The rotation recorded in the growth sedimentation is interpreted as formed by motion along a shallower detachment previous to the formation of the deep thrust ramp. The composite fault-bend fold associated with this deep thrust ramp could have also undergone shear during its formation, which would explain the limb rotation recorded in the growth strata. The sequences of imbrication inside this system are complex and are resolved using the patterns of growth sedimentation, as illustrated in the structural sequential restoration presented in the following section.

The relative positions and relationships of the type I and type II imbricate systems presented in this study are shown by a structural contour map of the deepest basal detachment level for each system (Figure 17). This contour map shows that the two systems involve the same upper Akata basal detachment in the southernmost part of the fold belt and, thus, are continuous along the strike. To the north, however, the type I imbricate, with an upper Akata basal detachment, and the type II imbricate, with a lower Akata basal detachment, and master ramp are separated by a north-south–trending lateral ramp. This lateral ramp correlates with a major change in stratigraphic thickness of the Akata Formation (Corredor et al., 2001) and a north-south–trending lineament that can be observed in the oceanic basement. Our interpretation suggests that changes in the basement topology localized the boundary between the two different basal detachment levels and, thus, formed a lateral ramp separating the type I and type II imbricates. A major tear fault occurs above this lateral ramp that separates the hanging-wall parts of these two thrust sheets.

The thickness, rheology, and lateral continuity of the Akata Formation presumably influence whether it acts as a regional shear zone (as in simple-shear folding) or if it thickens at the base of thrust ramps (as in pure-shear folding) and, hence, the general structural style of the thrust systems (Rowan et al., 2004). Moreover, the strength of this layer probably changes through time because of the buildup and release of overpressure. This could affect both the sequence of thrusting as critical taper is maintained and where the basal detachment occurs (i.e., the development of multiple detachments). Thus, we speculate that spatial and temporal variations in the strength of the Akata Formation, as well as the varying patterns of deposition, are largely responsible for the range of structural styles and detachment levels that we observe in the Niger Delta.

SEQUENTIAL RESTORATIONS OF THE THRUST BELTS

Based on the structural styles, folding mechanisms, thrusting sequences, and detachment levels described in this study, we present two regional, sequentially restored structural cross sections (Figures 18, 19). These palinspastically and kinematically restored sections serve to validate our structural interpretations and to illustrate the kinematic evolution and sequences of imbrication in the deep-water Niger Delta. Figure 18 represents a sequential restoration of the line presented in Figure 16A and B, which includes a type I imbricate system, and that extends across the inner and outer fold and thrust belts. Figure 19 represents the sequential restoration of the line presented in Figure 16B, which includes a type II imbricate system, and that extend across the outer fold belt only. Both sections show modest amounts of shortening: 25 km (16 mi) for type I imbricate system (Figure 18) and 17.5 km (10.8 mi) for type II imbricate system (Figure 19).

The structural restoration in Figure 18 shows the youngest fault imbricate to be the most frontal thrust sheet in the foreland, whereas the oldest fault imbricate is located to the far right side of the section or hinterland. This relative age between these two fault imbricates suggests a regional break-forward sequence of imbrication. The internal sequence of imbrication for this fold belt, however, is more complex, based on the patterns of growth sedimentation. The sequential

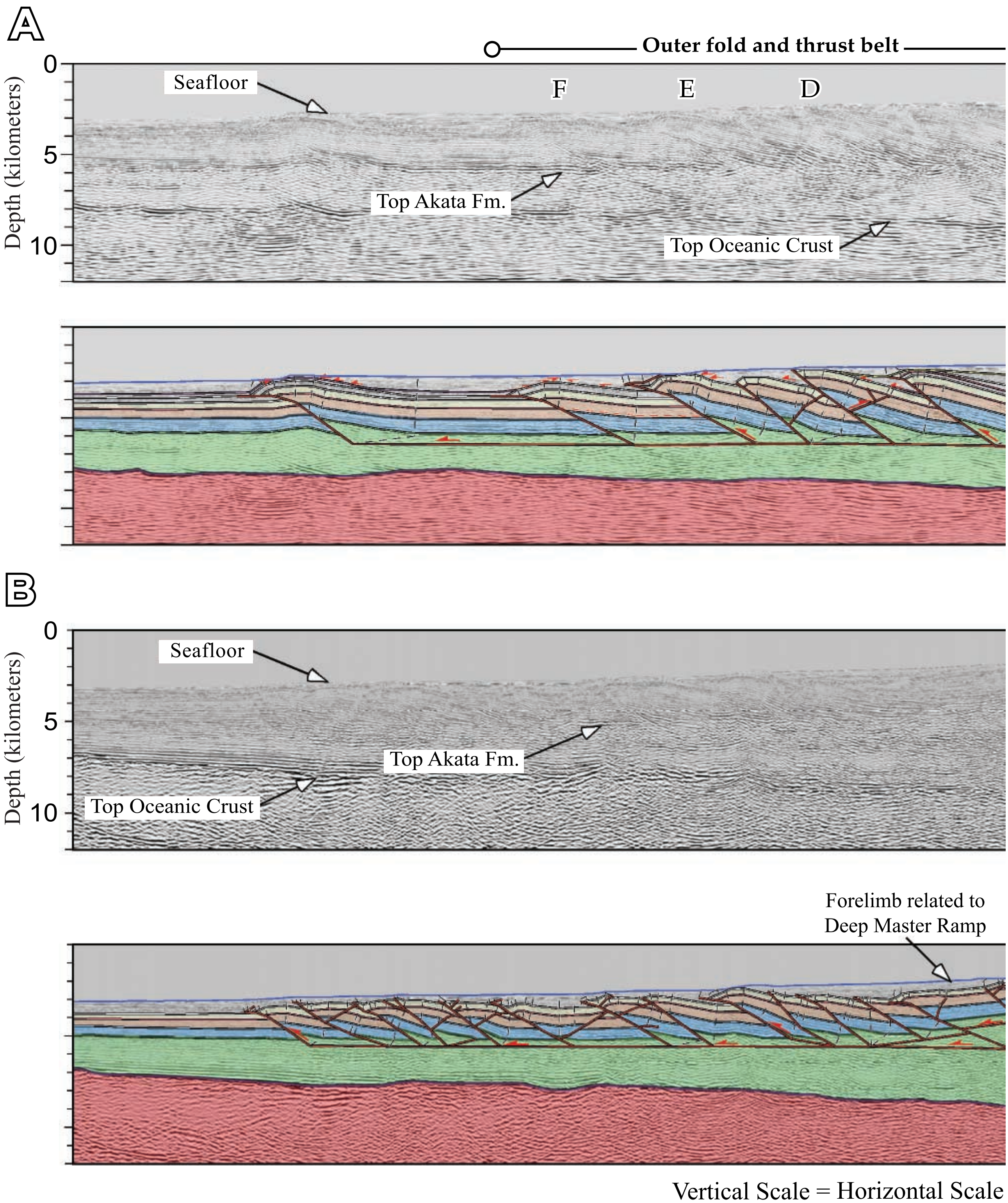


Figure 16. Regional uninterpreted and interpreted seismic profiles through (A) a single detachment imbricate thrust system (type I) and (B) a master ramp hanging-wall imbricate thrust system (type II) in the outer fold and thrust belt of the deep-water Niger Delta. Both seismic lines are displayed at the same scale. See Figure 3 for location (seismic data in [A] are courtesy of Mabon Ltd., and seismic data in [B] are courtesy of Veritas DLG). D, E, and F fault imbricates are used to identify multiple sequences of imbrication (see text). For an oversized image of this figure see Datashare 20 (www.aapg.org/datashare/index.html).

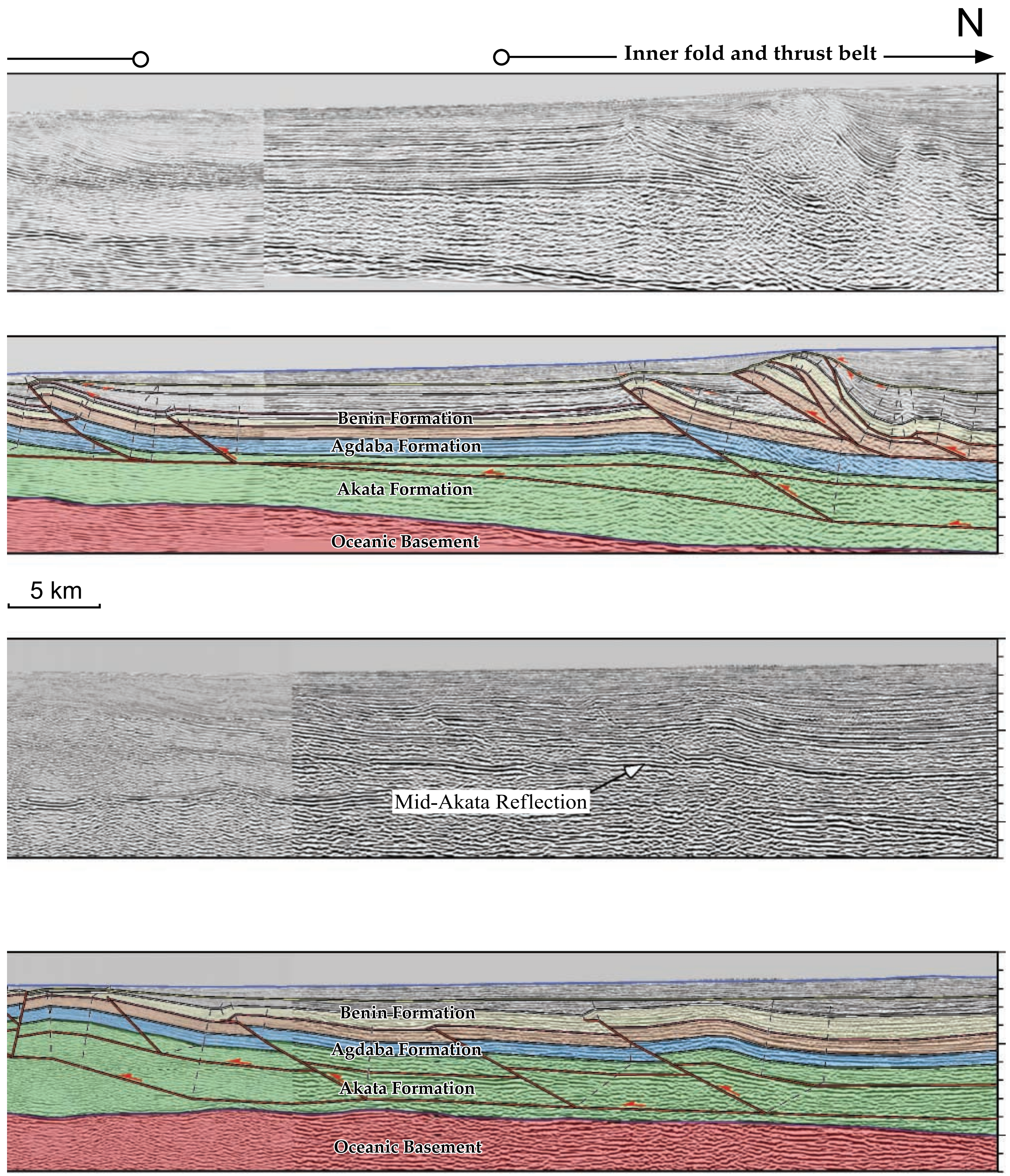


Figure 16. Continued.

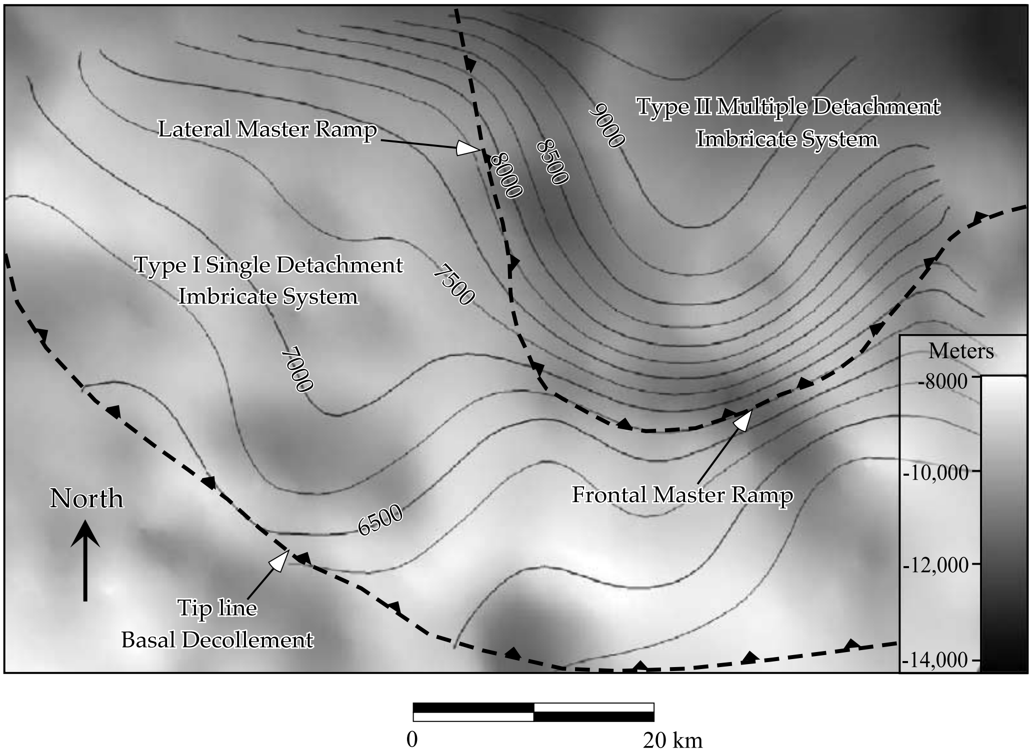


Figure 17. Structural gray-scale colored image map of the top of the oceanic basement and structural contours of the main decollement in the Akata Formation (black lines) for the southernmost part of the outer fold and thrust belt (see Figure 3 for location). Contours are in meters below sea level. Location of the lateral and frontal master ramps that separate a single detachment from multiple detachment imbricate systems and tip line of the basal decollement is shown. A north-south–trending lineament in the basement topology can be observed that correlates with the location of the lateral ramp that separates the type I imbricate system from type II. Contour interval is 250 m (820 ft).

restoration in Figure 18 shows evidences that coeval deformation was spread across large distances between the outer and inner fold belts. For instance, step 2 of the restoration shows that while removing the slip for the youngest leading edge fault imbricate in the outer fold belt, some structural relief is also removed from the imbricate faults and the low-relief detachment fold located in the inner fold belt. This illustrates coeval activity of the outer and inner fold belts. Similar coeval activity is observed through many of the remaining steps of the restoration; however, the inner fold belt clearly initiated first and accommodated the majority of shortening during the earliest stages of deformation.

Within the outer fold belt, restoration steps 3–5 show that a break-backward sequence of imbrication occurred. This is based on our observation that increasingly older growth strata onlap the backlimbs of the fault-related folds toward the foreland. The final restoration shows the total amount of simple shear that has been applied to the imbricate system, and that is responsible for the simple-shear fault-bend fold kinematics present in this system.

Figure 19 represents a sequential restoration across the type II imbricate system with multiple detachment levels that were described in Figure 16B. The youngest thrust sheet in this system is not located at the leading edge of the outer fold belt but rather is located at the frontal culmination of the large forelimb located above the master ramp connecting upper and lower detachments. As depicted in the restoration, the oldest fault imbricate in this fold belt is similarly not located at the trailing (hinterland) edge of the thrust system, as in the previous case. The oldest imbricate corresponds to a thrust fault that sits above the backlimb of the broad anticline, suggesting an internally complex sequence of imbrication. Steps 1–3 of the structural restoration in Figure 19 show how the slip along three young thrust faults with a break-forward sequence of imbrication is removed, as well as the forelimb formed by the slip transfer from the deep master ramp into a shallower detachment. Once the slip along the deep master ramp is completely restored, a few thrust sheets remain in front of this ramp. This implies that it is required to have slip along a shallow detachment to the north of the

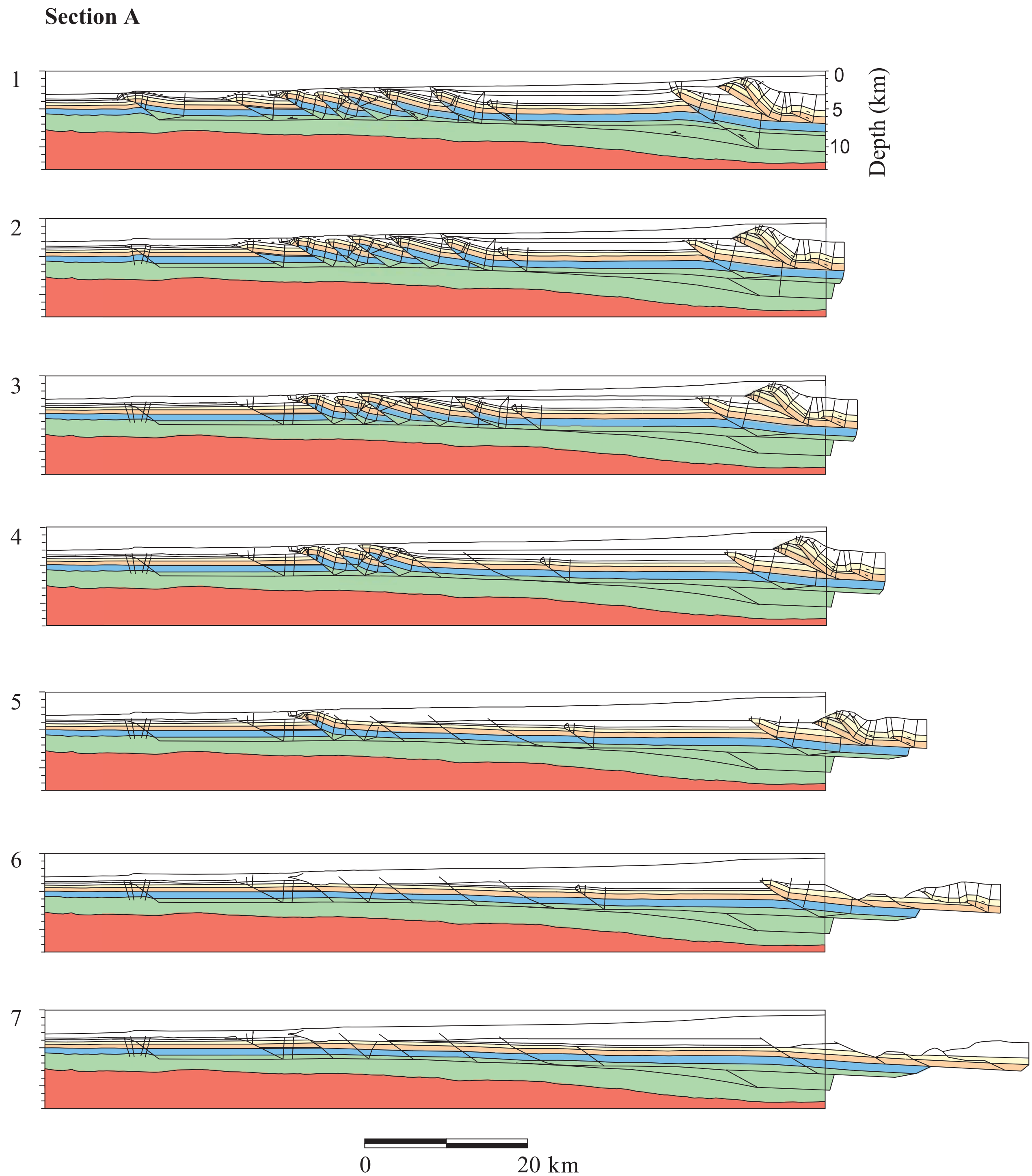


Figure 18. Palinspastic sequential restoration of the interpretation presented in Figure 16A for a type I single detachment imbricate thrust system.

master ramp to restore the section. Notice how the two fault imbricates in the right side of the section that sole to the deep detachment have to be removed to restore the slip along the shallow detachment. Moreover, the fault imbricates that sole to this shallow detachment have a break-backward sequence of imbrication, as illustrated in steps 3–5 of the structural restoration. In summary, this system originated first along the shallow detachment, as in the type I imbricate system, but was later refolded by slip along a deep detachment and the

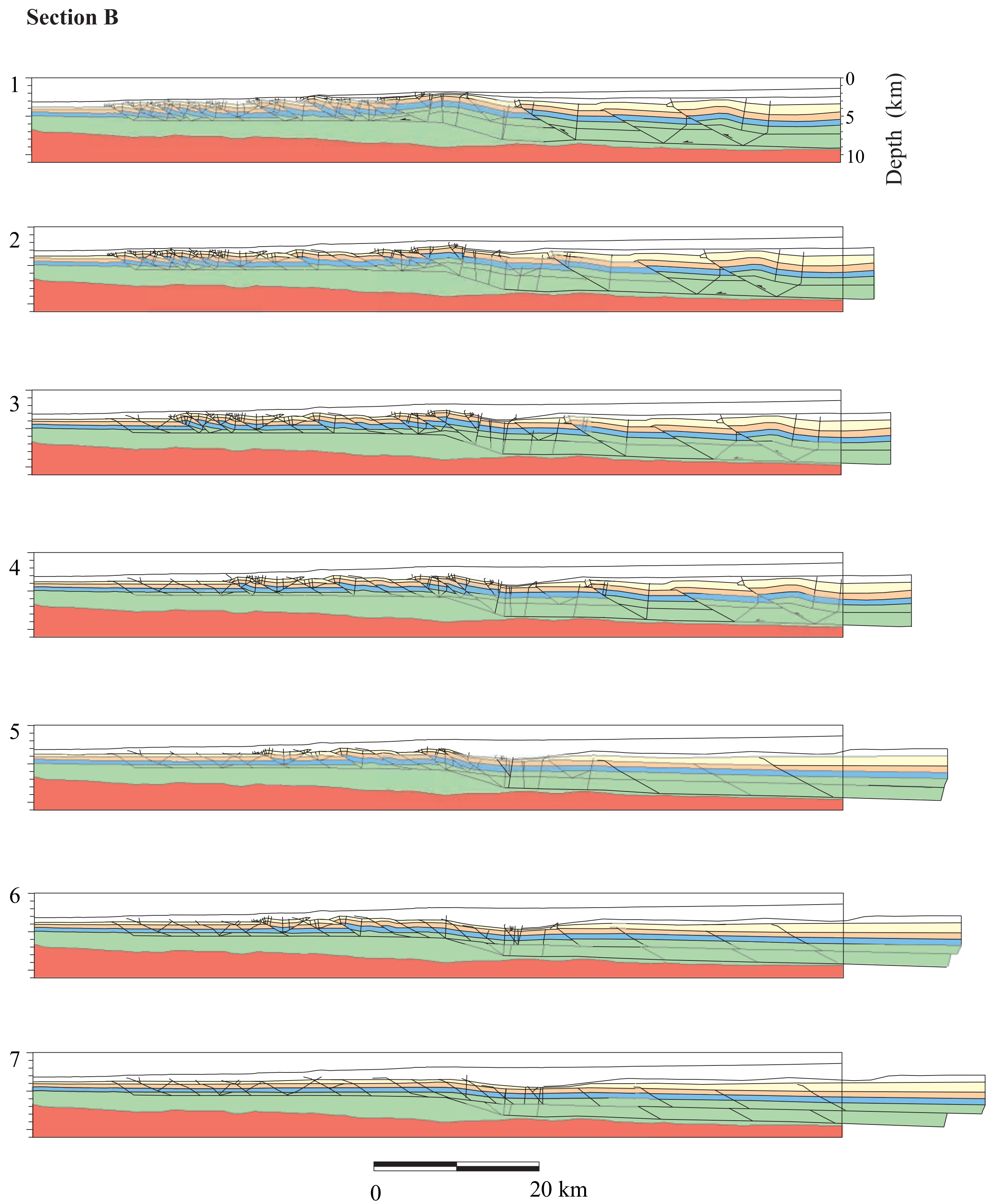


Figure 19. Palinspastic sequential restoration of the interpretation presented in Figure 16B for a type II master ramp hanging-wall imbricate thrust system in the outer fold and thrust belt of the deep-water Niger Delta.

master ramps that connect the two detachments. Thus, the complex sequence of thrusting probably results, in part, from the interplay of these two basal detachment levels.

SUMMARY AND CONCLUSIONS

The imbricate systems in the deep-water Niger Delta show particular characteristics that have not been widely documented in other thrust systems, including shear fault-bend fold kinematics, complex sequences of imbrication reflected in growth strata, and fault-related folding involving multiple basal detachment levels. Combined conventional fault-bend folding and shear fault-bend folding kinematic theories have helped to model the structural geometries observed in the deep-water thrust systems, including the patterns of growth sedimentation. The geometries that result from these models and that are reflected in our interpreted sections suggest that the strength of the Akata Formation is low relative to the strength of the overlying deltaic section that is involved in the thrust sheets. This seems reasonable for the Niger Delta, where the Akata Formation is poorly consolidated and has anomalously low velocities, reflecting high fluid pressures (Bilotti and Shaw, 2001).

In conclusion, the deep-water Niger Delta includes two complex, imbricated fold and thrust belt systems (the inner and outer fold and thrust belts) that are the product of contraction caused by gravity-driven extension on the shelf. In these systems, we described both pure- and simple-shear fault-bend folds that form above a weak decollement zone in the Akata Formation. We expand on shear fault-bend fold theories to describe imbricate thrust systems, which tend to display complex thrusting sequences involving different detachment levels. Based on these characteristics, we propose two major types of imbricate systems: type I imbricate system, with a single basal detachment level that is typically near the top of the Akata Formation, and type II imbricate system, with two basal detachment levels, one typically near the top and the other near the bottom of the Akata Formation. A master ramp that connects these two basal detachment levels forms large anticlines that are cored by the structurally thickened Akata Formation. In the example that we documented, the deep detachment and master ramp moved in a later phase of deformation, refolding the shallow detachment level.

On local and regional scales, the basement topography controls the distribution of the thrust systems in the deep-water Niger Delta. Most highly imbricated thrust systems appear to form behind basement uplifts, and lateral ramps that bound regions with different detachment levels are nucleated above basement structures. In a regional sense, break-forward propagation of the thrust system is observed, with the earliest contractional deformation occurring in the inner fold belt. At local scales, however, we document a complex internal sequence of imbrication with break-forward, break-backward, and coeval thrusting based on geometric relationships between fault imbricates, as well as patterns of growth sedimentation.

The complexity in the structural styles and sequences of imbrication observed in the deep-water Niger Delta tends to obviate simple rules that are commonly used to prescribe structural geometry and thrusting sequences in other fold belts. Nevertheless, guided by the principles of shear fault-bend folding and imbricate thrusting, as well as the patterns of growth structure, the geometry and history of most structures can be resolved. In support of exploratory and development efforts, these methods can help describe the size and shape of hydrocarbon traps and reservoirs, as well as constrain the timing of deformation relative to hydrocarbon migration and charge.

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