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The role of deformation in controlling depositional patterns in the south-central Niger Delta, West Africa

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Abstract

The Niger Delta has a distinctive structural and stratigraphic zonation. Regional and counter-regional growth faults, developed in an outer-shelf and upper-slope setting, are linked, via a translational zone containing shale diapirs, to a contractional zone defined by a fold-thrust belt that developed in a toe-of-slope setting. Structural and depositional systems have migrated with the progradation of the delta. A paleo fold belt is buried under the modern upper/middle slope. The structural system in this paleo fold belt is complex and comprises a series of en échelon thrust-cored folds and associated ponded slope-basins, shale diapirs, and extensional growth faults. Analysis of the growth sections filling the ponded slope-basins provides a record of how this accommodation was created and subsequently filled and how the individual structural elements interact to create and modify the available space. The depositional systems initially exploit primary accommodation on the slope created by structural movement—the synchronous growth of the fold, the extensional faults and the shale diapir. As the pond is progressively filled, the previously deposited strata modify the accommodation and subsequent depositional systems compensate accordingly. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Deformation; Depositional patterns; Niger Delta

1. Introduction

The Niger Delta, which builds out into the Gulf of Guinea on the Atlantic coast of West Africa, is one of the largest modern delta-systems on earth. The delta is situated at the seaward-end of the Benue Trough (Fig. 1), a tectonic mega-structure formed during the Cretaceous opening of the Equatorial Domain of the South Atlantic Ocean (Fairhead and Binks, 1991; Maluski et al., 1995). The Benue Trough has been a long-standing focus for sedimentation on the West African margin. Following the opening of the Equatorial Atlantic in the late Early Cretaceous (Mascle et al., 1986; Nünberg and Müller, 1991; Maluski et al., 1995), the trough progressively filled with Albian and younger post-rift deposits and by the Late Eocene, a delta had begun to build out over the continental margin (Burke, 1972; Damuth, 1994). Seaward progradation and enlargement of the delta, via the deposition of a thick succession of marine and marginal-marine sediments, continues to the present day (Whiteman, 1982; Doust and Omatsola, 1990). The subaerial portion of the modern delta top is a complex combination of wetlands and drylands covering an area of ~75,000 km^2. The delta top extends for more than 300 km from its apex in interior Nigeria to its broadly seaward-convex coastline (Fig. 1). The modern sedimentary prism is, at its maximum extent, up to 12 km thick. It has a broadly arcuate form covering an area of ~140,000 km^2 and comprises two main lobes—one building out to the west, the other to the south (Fig. 1).

The Niger Delta has a distinctive structural and stratigraphic zonation. The delta top comprises a series of nested depobelts that follow the general arcuate form of the delta and that are bound by large regional and counter-regional faults (Knox and Omatsola, 1989; Doust, 1990; Doust and Omatsola, 1990; Cohen and McClay, 1996). The deltaic sequences in each of these depobelts have a restricted age and represent successive stages in the step-wise progradation of the delta (Doust, 1990; Doust and Omatsola, 1990). The outer shelf and upper slope are characterised by a structurally complex zone in which a series of fault-bound sedimentary depocentres are separated by highly-deformed shale-cored structures (see illustrative sections in Damuth (1994) and Cohen and McClay (1996)). Widespread zones of imbricated thrusts are present in the deep offshore (Lehner and DeRuiter, 1977; Doust and Omatsola, 1990;

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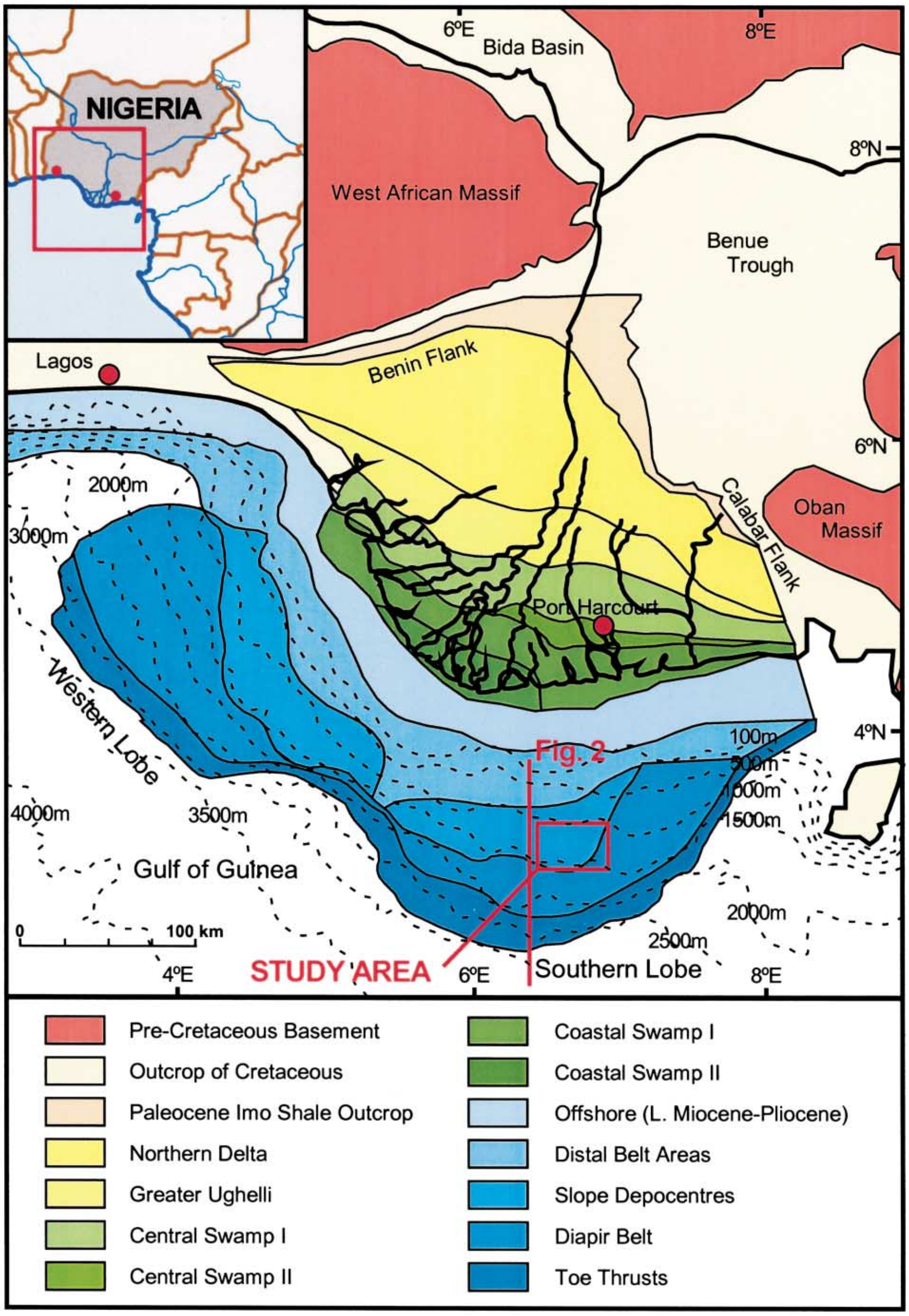


Fig. 1. Schematic map of the Niger Delta showing the distribution of depositional and structural belts (modified after Whiteman (1982), Damuth (1994) and Cohen and McClay (1996)). The line in the south central part of the delta indicates the location of the cross-section in Fig. 2. The local study area is indicated by the box.

Damuth, 1994; Cohen and McClay, 1996). These contractional structures are in a toe-of-slope setting outboard of both the zone of shale structures and a more distal 'translational' zone comprising relatively undeformed strata.

In this paper, we discuss the development of a thrust-cored fold system that lies buried under the upper slope just seaward of the modern shelf-slope break in the southern part of the delta (Fig. 1). The modern tectonostratigraphic setting is not, however, the setting at the time of formation of the structures. The fold system formed in a toe-of-slope setting analogous to the modern deepwater fold belt. This 'paleo fold belt' has been subsequently buried by the southward advance of the delta. We present 2-D and 3-D data that define the form of the fold system and the associated extensional and diapiric structures. As the fold system developed, sediments were trapped behind the fold belt in a ponded slope-basin. The form of the stratal packages filling the pond provides a direct record of the growth of the structural system. We present stratal models, which are derived from

3-D seismic analysis of part of the section filling the basin, that illustrate the development of the fold system and the influence it had on the slope depositional systems. From these data, we conclude that the structural system developed from the complex, simultaneous interaction of contractional faulting and folding, extensional faulting, and shale diapirism and withdrawal.

2. Structural setting

Three structural zones were defined in the southern lobe of the delta by Damuth (1994)—an extensional zone, characterised by extensional growth faults, is linked, via a translational zone containing shale diapirs, to a contractional zone that is characterised by the presence of toe thrusts (Fig. 1). This structural zonation is illustrated in Fig. 2, which is a chronostratigraphic section through the southern part of the delta that extends from the delta-top near the shelf-slope break out into the deepwater beyond the fold belt. A paired extensional fault system, comprising back-to-back counter-regional and regional, extensional growth faults, is present at the shelf-edge. Under the upper slope, in the 'translational zone', are a series of buried thrust-cored folds and numerous shale diapirs. Seismic examples of shale diapirs in the Niger Delta can be found in Damuth (1994) and Cohen and McClay (1996). The modern fold belt lies at the toe-of-slope, in the 'contractional zone.' The modern fold belt at this location is characterised by a train of a dozen or so thrust-cored folds and associated ponded slope-basins (Fig. 2b). The fold belt at this location, however, is largely deactivated with just a few small hummocks deforming the seabed (Fig. 2b). The extensional systems at the shelf edge are also relatively inactive (Fig. 2c), and few, if any, sediments are currently reaching the deepwater areas at this location (Fig. 2a). Units 10, 11 and 12, which fill the upper part of the regional and counter-regional extensional growth faults at the shelf edge (Fig. 2c) do not extend as far as the modern fold-belt at this location (Fig. 2b).

The structural and depositional zonation seen today is not vertically coincident with zonation in the past because the structural and depositional systems have migrated with the southward advance of the delta. Chronostratigraphic

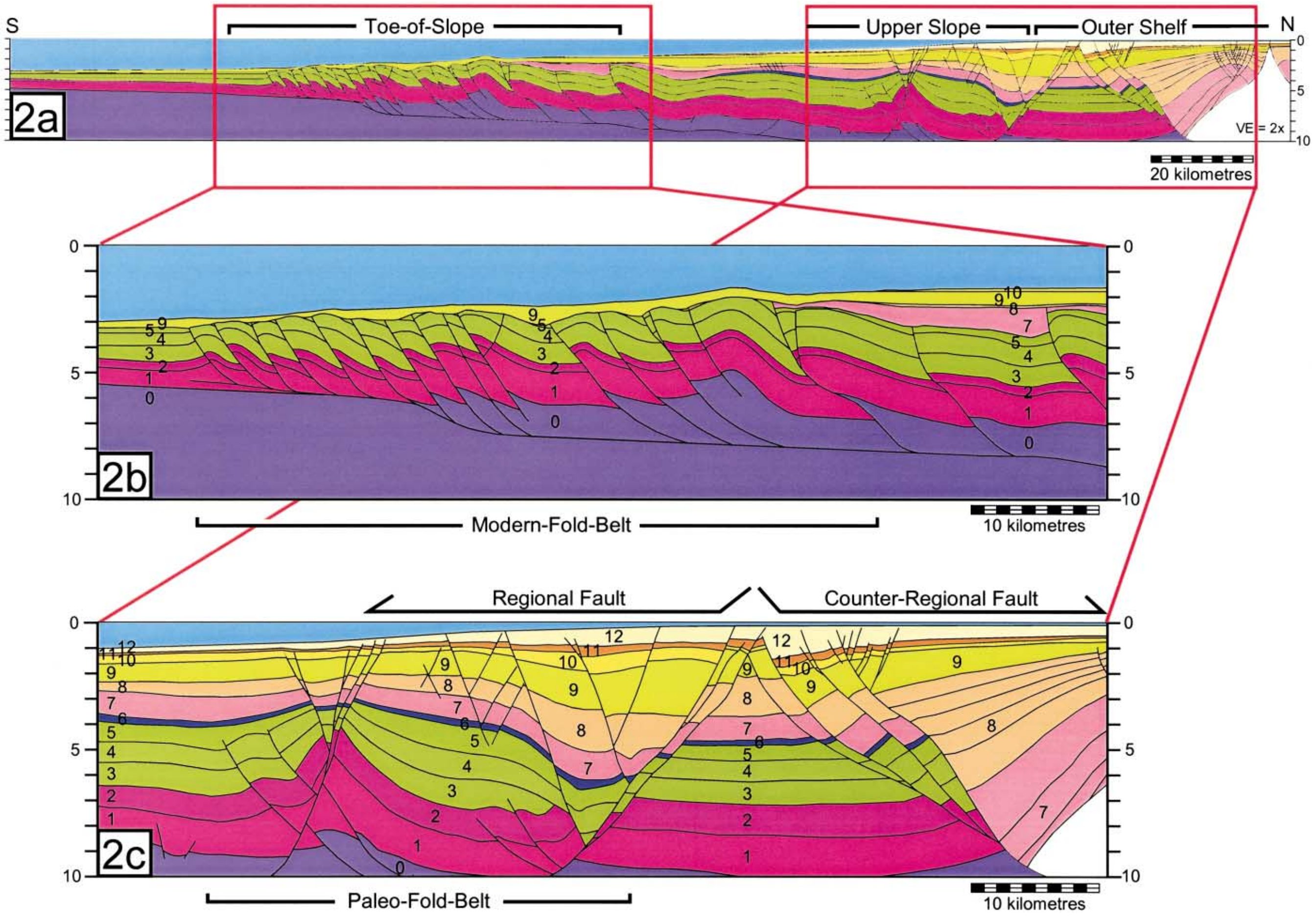


Fig. 2. (a) North–south regional geological cross-section across the south central part of the Niger Delta. Location is shown in Fig. 1. Boxes outline the modern and paleo fold belts ((b) and (c)). (b) Enlargement of the section across the modern fold belt. (c) Enlargement of the section across the outer-shelf–upper slope to illustrate the form of the paleo fold belt.

divisions of the delta are shown in Fig. 2. Along each chronostratigraphic surface we can define the progressive up-dip transition from abyssal to slope to shelf facies. The position of these facies, however, migrates seaward with time and thus is not always in the same position on successive chronostratigraphic surfaces. The key to unravelling the structural and stratigraphic development is accurately mapping and assigning the chronostratigraphic surfaces and understanding the type, proportion and thickness of the associated depositional systems. Three major stratigraphic envelopes can be defined in the deltaic wedge (Fitzsimmons et al., 1999) (Fig. 3).

1. Basin-centered depositional systems—in which the main sediment mass is located beyond the toe-of-slope,
2. Transitional depositional systems—in which the sediment mass is distributed across the slope and basin floor, and
3. Slope-centered depositional systems—in which the main sediment mass is located upon the slope.

The structural and depositional systems are co-dependent because the spatial distribution of each of the depositional systems is controlled by the structural evolution of the delta. In an interesting paradox, however, the spatial distribution of the depositional systems, particularly the presence of a thick succession of 'mobile' shales at the base of the section, in turn controls the structural zonation.

The structural systems have migrated seaward with the southward advance of the delta and are thus not always in the same position on successive chronostratigraphic surfaces. A progressive down-dip transition from extensional to contractional to undeformed structural systems can be defined along each chronostratigraphic surface. The period of maximum growth of the counter-regional and associated regional extensional faults at the modern shelf-edge was during the deposition of units 7, 8 and 9 (Fig. 2c). These strata are time equivalent to units 7, 8 and 9 (Fig. 2b) which were deposited in the ponded slope-basins associated with the modern fold belt. The syn-kinematic strata in the ponded section in the paleo fold belt (units 3, 4 and 5 in Fig. 2c) when traced down-dip are equivalent to the upper pre-kinematic strata in the modern fold belt (units 3, 4 and 5 in Fig. 2b). In broad terms, therefore, a kinematic balance exists at any given time between up-dip extensional systems on the delta top and down-dip contractional systems in the fold belt at the toe-of-slope. This simple kinematic balance is complicated somewhat at our location by out-of-sequence thrusting, the effects of which can be seen in Fig. 2b.

3. Local setting—present day form

Our structures of interest are in a paleo fold belt buried beneath the present-day upper slope (Figs. 2–4). At the base

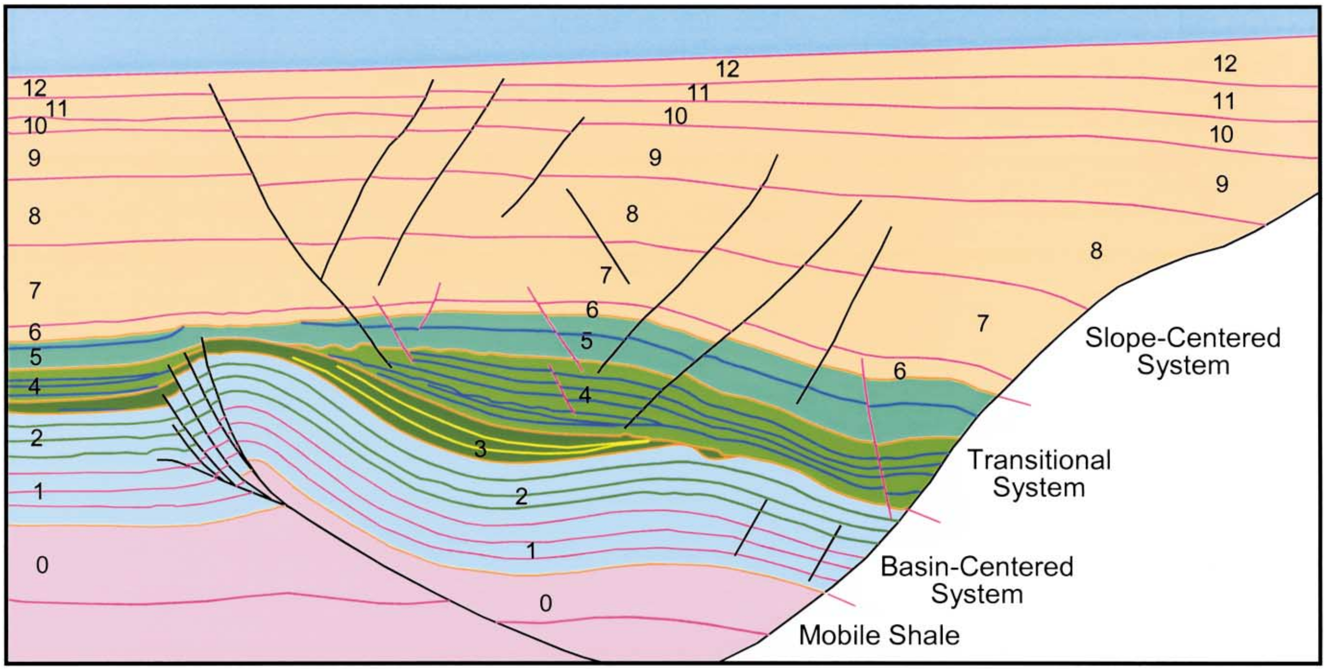
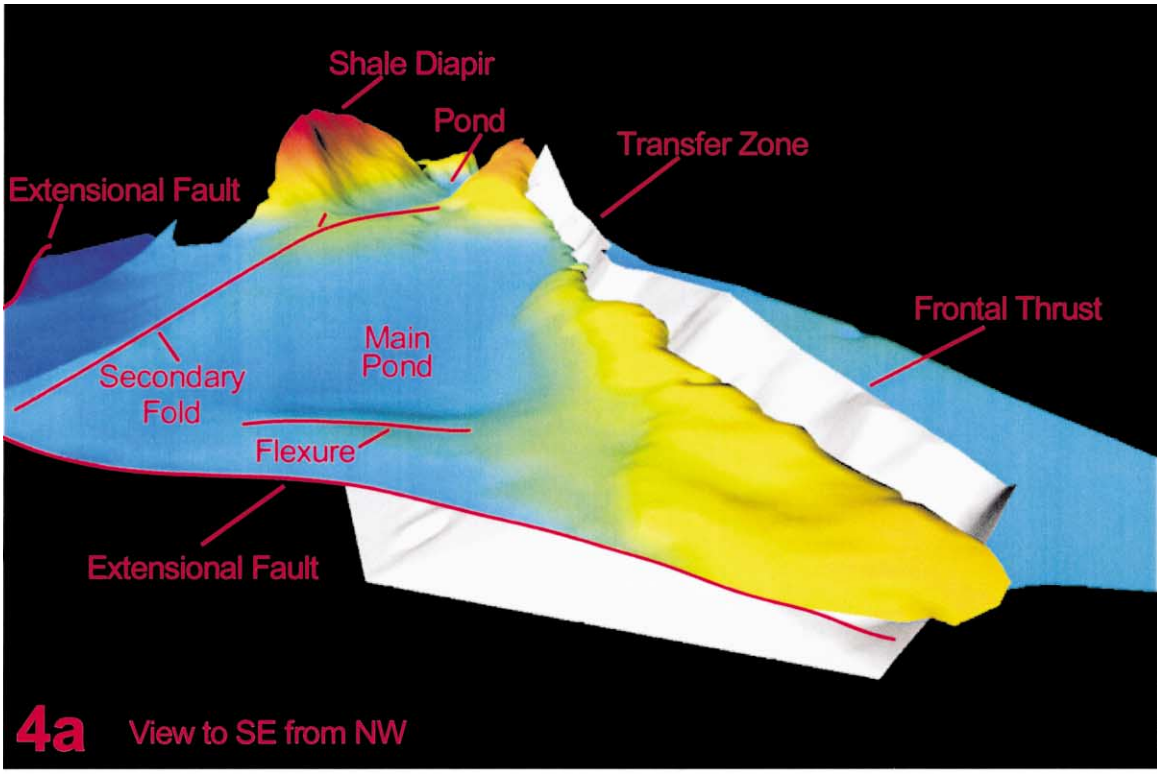


Fig. 3. 2-D Geoseismic section through the frontal fold of the paleo fold belt that illustrates the form of the associated ponded slope-basin and extensional faults. Chronostratigraphic divisions 0–12 correspond to the divisions in Fig. 2. Three major stratigraphic envelopes, bounding contrasting depositional systems, can be defined in the deltaic wedge. The ponded section can be divided into several units confined between the pre-kinematic strata below and syn-extensional strata above. The depositional axis of the pond migrates as the structure develops; strata deposited early in the development of the fold are progressively rotated into the back limb of the fold. The form of the whole ponded-section has been modified by rotation associated with the regional extensional fault.



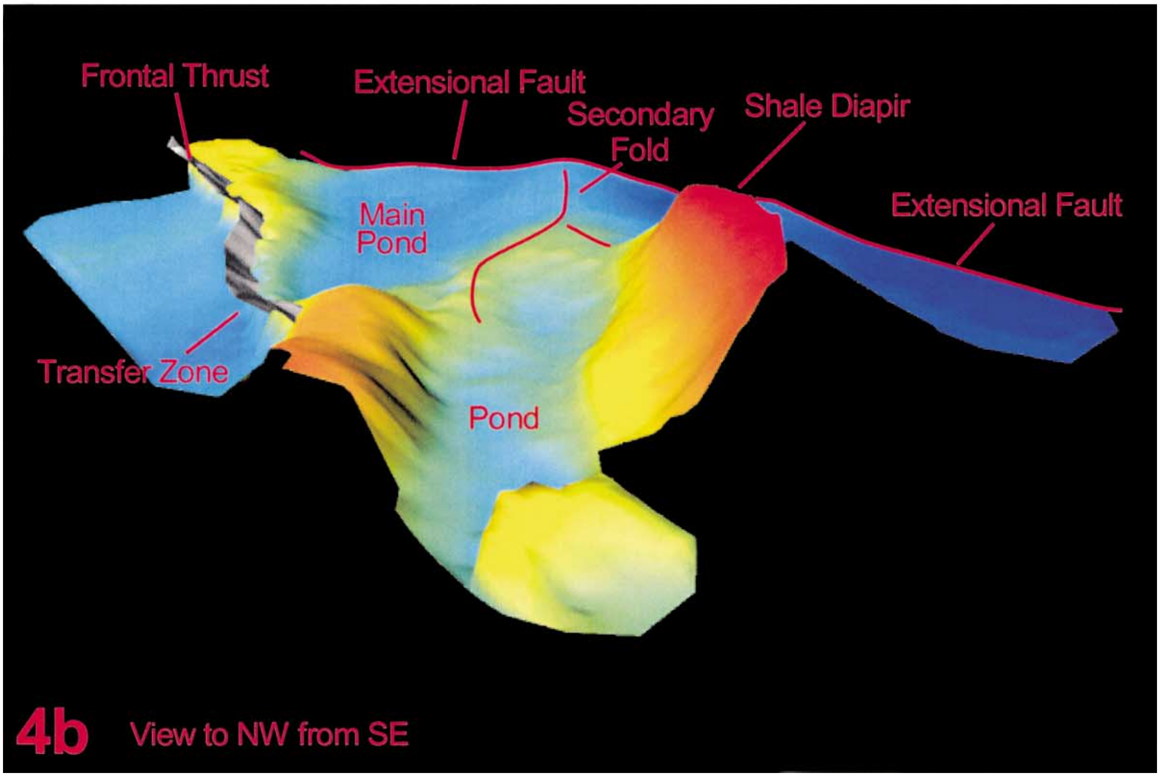


Fig. 4. (a) and (b) 3-D Models of the base of the ponded section (base of unit 3 from Fig. 2). The structural system comprises a series of en échelon, thrust-cored folds and associated ponded slope-basins, a set of nested, overlapping, extensional growth-faults and a shale-cored diapir. The crestal height of the folded structure is variable and is at a minimum in a prominent transfer zone. The maximum height of the fold crest above the adjacent main pond is ~3 km. A second fold, with lower relief, is present behind the main fold and links into the shale diapir. The prominent main pond is behind the frontal fold and is separated by a flexure from a secondary pond adjacent to the shale diapir. The height of the diapir crest above the adjacent secondary pond is ~5 km.

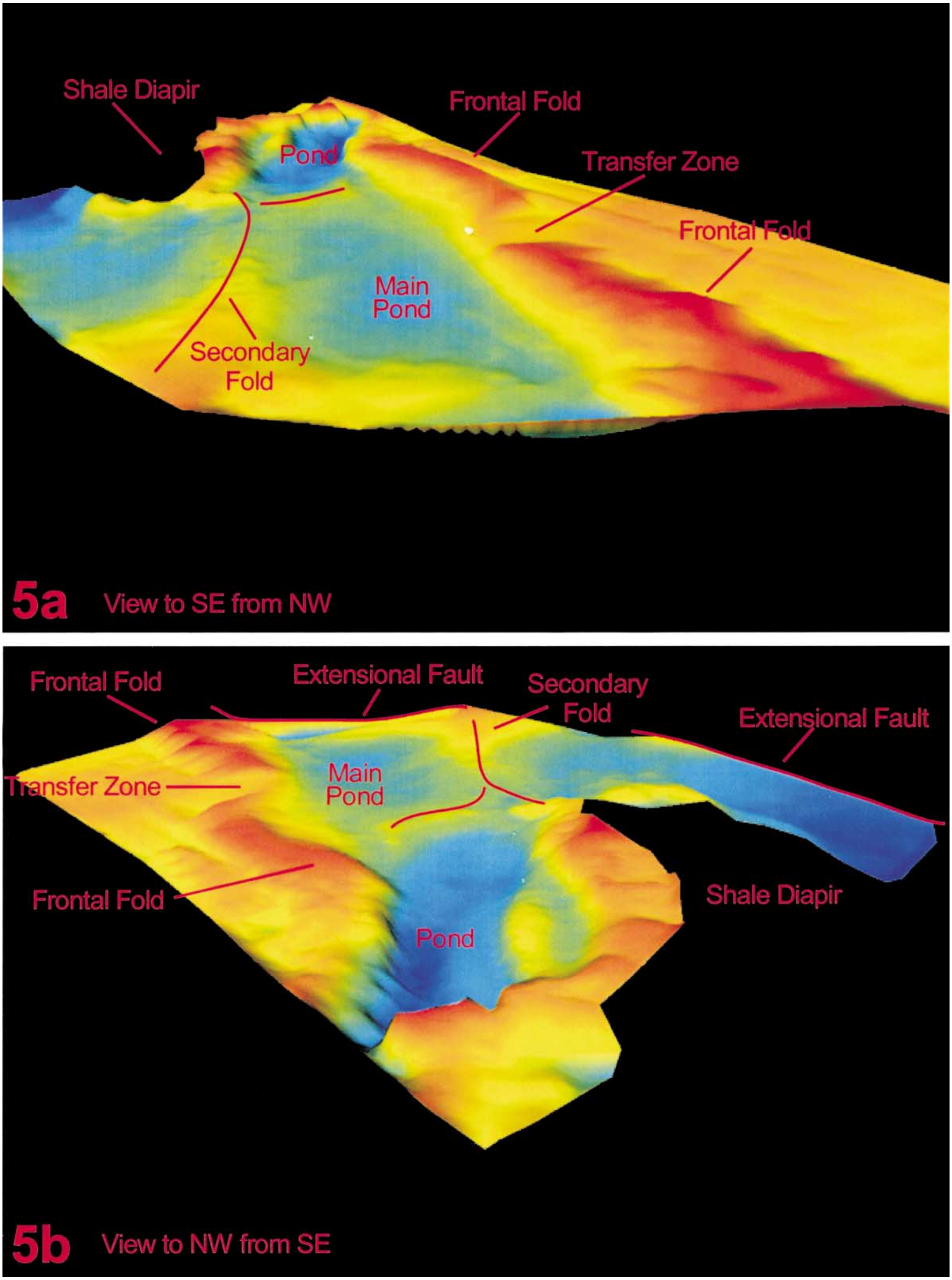


Fig. 5. (a) and (b) Restored 3-D models to illustrate the form of the base of ponded section shortly after the inception of the fold and associated ponds. The fold and ponded section have considerably lower relief than will develop later (Fig. 4). The maximum height of the fold crest above the adjacent main pond is ~1 km. A prominent transfer zone is visible. The main thrust has yet to propagate through this level.

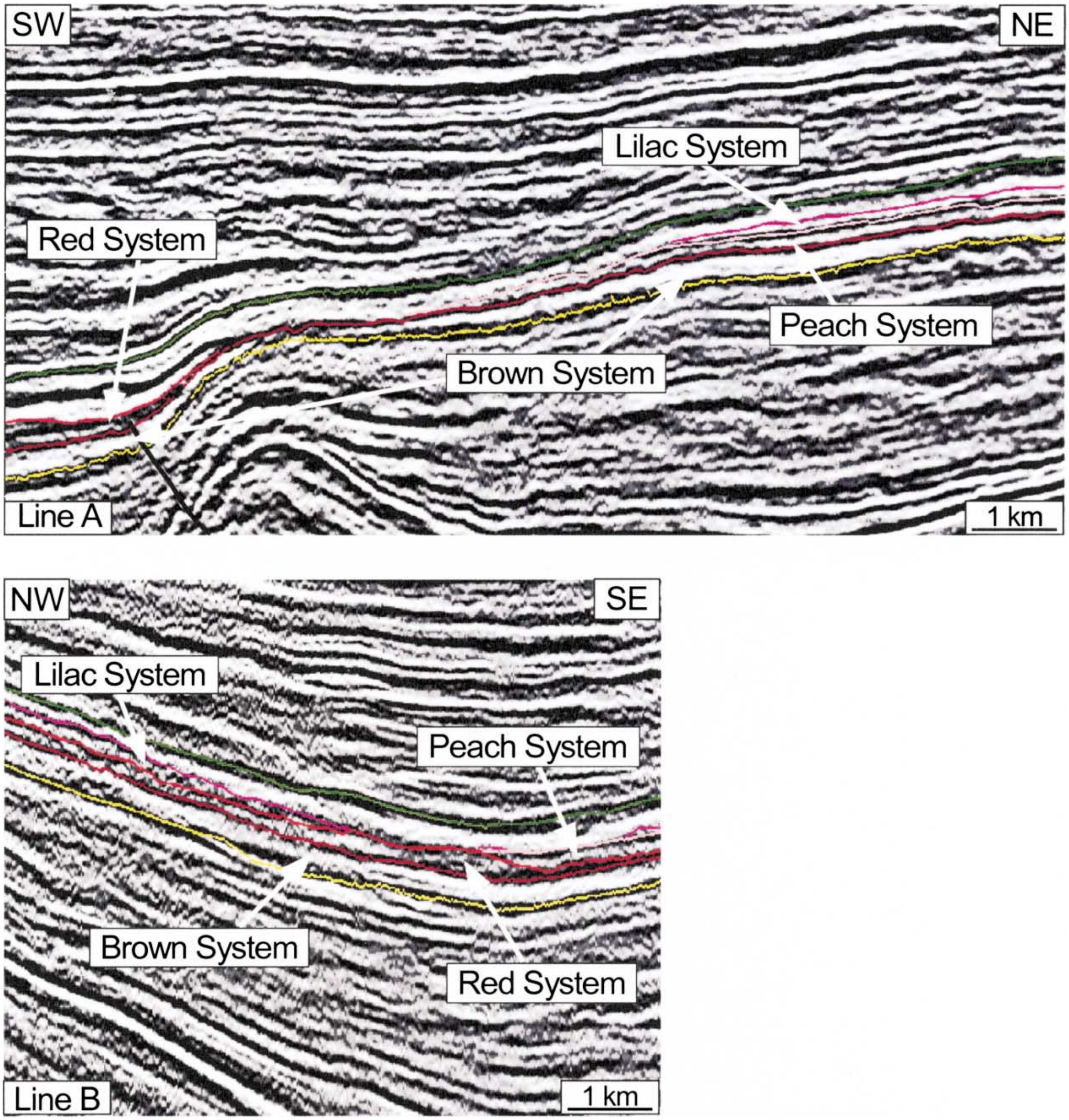
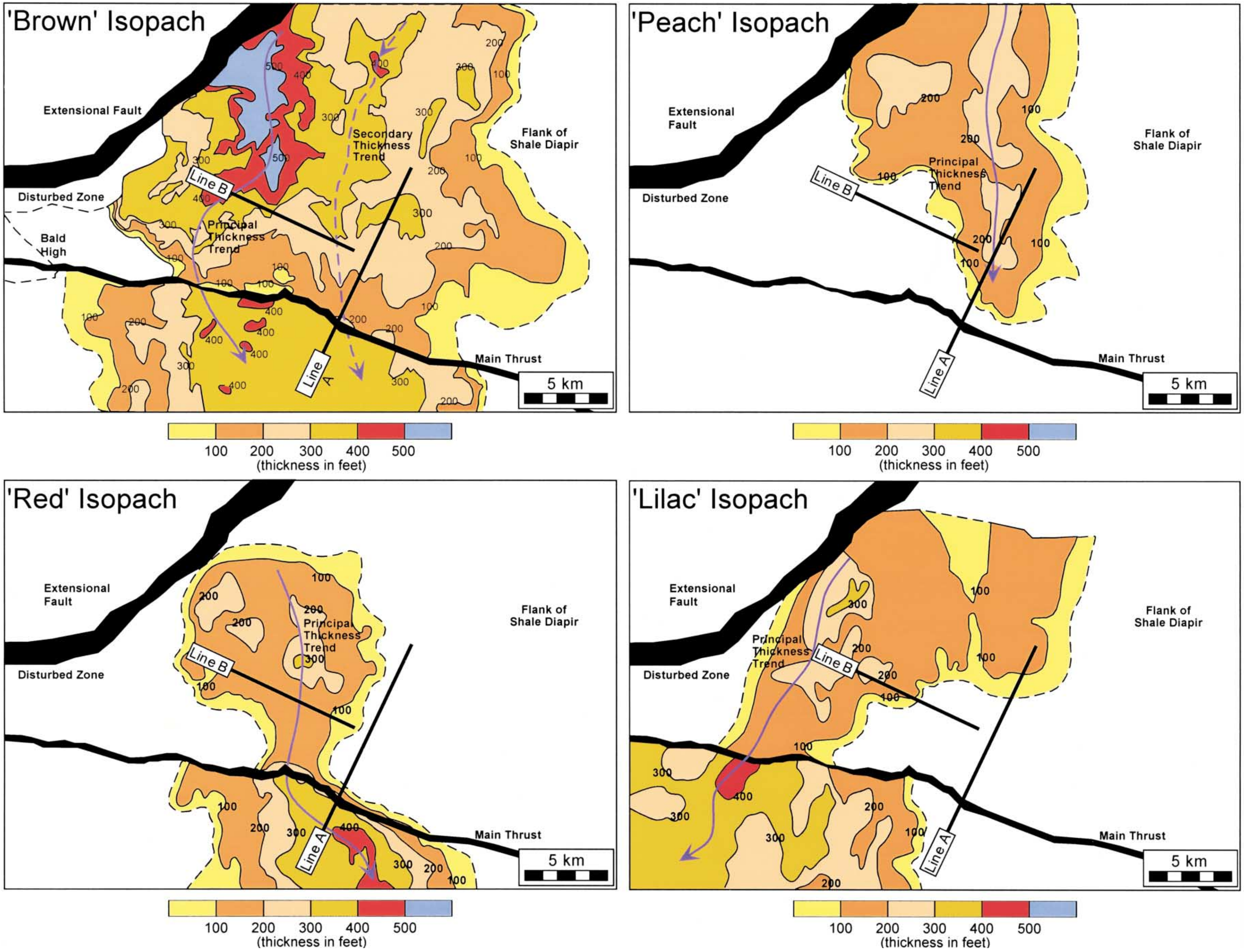


Fig. 6. 3-D Seismic sections normal (Line A) and parallel (Line B) to the fold trend to illustrate the form of the depositional systems that fill the upper ponded section above the base of unit 5 (Fig. 3). Four systems can be defined—brown, red, peach and lilac. The location of seismic lines A and B are indicated in Fig. 7.

of the section are a series of marine shales and claystones (unit 0, Figs. 2c and 3). This 'weak' basal layer is extremely important because not only does it serve as the decoupling surface for the fold-thrust structures but it also provides material for the shale diapirs. Deposited above this sequence are a series of pre-kinematic strata (units 1 and 2, Figs. 2c and 3), which are characterised by simple parallel-sided layers with good reflector continuity. These strata have uniform thickness over a wide area and can be traced down-dip into and beyond the modern deepwater fold-belt (Fig. 2b).

The current form of the fold system and associated structures is illustrated in Fig. 4. The local structural system comprises a series of en échelon, thrust-cored folds and associated ponded slope-basins, a set of nested, overlapping, extensional growth-faults and a shale-cored diapir. The main fold is cored by a thrust that, though mappable as a continuous feature, is actually a series of segments linked by relay structures. The crestal height of the folded structure varies along strike and is at a minimum in a series of prominent transfer zones (Fig. 4). The points of maximum crestal height along the main fold correspond to points of


'Brown' Isopach
Extensional Fault
Disturbed Zone
Bald High
Secondary Thickness Trend
Principal Thickness Trend
Flank of Shale Diapir
Main Thrust
Line A
Line B
5 km
'Peach' Isopach
'Red' Isopach
'Lilac' Isopach
100
200
300
400
500
(thickness in feet)

maximum displacement on the main thrust. A second fold, with lower relief, is present behind the main fold and links into the shale diapir. A prominent main pond is visible behind the main fold and is separated by a flexure from another pond adjacent to the shale diapir (Fig. 4).

The structural form of the area has been significantly modified by a series of extensional faults that have a seaward-concave, spoon-shaped profile (Figs. 3 and 4). The general strike of the extensional faults is sub-parallel to the paleo fold system. However, because of the spoon-shaped form of the extensional faults, they locally strike at a high angle to the fold belt. Consequently, the rollover associated with these faults locally trends at a high angle to the fold belt (Fig. 4).

The 2-D form of the structural system is illustrated by Fig. 3. The ponded section can be divided into several units that are confined between the pre-kinematic strata below and syn-extensional strata above. A significant characteristic of the ponded section is that the depositional axis of the pond migrates as the fold develops (Fig. 3). The lower ponded section lies unconformably on the pre-kinematic strata below and was deposited soon after the frontal fold and its associated thrust began to develop. The pond initially had relatively low relief and was restricted by a second fold in the back (Fig. 3). The middle ponded section formed during the maximum period of growth of the fold-thrust system. Coincident with this is the initiation of slip on the extensional faults that frame the up-dip end of the pond. Deactivation of the second fold allowed the ponded section to become significantly larger and expand up to the extensional fault (Fig. 3). Relief of the pond was further enhanced by subsidence caused by withdrawal of shale from the mobile layer underneath the pond to feed the rising diapir. As the fold grew, its amplitude and wavelength increased and the crestal region moved forward as the thrust began to propagate through the section. Early deposited strata in the pond become progressively rotated and incorporated into the backlimb of the growing fold (Fig. 3). The uppermost ponded section was deposited after the fold and thrust system had deactivated. This sequence exploits space created by differential compaction over the fold and thus enhances the form of the folded section. This compactional effect diminishes upwards and above the uppermost ponded section, the paleo fold belt no longer influences the slope depositional systems.

The pair of overlapping extensional faults that frame the northern side of the pond have caused significant rotation of the strata in the ponded section (Figs. 3 and 4). In an attempt to remove the effects of this younger extension, we have restored the ponded section in three-dimensions using Geosec3D. The reconstruction datum was within the pre-kinematic section (Top Layer 1 in Fig. 2c) which was assumed to be flat at the time of inception of the fold system. The upper surface was the top of the lower ponded section, which is equivalent to the Top of Layer 3. Layer 3 was then removed. The resultant 3-D image (Fig. 5) thus represents the form of the bottom surface of the pond (Top of the pre-kinematic strata = Top Layer 2) just after the initiation of the frontal fold.

The frontal fold now has considerably less relief and the frontal thrust has yet to propagate through the crest of the structure at this level. A prominent low-relief transfer zone is visible in the middle of the fold. The main pond is neither as broad nor as wide as it will become later in its development. The pond is asymmetrical with the main axis of the pond being closer to the frontal fold. The extensional faults framing the structure are already in place, but at this stage, stratal rotation into the fault is relatively minimal. The precise form of the diapir is difficult to discern at this stage because of difficulty mapping surfaces into and over the diapir in the modern section. The diapir has considerably less relief and appears as a high point on the secondary fold sitting behind the main frontal fold (Fig. 5). A prominent pond is visible immediately adjacent to the diapir and we infer that this is related to the local withdrawal of shale into the diapir.

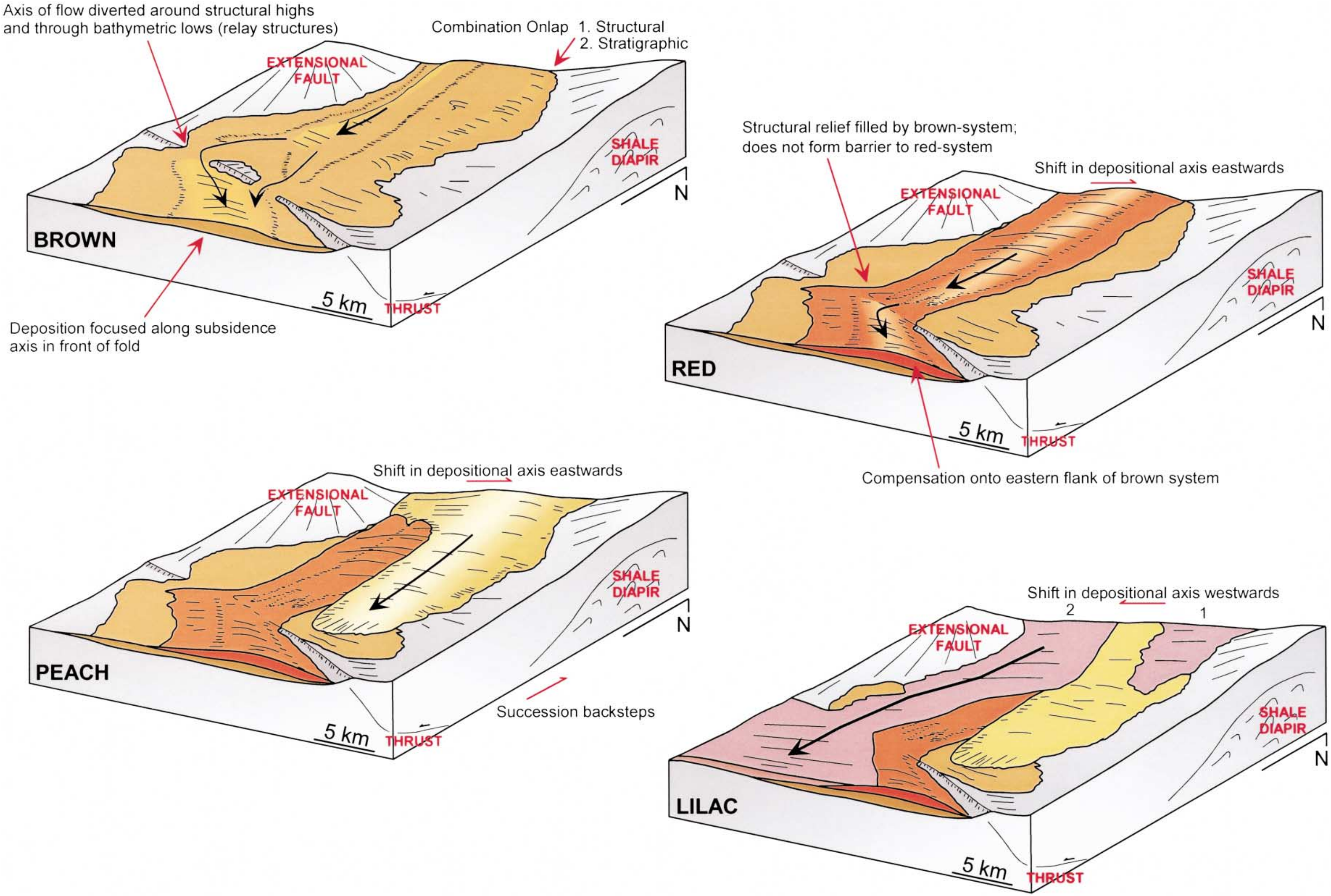
4. Development of the ponded section

The linkage and interaction amongst the various elements of the structural system can be described by analysis of the upper ponded succession (Figs. 6–8). The thrust does not propagate through this final succession, thus enabling the linkage between the ponded section and its equivalent section down-slope of the fold to be defined explicitly. The upper ponded section is filled by a succession of four depositional systems that have a lobate, shingled character. Each system is arbitrarily referred to by the colour of the upper seismic surface with which it was interpreted (Fig. 6). Isopach maps of the individual systems are presented in Fig. 7a–d; complementary 3-D cartoons that summarise the stacking of the depositional systems, are presented in Fig. 8a–d.

4.1. The 'brown' depositional-system (Figs. 7a and 8a)

The 'brown system' sits immediately above a regionally correlative sequence-boundary at the base of the upper part of the ponded section. Prior to the deposition of the 'brown system', primary accommodation had been created on the slope by structural movement. The main fold presented an obstacle to the down-slope transportation of sediments in the 'brown system'. The depositional axis of the 'brown system' was diverted around high-points on the folded

Fig. 7. (a)–(d) Isopach maps of the four depositional systems—brown, red, peach and lilac—that fill the upper ponded section above the base of unit 5 (Fig. 2). The location of seismic lines A and B from Fig. 6 are marked.



Originally the lilac system follows the eastward migrating trend (1). The lack of available accommodation, however, results in a shifting of the system to the west, (2), where it exploits the depositional low to the south of the fold surface (which correspond to points of high net-displacement on the thrust surface) and through bathymetric lows. The bathymetric lows correspond to relay structures where individual components of the thrust surface overlap. Sedimentation became focussed along a subsidence axis located in front of the developing fold. The eastern limit of the ‘brown system’ in the pond is defined by combined structural and stratigraphic onlap onto the flank of the diapiric structure.

4.2. The ‘red’ depositional-system (Figs. 7b and 8b)

Structural bathymetry filled by the ‘brown system’ did not form an obstacle to the ‘red system’. Whereas there was a general shift eastwards in the depositional axis of the ‘red system’, it is less laterally extensive than the ‘brown system’. This eastward shift reflects the modification of the primary accommodation by the partial depositional filling of the ‘brown system’. Growth of the shale diapir removed accommodation and caused the ‘red system’ to offlap the diapir flank. In the frontal area, there was differential compensation onto the eastern flank of the ‘brown system’.

4.3. The ‘peach’ depositional-system (Figs. 7c and 8c)

The ‘peach system’ is entirely contained in the ponded section. As with the ‘red system’ it compensates laterally to the east, exploiting the remaining unfilled primary accommodation in the pond.

4.4. The ‘lilac’ depositional-system (Figs. 7d and 8d)

The ‘lilac system’ originally follows the same eastward-migrating trend of the underlying ‘peach’ and ‘red systems’. The lack of available accommodation on the flank of the rising diapir, however, results in an abrupt shifting of the depositional system to the west to exploit space now available in front of the extensional fault. The ‘lilac system’ exploits the last vestige of primary accommodation on the western flank of the ‘brown’ and ‘red systems’. The ‘lilac system’ exits the pond through a low-point on the fold surface, and is then free to exploit the depositional low on the western flanks of the ‘brown‘ and ‘red systems’ in front of the fold.

5. Discussion

The change in spatial stacking of the depositional systems comprising the youngest ponded section illustrates how accommodation on the slope is progressively created and filled. Analysis of this section also reveals how the individual structural elements interact to create and modify the available space. The depositional systems initially exploit primary accommodation on the slope created by structural movement—the growth of the fold, the extensional faults and the shale diapir. As the pond is progressively filled, the previously deposited strata modify the accommodation and subsequent depositional systems compensate accordingly.

5.1. Accommodation in slope settings

Implicit in the definition of accommodation (Jervey, 1988) is that space, into which sediment can be deposited, is created by sea-level rise, subsidence or a combination of both of these processes. This definition works well in shelfal settings where the primary control on accommodation is sea-level variation. However in slope and basin floor settings, sea-level change does not result in a significant change in accommodation. Accommodation on a submarine slope is controlled by its graded profile. This profile represents a long-term morphodynamic equilibrium between depositional and erosional processes on the slope (Ross et al., 1994; Winker, 1996; Prather et al., 1998; Badalini et al., 2000; Beaubouef and Freidman, 2000; Booth et al., 2000), establishing a stable angle of progradation. In the deepwater Niger Delta, this ‘ideal’ profile is disrupted by the tectonic processes and by the erosional and depositional topography generated by sediment gravity-flow systems. Thus, when considering such slope settings, the definition of accommodation thus needs modification to include the observation that the ‘space, into which sediments can be deposited’ is created by structural movements, sediment distribution or a combination of both.

5.2. Controls on accommodation

A hierarchy of controls can be identified as influencing the generation of accommodation in the deepwater Niger Delta. The primary control on accommodation is structural movement. Low-relief structures create the principal highs and lows across the depositional fairway, providing a template across which submarine flows are focused. In our study area, the grade of the slope is initially perturbed by the growth of the fold-thrust system. The extensional fault and the shale diapir create further primary accommodation that is accentuated by shale withdrawal underneath the pond. The primary accommodation created by structural movement, such as the slope-basin (pond) behind the frontal fold, is progressively infilled by sediments that have been

Fig. 8. (a)–(d) Schematic 3-D depositional-models, based on the isopach maps in Fig. 7, to illustrate the spatial stacking of the depositional systems that fill the upper ponded section above the base of unit 5 (Fig. 2). Four systems can be defined—brown, red, peach and lilac. The depositional systems initially exploit primary accommodation on the slope created by structural movement—the growth of the fold, the extensional faults and the shale diapir. As the pond is progressively filled, the previously deposited strata modify the accommodation and subsequent depositional systems compensate accordingly.

intercepted as they moved down the slope (cf. topographic compensation; Mutti and Sonnino, 1981). Secondary control on accommodation is provided by fairway-scale depositional-processes including large-scale topographic compensation of the depositional systems themselves. This compensation can be constructive (lobes, levee systems, solidified debris flow fields) or destructive (channel scours and bypass, mass-wasting scars). Intra-fairway scale depositional processes provide a final tertiary control on accommodation where the hydrodynamic properties of an individual flow (plastic or fluidal) will control the local facies distribution within a depositional fairway.

6. Summary and conclusions

The growth and development of the structural and depositional systems in the Niger Delta involves the complex interaction of extension, contraction and subsidence. In the broadest terms, at any given point in time up-dip extensional systems are kinematically linked to down-dip contractional systems via a translational zone. Differential subsidence is present on a regional scale because of the load imposed by the deltaic section and creates the regional backward tilting of the pre-kinematic strata visible on regional sections across the delta (Fig. 2). Superimposed on the regional tectonostratigraphic zonation are local structural and depositional systems associated with individual extensional faults and thrust-cored folds, and the local subsidence and withdrawal associated with shale diapir growth.

The modern delta configuration, particularly the relationship between the deepwater fold-thrust belt and the up-dip regional and counter regional extensional fault-systems, provides a useful ‘key to the past’. At any given location, however, what you see today is not the way it was in the past; structural and depositional systems have migrated with the seaward propagation of the delta.

The structural system in the paleo fold belt, now buried under the upper slope, comprises a complex suite of en échelon thrust-cored folds and associated extensional faults, shale diapirs and ponded-slope-basins. These structural elements are the primary control for accommodation on the slope. Analysis of the depositional systems of the growth strata in the ponded slope-basins associated with the paleo fold belt illustrates how accommodation on the slope is progressively created and ultimately destroyed. The spatial stacking of the depositional systems reveals that the structural system developed from the complex, simultaneous interaction between contractional faulting and folding, extensional faulting, and shale-diapirism and withdrawal.

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