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Quantitative bathymetric analyses of selected deepwater siliciclastic margins: receiving basin configurations for deepwater fan systems

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Abstract

Comparative bathymetric analyses of four siliciclastic continental margins reveal important distinguishing characteristics in deepwater receiving basin configurations. These characteristics have potential impact on deepwater sedimentation patterns and associated fan development. Present-day bathymetry was analysed quantitatively, using advanced software and digital bathymetry data. Various physical attributes of dip, basin geometry, and accommodation were quantified and mapped in 3D. Results show significant differences in receiving basin configurations between salt-based and shale-based continental margins in the Gulf of Mexico, Angola, Nigeria, and NW Borneo, especially in the type, amount, and distribution of accommodation. Salt-based systems have more ponded accommodation than shale-based systems; however, all the margins have a relatively small percentage of ponded to total accommodation. Two exceptions to this are the central portion of the Northwest Gulf of Mexico where ponded accommodation constitutes 55% of the total accommodation and the Kwanza Basin of Offshore Angola with 39% ponded accommodation. Shale-based systems may be more prone to bypass on the upper to mid slope than salt-based systems. Evidence for this is found in the linear grade trend analyses where large below-grade areas (sinks) are pervasive on the upper and mid slope of salt-based systems for deepwater sediment to accumulate, while shale-based systems show extensive above-grade highs across the entire slope. Ponded accommodation trends and drainage analyses also demonstrate that shale-based systems are more susceptible to extensive bypass than salt-based systems. The tectonically active margin of NW Borneo has steeper slope profiles than the passive margins, with areally small ponded accommodation largely restricted between active toe-thrusts on the lower slope and locally distributed on the shelf. These and other quantitative analyses suggest that the type of substrate and overall tectonic setting are important factors to consider for receiving basin configuration and its potential impact on deepwater sedimentation patterns.

Keywords: Deepwater; Gulf of Mexico; Angola; Nigeria; Northwest Borneo; Sabah; Brunei; Bathymetry; Seafloor morphology; Trend surface analysis; Drainage analysis; Accommodation; Ponded; Healed slope; Gradient; Mobile salt; Mobile shale

1. Introduction

It is generally accepted that the ultimate, large-scale, controls influencing deepwater depositional systems on continental margins are sediment supply, regional basin tectonics and relative changes in sea level (Mutti & Normark, 1991; Posamentier, Jervey, & Vail, 1988; Posamentier & Vail, 1988; Reading & Richards, 1994; Vail et al., 1977). The inter-relationships between these controls yield a large number of possible scenarios for deepwater fan development on these margins. Consequently, it is difficult to discern the individual contribution each control had on a deepwater system. Furthermore, these controls are difficult to use in a predictive manner for classifying and characterizing deepwater fans, reservoir distribution and stacking patterns. Once the sediment reaches the shelf margin and beyond, however, the *sedimentary delivery system* and the *receiving basin configuration* are the primary factors that govern overall fan morphology and lithofacies distribution. Reading and Richards (1994) propose that the dominant grain size, sediment flux (volume, rate, duration) and the nature of the feeder system (point vs. multiple vs. line source) are the key components that comprise the delivery system and ultimately the morphology of a submarine fan. The deepwater receiving basin configuration is equally important in influencing deepwater sedimentation patterns.

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The important elements of the receiving basin configuration are its overall gross morphology, the type of accommodation available for deposition, and its equilibrium profile. Numerous papers explore the relationship between receiving basin setting and deepwater sedimentation patterns in terms of conceptual models and specific examples.

1.1. Conceptual models

Mutti and Normark (1987) recognize four basic types of turbidite basins, emphasizing that the long-term stability of the receiving basin and the volume of sediment primarily control the morphology and internal facies associations of submarine fans. Along with eustasy and tectonism, Mutti and Normark (1991) emphasize the composition and volume of turbidity currents as well as the basin type and configuration as primary factors controlling the geometry and facies patterns of turbidite systems. Ross, Halliwell, May, Watts, and Syvitski (1994) introduce a slope readjustment model, suggesting that depositional and erosional processes on continental slopes tend towards maintaining graded, steady state profiles. Kneller and McCaffrey (1995, 1999) show the depositional effects a bounding surface and salt-induced topography has on turbidity flows from experimental flume studies. Galloway (1998) stresses the importance of sediment supply history and inherited slope morphology on the development of seven basic facies found in slope and base-of-slope depositional systems. Prather, Booth, Steffens, and Craig (1998) demonstrate that various seismic facies assemblages predominate in the fill history of Gulf of Mexico (GOM) deepwater basins and relate them to different types of accommodation. Prather (2000) furthermore shows numerical forward models that simulate the sequential fill and spill down the continental slope in Gulf of Mexico intra-slope basins. Smith (2003) describes sediment distribution systems on topographically complex slopes as either cascades of silled sub-basins or connected tortuous corridors lacking effective sills. He proposes that fill patterns and reservoir architecture are controlled by the volume and flow properties of the sediment supply, the relative scale of the receiving basin space and the flows, the relative rates of basin subsidence, and the infilling depositional processes. Prather (2003) shows that slope topography strongly affects the distribution, quality, and production performance of many deepwater reservoirs. Continental slopes either exhibit: (1) above-grade slopes with well-developed ponded accommodation and large amounts of healed slope accommodation, (2) above-grade slopes with stepped or terraced profiles that have little or no ponded accommodation, or (3) graded slopes with minor topography. Sheet sands are often found in ponded accommodation, whereas cyclical alternation of channels, sheets and mass transport complexes predominate in healed slope accommodation (Booth, Dean, DuVernay, & Styzen, 2003); sinuous ribbon-like channel sands are common in stepped profiles (Prather, 2003).

1.2. Specific examples

Satterfield and Behrens (1990) and Winker (1996) describe in detail the Trinity/Brazos Fan in the Gulf of Mexico that progressively filled- and spilled-through the topography of four intra-slope basins, depositing various seismic facies in each basin. Further analyses by Badalini, Kneller, and Winker (2000), Beaubouef and Friedmann (2000), and Beaubouef, Friedmann, and Alwin (1998) show the progressive downslope filling of these basins and the systematic vertical and lateral arrangement of mass transport, distributary channel-lobe, and leveed-channel complexes in each of the basins. Similar processes and stacking patterns are documented for the shallow Auger Basin in the Central Gulf of Mexico as well (Winker & Booth, 2000). Booth, Prather, and Steffens (2002) provided numerous examples of submarine sands whose distribution and architecture vary significantly across partitioned slopes with different types of accommodation. Sinclair and Tomasso (2002) demonstrate flow ponding or the complete capture of incoming flows in the Annot System located in the south of France.

Booth et al. (2003) and Booth, DuVernay, Pfeiffer, and Styzen (2000) provide the most compelling evidence of receiving basin configuration control on deepwater sedimentation with a detailed calibrated stratigraphic framework of the Auger Basin, central northwestern Gulf of Mexico. They describe the overall stacking patterns, detailed architectures, and the different types of accommodation of the various reservoirs found in the Macaroni and Auger Fields. They emphasize and document the evidence for paleo-bathymetric control on different cyclical fill patterns and reservoir architectures observed in these fields.

1.3. Objective of this study

All of the papers cited above focus on predicting stratigraphic architecture and patterns in topographically complex slopes through examples and conceptual models. What is missing in these reviews is a consistent, systematic approach of characterizing partitioned slope settings. Therefore, this paper focuses on present-day deepwater receiving basin configurations of four siliciclastic continental margins with the aim of providing a useful context for placing these concepts and examples in proper perspective. The quantification and 3D analyses of receiving basin configuration in partitioned slope settings are specifically addressed, comparing the salt-based systems of northwest Gulf of Mexico and offshore Angola to the shale-based systems of offshore Nigeria and NW Borneo. 3D quantification of present-day bathymetries was conducted on each of these margins, including: (1) trend surface analysis and mapping of various attributes of dip (magnitude, rate of change, azimuth, and convergence/divergence), (2) accommodation, and (3) basin geometry. The results from these analyses provide new insights into the various receiving basin configurations that are available for deepwater fans to accumulate in salt- and shale-based systems. Characterizing the receiving basin configuration for various deepwater siliciclastic margins has value at both the exploration play and reservoir development scales, potentially helping to predict overall fan morphology, distribution of depositional environments, and reservoir/seal architectural styles and stacking patterns.

2. Methodology

This study builds on previous work by O'Grady (1996), who pioneered one of the first studies that systematically analysed the 3D complexities of 50 present-day siliciclastic continental passive margins using primarily the data set generated by Smith and Sandwell (1997). Adopting a quantitative and forward modelling approach, O'Grady (1996) and O'Grady, Syvitski, Pratson, and Sarg (2000) characterized the morphology of a continental margin in terms of slope profiles. This study uses more advanced 3D quantitative mapping techniques on significantly higher resolution bathymetric data than were used by O'Grady (1996) and O'Grady et al. (2000). These analyses yield a refined understanding of seafloor morphology and the types of accommodation for deepwater sediment in various siliciclastic margins. Specifically, a new technique was developed that allows for a rigorous, consistent and reproducible 3D quantitative analysis of present-day seafloor morphology in deepwater settings. Applying such a technique reduces the subjectivity in characterizing deepwater basins while highlighting the possible effect of receiving basin configuration on deepwater depositional systems and associated potential reservoir/seal distribution. The technique utilizes proprietary algorithms in conjunction with ArcGIS™ mapping software to calculate, map and statistically compare various attributes of seafloor morphology from available digital bathymetry data sets. The attributes include various calculations of dip (e.g. magnitude, rate of change/curvature, azimuth, convergence/divergence trends, etc.), and receiving basin geometry (e.g. aerial shapes and sizes, trend surface and residuals, roughness, 'ponded' and 'local healed slope' accommodation, drainage paths, etc.). All of these attributes are potentially significant factors that influence deepwater sedimentation.

This study utilized geographically referenced 3D bathymetric digital datasets. Varying in both method of measurement and resolution, the data are broadly separated into either global scale or basin-scale (or smaller) data sets. The global dataset includes ETOPO5 and Sandwell data while the higher resolution basin-scale (and smaller) datasets were compiled from 3D seismic and NOAA multi-beam side-scan sonar (Table 1).

The initial available digital data sets analysed for this study were the global ETOPO5 and Sandwell data. The coarse resolution of ETOPO5 data (gridded to 2500 m cell size) was used for some of the regional analyses (see below), but was found to be of insufficient resolution to accurately depict accommodation and other key attributes (Fig. 1). Additionally, basin-scale higher resolution bathymetric data was compiled from various sources for the Gulf of Mexico, offshore Nigeria, offshore Angola, and NW Borneo. Because of the inconsistent resolution of the basin-scale bathymetry data used in this study, it was decided that the different data sets needed to be normalized to a least common denominator ('LCD') resolution of 200–250 m. The basin-scale datasets were therefore all depopulated down to the level of the 'LCD' prior to performing calculations and mapping of key attributes. In order to ensure that vital or critical information was not being lost through depopulating down to the LCD, a calibration study was performed with the highest and best quality data set in the Gulf of Mexico wherein the key attributes were calculated, mapped, and compared at both the highest resolution scale (61 m) and at the LCD scale (200–250 m). The results of the calibration exercise demonstrated that the LCD resolution was sufficiently accurate for the purposes of this study.

The 3D methodology proceeds in two steps: first, low-resolution ETOPO5 bathymetry data are used to perform geomorphological classification and a coarse resolution drainage analysis of the entire basin and updip watershed; secondly, 3D topological analysis is performed on

Table 1

Global datasets

Source	Grid spacing	Type of data	Basins
NOAA Etopo5	5–9 km	Bathymetry	All
Sandwell	< 5–9 km (variable)	Bathymetry from satellite altimetry	All

Basin-scale or smaller data sets

Source	Grid spacing	Method of measurement	Basins
2D seismic	1–5 km (variable)	Seismic travel time	GOM, Nigeria, Angola, Borneo
3D seismic	< 100 m	Seismic travel time	GOM, Nigeria, Angola, Borneo
NOAA High Res.	61 m	Multi-beam side-scan sonar	GOM only

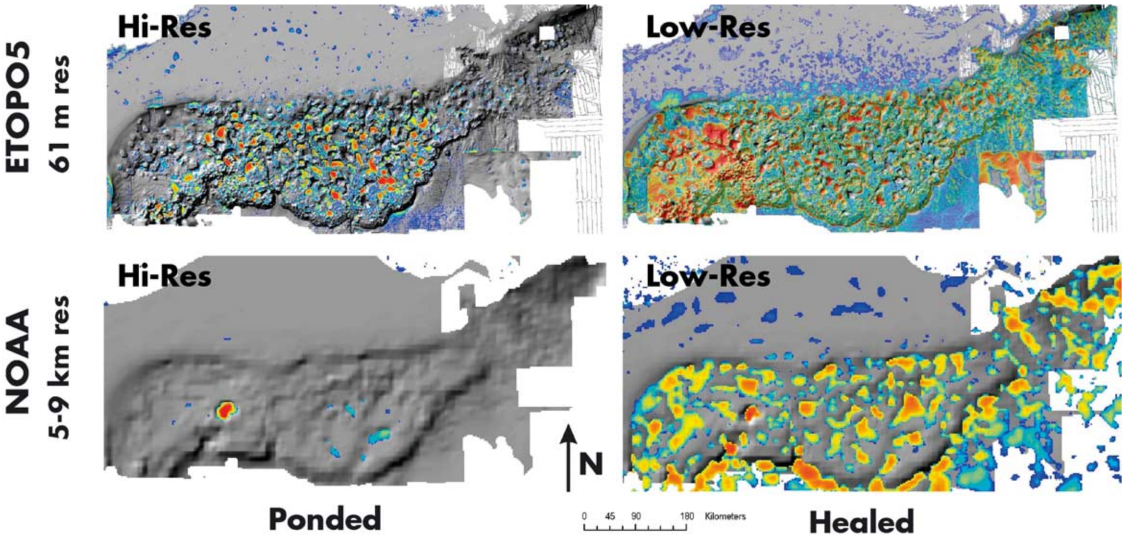

Fig. 1. A comparison of Northwest Gulf of Mexico accommodation calculations (ponded and healed slope), using low-resolution ETOPO5 data (lower row) and high-resolution NOAA and 3D seismic data sets (upper row). The low-resolution data were gridded to 2500-m cell size, while the high-resolution data were gridded to 200–250 m. Note that the low-resolution data does not provide sufficient detail for detecting and delineating either type of accommodation.

the high-resolution bathymetry data to compute accommodation and detailed drainage patterns on the slope and beyond.

Specifically in Step I, 3D attributes such as dip, azimuth, curvature, divergence, and roughness computed from the low-resolution regional bathymetry and topography data are combined in a multi-variable algorithm to classify the basin into regions of land, shelf, continental slope, proximal basin floor, and distal basin floor (Fig. 2A and B). These classifications generally agree well with historical

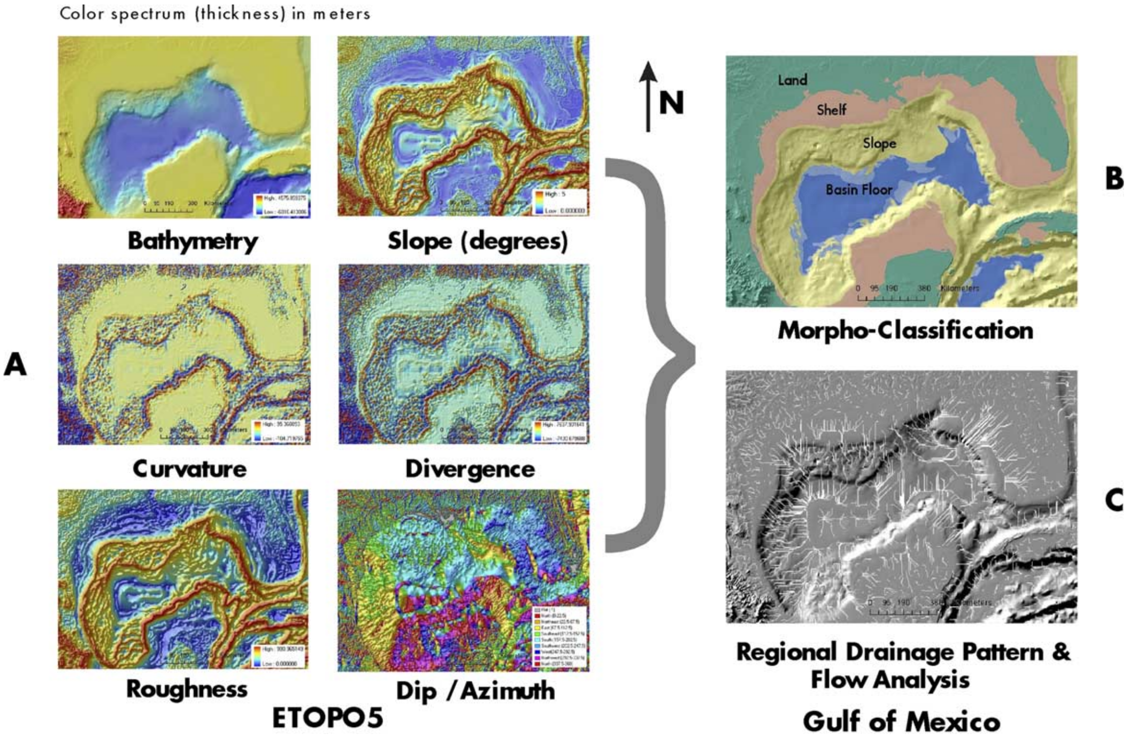

Fig. 2. 3D attribute analysis for topo-morphological classification, drainage pattern, and flow analysis. (A) 3D attributes such as dip, azimuth, curvature, divergence, and roughness are computed from the low-resolution regional bathymetry data. (B) These attributes are combined in a multi-variable algorithm to classify the basin into regions of land, shelf, continental slope, proximal basin floor, and distal basin floor. These classifications generally agree well with historical definitions and with conventional usage, but are computed directly from the data. Shelf break and toe-of-slope are important features that are used, with the classifications, in later steps of the analysis. (C) Bathymetry, slope, azimuth, curvature, and divergence are used in a coarse resolution drainage pattern and flow analysis. These attributes can be used in 3D modelling of turbidite flows at a regional scale.

definitions and with conventional usage, but are computed directly from the data. Also in Step I, a regional drainage pattern and flow analysis is performed on the low-resolution data, generating regional watersheds and stream flows that describe the overall mass transport from the shelf to the basin floor (Fig. 2C).

In Step II, detailed drainage patterns and watersheds are calculated from the high-resolution data (and from the regional watersheds defined in Step I) on the continental slope to analyse flows around local topography and intra-slope basins. Accommodation on the slope is also derived in a consistent manner from the high-resolution bathymetry data sets using 3D topographical analysis. Four types of accommodation are computed and displayed in three dimensions.

Linear grade trend surface is computed by fitting a slowly varying 3D surface to the bathymetry data between the shelf break and toe-of-slope derived in Step I (Fig. 3A). In an arbitrary 2D dip profile down the slope, this surface is approximately linear. Where the local bathymetry is shallower than (above) this approximate linear grade or trend surface, the residual is termed ‘positive’, whereas ‘negative’ residuals are where local bathymetry is below the linear grade. This is particularly useful for quickly visualizing the general accommodation trends associated with the continental slope and where potential sites may occur for regional sedimentation patterns. The regional dip for the various deepwater slopes is an average calculation from the linear trend surface of the bathymetry between the shelf break and toe-of-slope; this provides the most consistent and reliable method for describing regional dip.

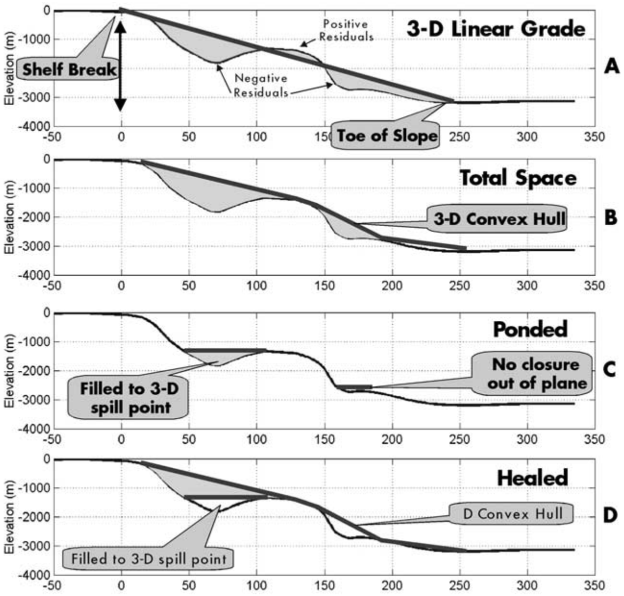

Fig. 3. Accommodation definitions. All computations are done in 3D, although this figure only shows 2D profiles to demonstrate the accommodation definitions. (A) 3D linear grade trend surface is computed by fitting a slowly varying 3D surface to the shelf break and toe-of-slope surfaces. In an arbitrary dip profile down the slope, this surface is approximately linear. Where the local bathymetry is shallower than this linear grade, the residual is termed positive and is shaded red; where the bathymetry is deeper than this linear grade, the residual is termed negative and is shaded blue. (B) Total accommodation is determined by first locating the points of maximum positive curvature (the ‘hills’) on the slope and then by creating a 3D convex hull passing through those points. Because this surface essentially ‘drapes’ across the local bathymetry maxima, the total accommodation space will generally be greater than the linear grade accommodation. (C) Ponded accommodation is an area of negative curvature with 3D closure (the ‘bowls’ or ‘sinks’ related to intra-slope basins). This closure is filled to the lowest spill point. (D) Healed slope accommodation is simply the difference between the total and ponded accommodation. Note that by construction, the total accommodation will always be greater than or equal to the healed slope accommodation. In the figures, thick accommodation is shaded red while thin accommodation is shaded blue. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Total accommodation is determined by locating the points of maximum positive curvature (the ‘hills’) on the slope in 3D and then draping a 3D convex hull that passes through these points (Fig. 3B). Because this surface essentially ‘drapes’ across the local bathymetry maxima, the total accommodation will generally be greater than the linear grade accommodation.

Ponded accommodation is the volume identified by the points of maximum negative curvature (the ‘bowls’, ‘sinks’, or intra-slope basins) that have 3D closure (Fig. 3C). The ponded accommodation thus represents intra-slope basins that are ‘filled to spill’. Areas of negative curvature without 3D closure do not contribute to the ponded accommodation.

Healed slope accommodation is simply the volume difference between the total and the ponded accommodation (Fig. 3D). In situations where there is no ponded accommodation, such as along stepped or terraced profiles (in sensu stricto Prather, 2003), or where there is no 3D closure, the healed accommodation is equal to the total accommodation.

3. Results

The four basins that were analysed for this study are the Northwest Gulf of Mexico, offshore Nigeria, offshore Angola, and Northwest Borneo. The Gulf of Mexcio, Nigeria, and Angola margins are all large progradational clastic Tertiary depocenters on passive margins. They are dominated by gravitationally driven linked extensional–contractional tectonic systems on mobile substrates (Fig. 4A–C); the Northwest Gulf of Mexico and offshore Angola are underpinned by mobile salt while offshore Nigeria is underpinned by mobile over-pressured shale. All three of these basins experienced interplay between rapid loading and the underlying mobile substrates, resulting in morphologically complex partitioned slope settings. In contrast to these three passive margins, Offshore NW Borneo is an active convergent margin setting underlain by the complex Crocker thrust belt system and mobilized shale (Fig. 4D). Unlike a passive margin setting where compressional deformation is thin-skinned and largely confined to

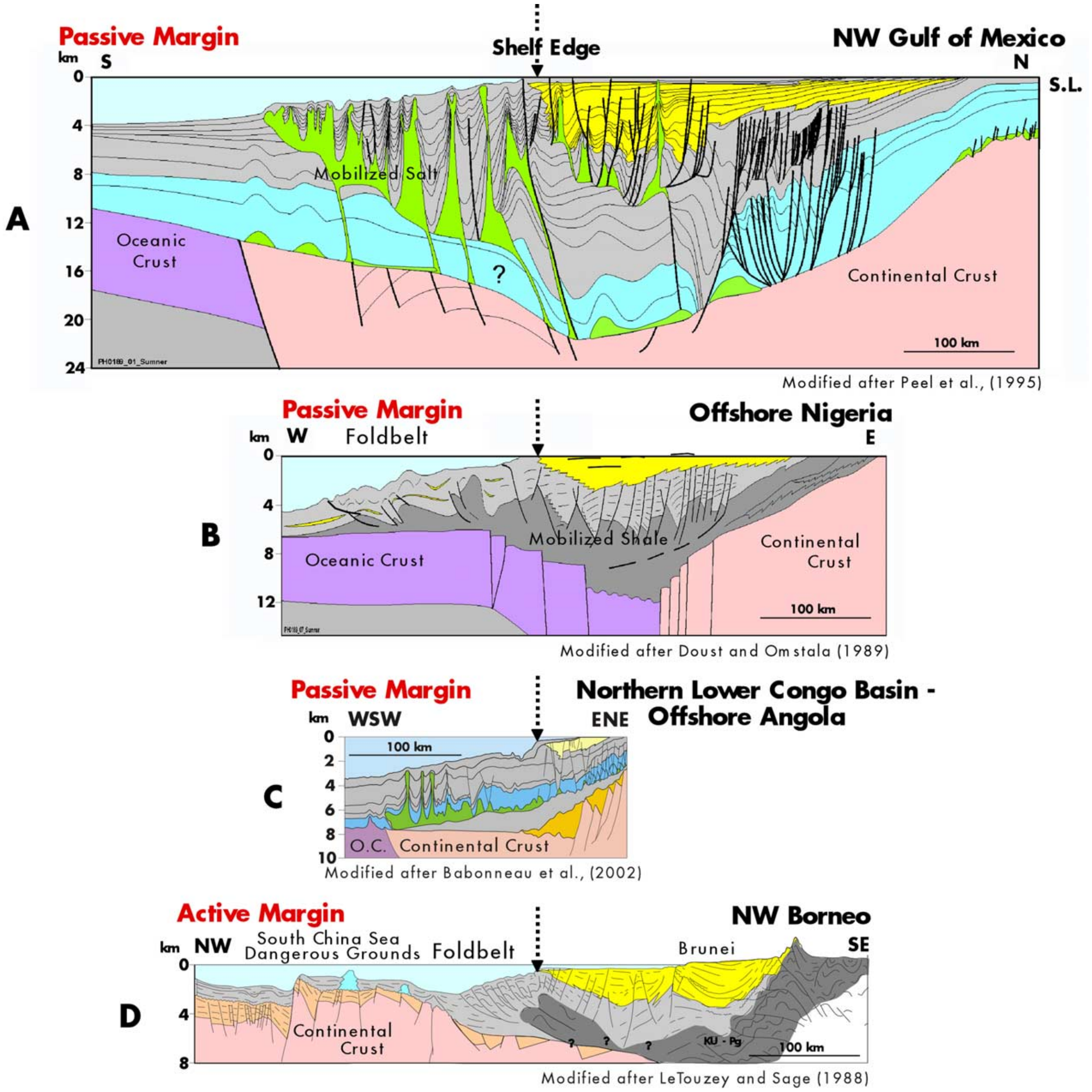

Fig. 4. Regional cross-sections of the Northwest Gulf of Mexico, Nigeria, Angola, and Northwest Borneo continental margins are displayed at the same scale for direct comparison. Gulf of Mexico and offshore Angola are salt-based systems while offshore Nigeria and Northwest Borneo are shale-based systems. Gulf of Mexico, Angola, and Nigeria are passive margin settings, dominated by gravitationally driven linked extensional–contractional tectonic systems detaching on mobile substrates (thin-skinned). In contrast, Northwest Borneo is an active margin setting underlain by the Crocker thrust belt and mobilized shale; much of the compressional deformation is basement related (thick-skinned) and is pervasive throughout the margin (slope, shelf, and hinterland). see Babonneau et al., 2002; Doust & Omatsola, 1989; Letouzey & Sage, 1998; Peel et al., 1995.

the lower slope/toe-of-slope, NW Borneo experiences widespread basement-related compressive deformation and partitioning throughout its margin (slope and shelf).

3.1. Northwest Gulf of Mexico

The continental slopes around the circum Gulf of Mexico Basin are separated into three broad families. The carbonate margins along the Florida and Campache Escarpments (eastern and southern Gulf of Mexico) typify steep slopes, with gradients often exceeding 1.75°. Intermediate slopes of 1.25–1.75° are observed in the western Gulf of Mexico associated with the shale-based Mexican Ridges fold belt. Shallow slopes with gradients less than 1.25° are observed in the northwest and southwest areas of the Gulf of Mexico associated with mobilized salt substrates. This paper focuses on only the Northwest Gulf of Mexico where the slope is predominantly shallow and underpinned by mobile salt (Callovian age and nearly 99% halite). In this area, the width of the slope averages 175–250 km. For this area, the regional average gradient is 0.76 ± 0.06°. The average gradient is steeper primarily in the eastern portion where the salt substrate is thin or absent. Local gradients on the flanks of intra-slope basins can often exceed 10–12°.

Linear grade (i.e. ‘trend surface’) analysis of the Northwest Gulf of Mexico slope shows a prominent negative residual below the regional linear grade on the upper and middle slope in the central portion of the basin (colored blue in Fig. 5A). This low area below-grade roughly corresponds with a part of the basin that is dominated by large extensional salt withdrawal intra-slope basins and thick total accommodation (Fig. 5B). The lower slope exhibits a major strike-oriented positive residual (above-grade) shaded red in Fig. 5A. This is where the Sigsbee salt canopy has ‘lifted’ this region above the regional linear grade, resulting in a region of probable sediment bypass (Fig. 5A).

The Northwest Gulf of Mexico intra-slope basins exhibit abundant ponded accommodation throughout the central portion of the slope with the largest areas located on the upper slope and becoming progressively smaller down slope (Fig. 5C). They are often circular to elliptical in plan view with diameters up to 25–30 km. Ponded accommodation constitutes 55% of the total accommodation in the central slope of the Gulf of Mexico. In general, the overall morphology of the central region is above-grade (in sensu stricto Prather, 2000, 2003) where large amounts of ponded and healed slope accommodation prevail in the upper and middle slope. The lower slope is dominated by an outboard high (positive residual), which is underpinned by the Sigsbee salt canopy. Ponded accommodation is rare both east and west of the central area. Healed slope accommodation is more pervasive throughout the slope (particularly in the west, in offshore Texas) and displays similar size distribution trends to the total accommodation (Fig. 5D).

Drainage path analysis shows that the pathways are disconnected in the complexly partitioned central portion of the Northwest Gulf of Mexico (Fig. 6). In general these drainage pathways are <20 km in length, and often cluster within and near individual salt withdrawal intra-slope basins. This drainage texture most closely correlates with Smith’s (2003) ‘cascades of silled sub-basins’ morphologic end-member. Areas immediately east and west of this large partitioned central area are characterized by more continuous but complex drainage corridors with maximum dip extents of ~60 km, similar to Smith’s (2003) ‘connected tortuous corridors’. The steeper area east of the Mississippi Canyon displays unconfined linear pathways with dip-oriented drainage paths up to ~130 km in length. This drainage texture occurs in a graded unconfined slope setting with little or no salt substrate and complex topography.

3.2. Nigeria

The continental slope in offshore Nigeria has an average regional gradient of 1.18°. Large areas of the continental slope have regional gradients ranging from 1.0 to 1.2°, separated by steeper areas ranging from 1.7 to 2.2°. These areas are in general, underlain by mobilized shale. Shallow slopes lie to the southeast of the Cameroon volcanic ridge,

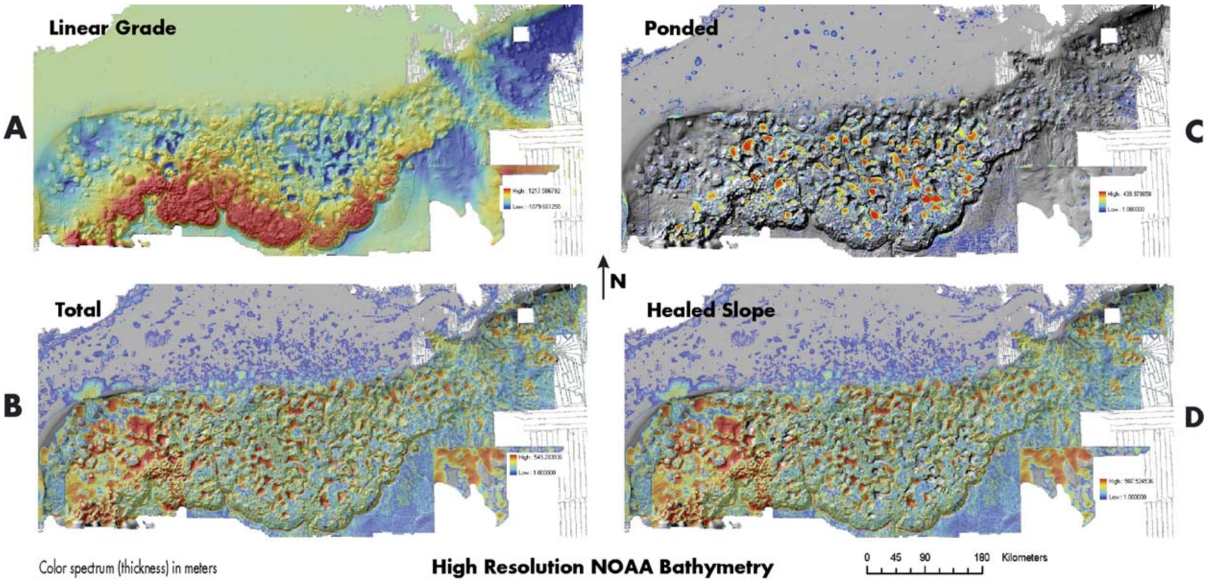

Fig. 5. Various types of accommodation calculated for the deepwater of Northwest Gulf of Mexico, using high-resolution NOAA bathymetry data. (A) Linear grade trend surface, red above linear grade (positive residual—‘hills’), yellow at or near linear grade, blues/lavender below linear grade (negative residual—‘sinks’). Note the widespread positive residual (high) on the lower slope, underpinned by the Sigsbee salt canopy, while a large negative residual (sink) dominates the upper and middle slope. (B) Total accommodation, (C) ponded accommodation, and (D) healed slope accommodation. Ponded, healed slope and total accommodation are represented as isopach surfaces as well as for subsequent accommodation figures; red colors represent thick accommodation while blue colors represent regions of thin accommodation. Note that ponded accommodation is most prevalent in the central area on the upper and middle slope, while healed slope accommodation is pervasive throughout the slope. Total and healed slope accommodation show similar map distributions with slightly different ranges of thickness. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

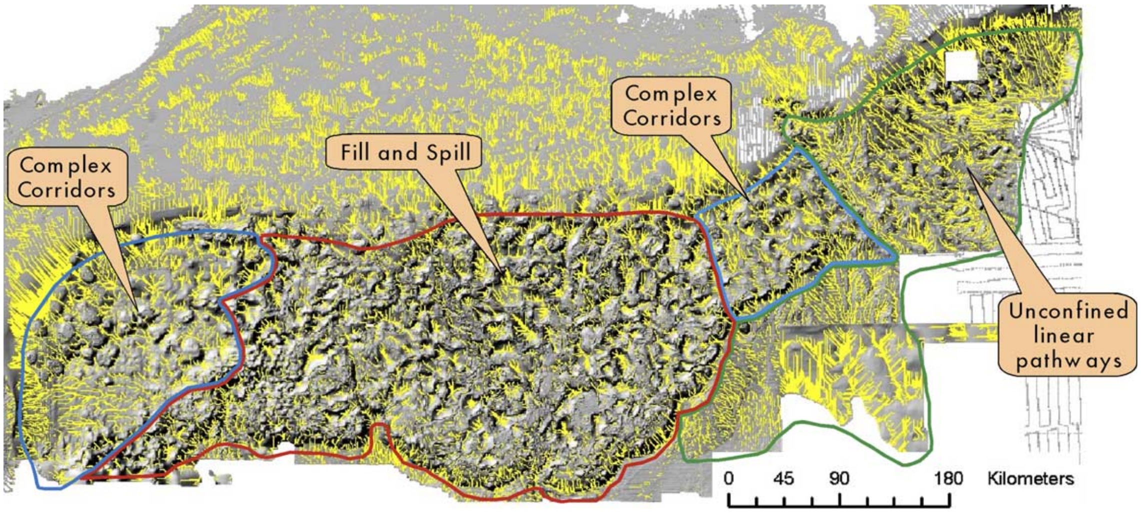

Fig. 6. Drainage patterns and flow analysis of the Northwest Gulf of Mexico, using high-resolution NOAA data. Notice the central area of fill- and spill-patterns where drainage patterns are very discontinuous and get 'captured' in many 'sinks' or basins. This area corresponds with high salt volume and high occurrence of ponded accommodation. With decreasing salt volume and accommodation, the two areas on either side of the fill- and spill-pattern exhibit connected tortuous corridors that often extend for great distances along the slope (complex corridors). The far eastern area, where the slope is relatively unconfined with low volumes of salt, exhibits linear pathways that extend from the shelf to the toe-of-slope. Bathymetry, slope, azimuth, curvature and divergence are used in drainage pattern and flow analysis.

outside of the Nigerian depocenter where most of the area is underlain by salt. As noted for the Gulf of Mexico, local gradients throughout this margin can be considerably steeper than the regional average.

Linear grade (i.e. trend surface) analysis of the Nigeria slope shows that much of it is a positive residual above the regional linear grade (shaded red in Fig. 7A). This suggests that much of the present-day Nigeria slope may be a zone of dominant bypass with deposition focused further outboard on the lower slope and beyond. This is corroborated by the relatively smoothed and healed topography on the present-day upper and middle slope, while the lower slope has significant topography associated with the actively growing, strike-oriented, toe-thrust ridges. Total accommodation is also relatively thin throughout the slope (Fig. 7B).

Offshore Nigeria's ponded accommodation tends to be areally small, strike-elongate and largely restricted to the lower slope between strike-oriented active toe-thrust ridges (Fig. 7C). Some of these ponded areas are locally thick. Ponded accommodation is rare to non-existent on the middle and upper slope while healed slope accommodation is pervasive throughout the slope. The overall slope morphology can be classified as a stepped above-grade slope (in sensu stricto Prather, 2000, 2003). Ponded accommodation is restricted to the lower slope and the healed slope accommodation is uniformly thin on the upper and middle slope (Fig. 7D).

Drainage path analysis shows anastomosing dip-oriented drainage corridors typically exceeding 100 km in the western portion of offshore Nigeria upper and middle slope (Fig. 8). The lower slope exhibits strike-oriented corridors approaching 75 km in length and often trending between actively growing toe-thrust ridges.

3.3. Angola

Analyses were conducted over a large part of the West African margin, including southern Gabon, all of Angola and northern Namibia. Our analyses focus on the Angolan offshore immediately south of the Zaire/Congo Canyon and north of the Walvris Ridge. The area includes the Lower Congo and Kwanza Tertiary depocenters. Both basins are passive margin settings underlain by mobile salt (Aptian age, 90% halite) (Fig. 4C). The continental slope in offshore Angola is fairly uniform across its entire length (Fig. 9A). From south to north, the slope becomes narrower and steeper. The Kwanza Basin, for example, has a regional gradient of 0.79° (similar to the Central NW Gulf of Mexico) while the slope in the Lower Congo Basin is steeper with an average regional gradient of 1.2°. Linear grade (i.e. 'trend surface') analysis of the offshore Angola slope shows a prominent negative residual (sink) below the regional linear grade on the upper and middle slope (colored blue in Fig. 9A). This negative residual roughly corresponds with a part of the basin that is dominated by large extensional salt withdrawal intra-slope basins and thick total accommodation (Fig. 9B). Similar to the Gulf of Mexico, the lower slope exhibits a strike-oriented positive residual (above-grade 'high' colored red) corresponding with a salt canopy, which has 'lifted' this region above the regional linear grade resulting in an area of probable sediment bypass (Fig. 9A). Note that the positive residual

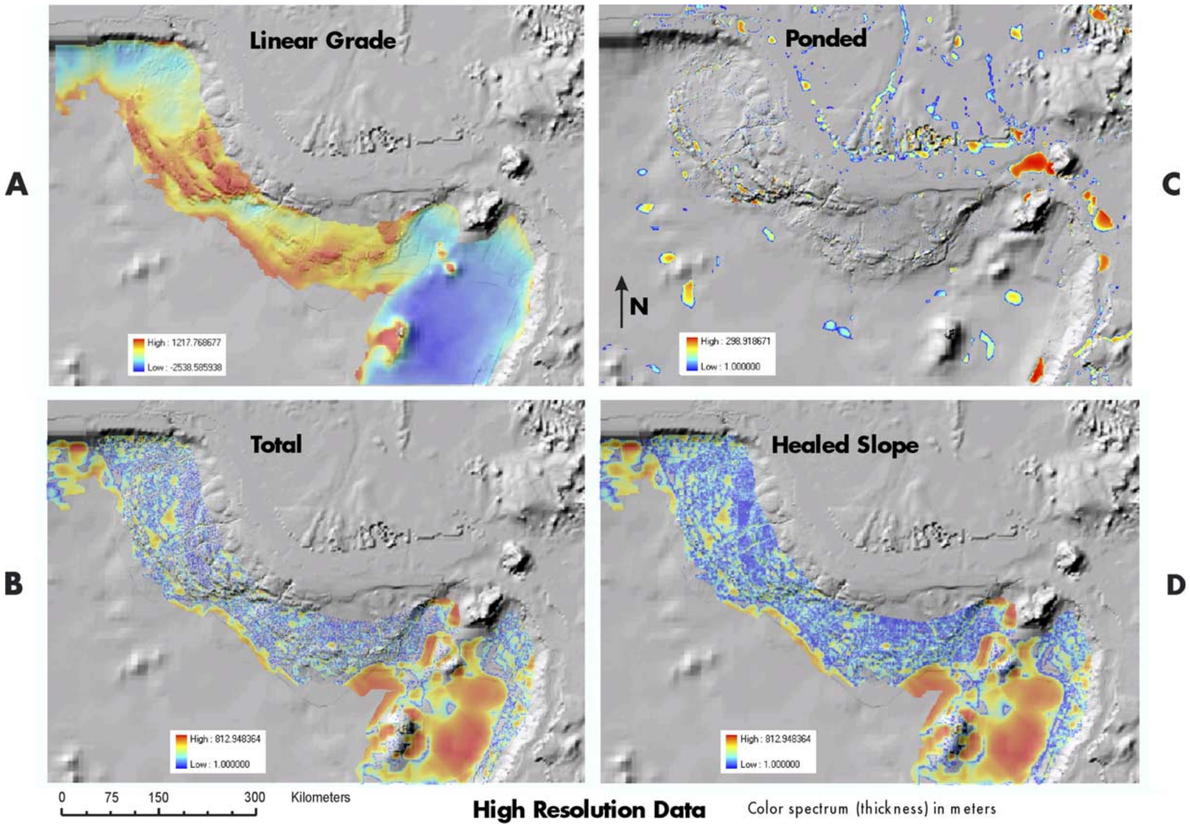

Fig. 7. Various types of accommodation displayed in the deepwater of Nigeria, using 2D and 3D seismic bathymetry data on the slope and shelf. Color scheme similar to Fig. 5. Notice the extensive linear grade highs and the corresponding low accommodation in the upper and middle slope. Note that ponded accommodation is restricted to the small areas on the lower slope and toe-of-slope between the strike-oriented emergent folds, while healed slope accommodation is thin but pervasive throughout the slope. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

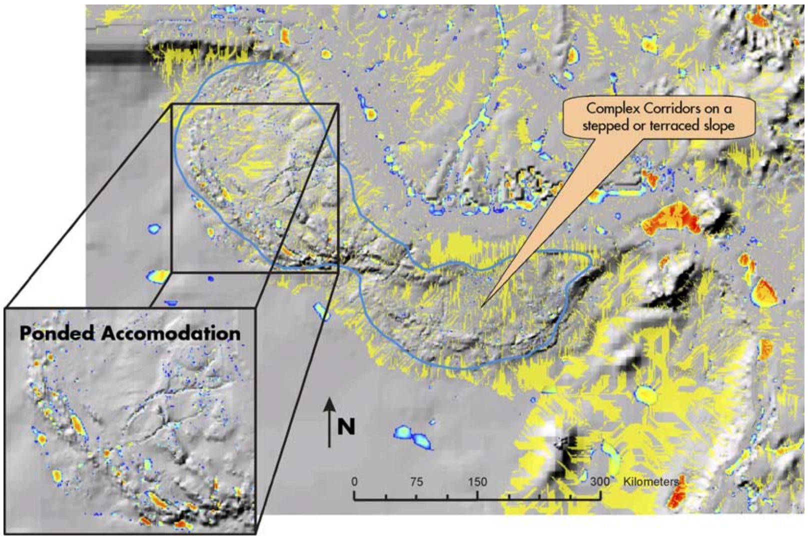

Fig. 8. Drainage patterns and flow analysis of Offshore Nigeria. Bathymetry, slope, azimuth, curvature, and divergence are used in the analysis. These attributes can be used in 3D modelling of turbidite flows. With extensive linear grade positive residuals and low accommodation in the upper and middle slope, the drainage analysis predictably shows complex corridors that extend from the shelf margin to the toe-of-slope. In particular, note that numerous dip-oriented drainage paths bypass the entire upper slope with some bypassing the emergent folds on the lower slope and extending to the abyssal plain.

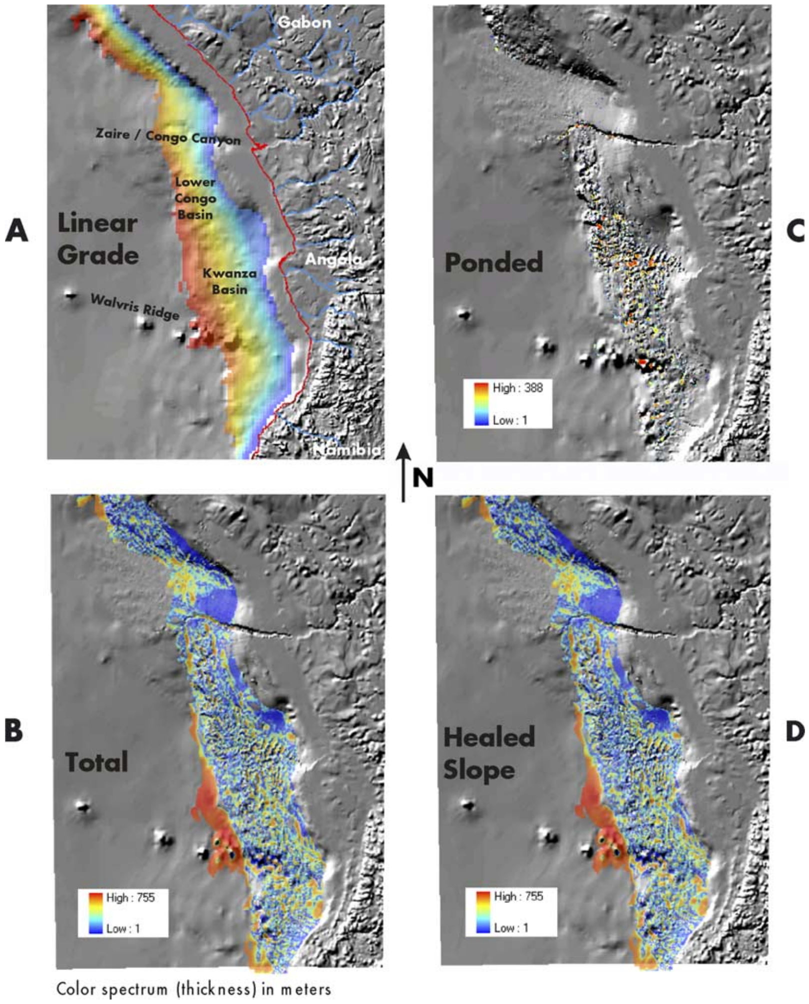

Fig. 9. Various types of accommodation in Offshore Angola are illustrated using 3D seismic and NOAA bathymetry data on the slope and shelf. Color scheme similar to Fig. 5. Note that the Angolan intra-slope basins exhibit widely distributed ponded accommodation from the southern portion of the Lower Congo Basin to the Walvris Ridge. There is a notable decrease in ponded accommodation south of the Walvris Ridge where the Alptian salt is very thin or absent. Much of the ponded accommodation in the Kwanza Basin is positioned over thick autochthonous salt on the middle slope. Additionally, healed slope accommodation is pervasive throughout the slope and has a similar distribution as the total accommodation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

gets wider in the south where the salt canopy is more extensive.

The Angolan intra-slope basins exhibit widely distributed ponded accommodation from the southern portion of the Lower Congo Basin to the Walvris Ridge (Fig. 9C). There is a notable decrease in ponded accommodation south of the Walvris Ridge where the Alptian salt is very thin or absent (Fig. 9C). The ponded accommodation areas (intra-slope basins) are circular to elliptical in plan view. Ponded accommodation constitutes 7% of the total accommodation in the Lower Congo Basin. Ponded accommodation in the Kwanza Basin is far more widespread, constituting 39% of the total. Much of the ponded accommodation in the Kwanza Basin is positioned over thick autochthonous salt on the middle slope. Conversely, the lower percentage of ponded accommodation in the Lower Congo Basin is most likely the result of this area experiencing nearly complete salt withdrawal into isolated bodies (‘grounding’), resulting in the healing of the seafloor bathymetry. Similar to the Gulf of Mexico, the overall morphology of the Angola margin is above-grade (in sensu stricto Prather, 2000, 2003) where both ponded and healed slope accommodation prevail in the upper and middle slope. Additionally, healed slope accommodation is pervasive throughout the slope and has a similar distribution as the total accommodation (Fig. 9D).

Drainage analysis over the region shows several trends (Fig. 10). In the Kwanza Basin, the drainage pathways are discontinuous and often cluster within and near individual salt withdrawal intra-slope basins. The Lower Congo Basin displays more continuous but complex drainage corridors in a steeper dip environment. The steeper areas (1.73°) display unconfined linear pathways with dip-oriented drainage paths. This drainage texture occurs in a graded unconfined slope setting with little or no salt substrate and complex topography.

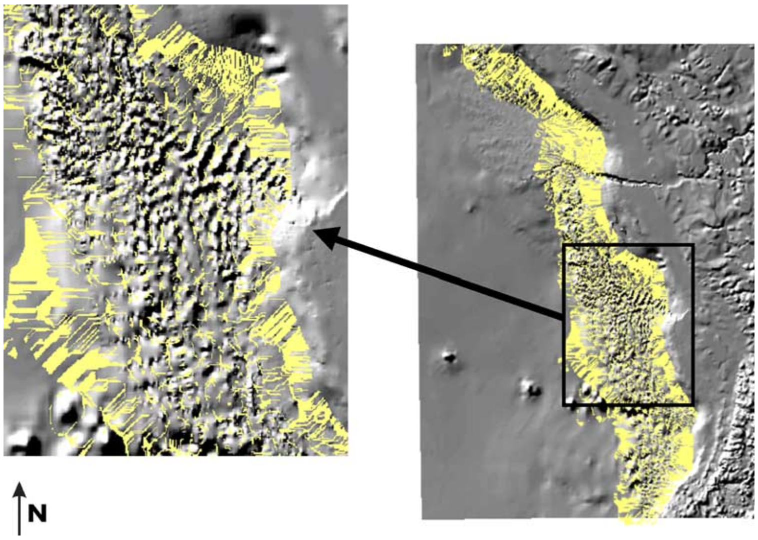

Fig. 10. Drainage patterns and flow analysis of Offshore Angola and surrounding areas. Bathymetry, slope, azimuth, curvature, and divergence are used in the analysis. The Kwanza Basin drainage pathways are short, discontinuous, and localized around salt withdrawal minibasins, while the Lower Congo Basin pathways are more dip-oriented, linear and continuous. These pattern differences between the Lower Congo and Kwanza Basins are probably attributable to differences in sediment loading and degree of salt grounding.

3.4. Northwest Borneo

Offshore Northwest Borneo is a tectonically active margin setting, underlain by the Crocker accretionary prism and mobilized, over-pressured shale (Fig. 4D). Linear strike-oriented emergent folds dominate the bathymetry of the entire slope (Fig. 11A). In contrast to the previously discussed passive margins, the slope of

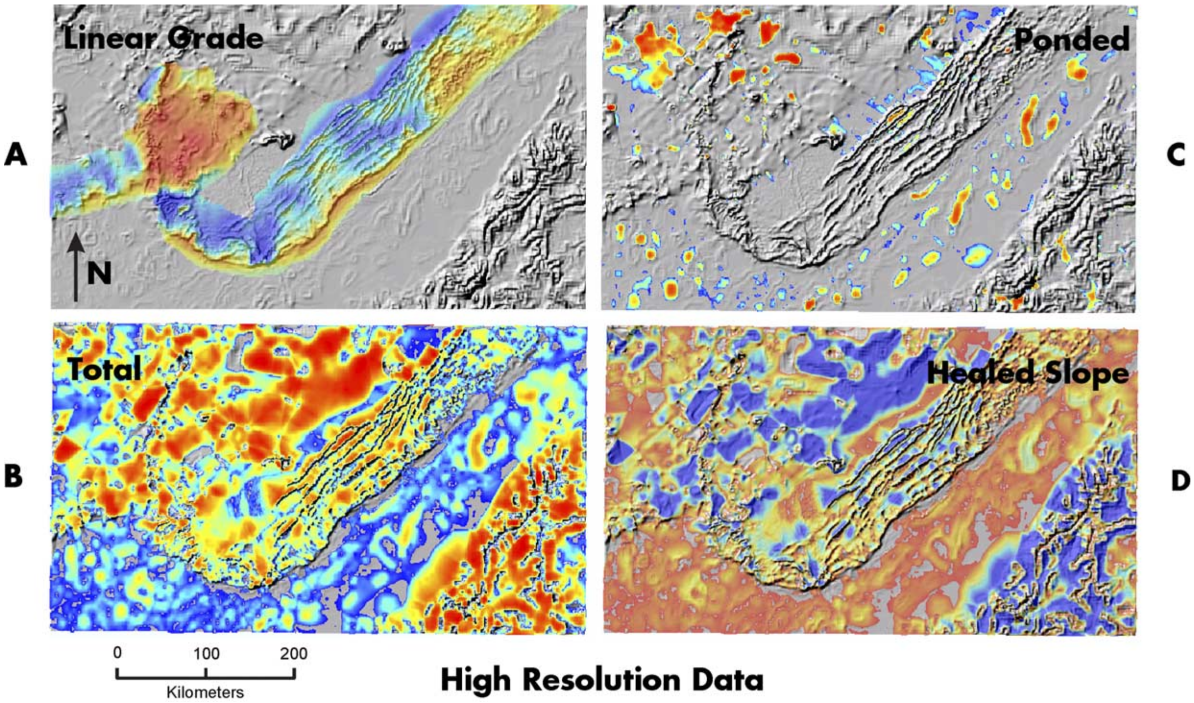

Fig. 11. Various types of accommodation in offshore Northwest Borneo are illustrated, using 2D seismic grid data on the slope and shelf. Color scheme similar to Fig. 5. Linear grade analysis shows that much of the slope is a negative residual at or below the regional linear grade. The positive residual in the northeastern area is underlain by a Crocker-related nappe while the large positive residual in the western portion of the margin is underlain by the Luconia carbonate platform. Ponded accommodation is generally areally small, strike-elongate and largely restricted to the lower slope between strike-oriented active toe-thrust ridges. Ponded accommodation on the shelf is between partially buried active folds. Ponded accommodation is rare to non-existent on the middle and upper slope while healed slope accommodation is pervasive throughout the slope. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

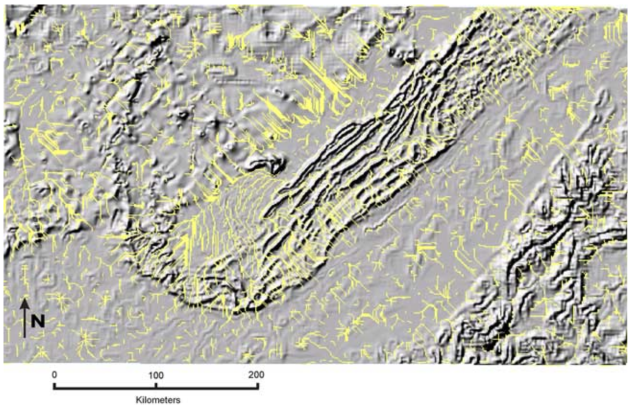

Fig. 12. Northwest Borneo drainage analysis displays complex patterns throughout the margin. Drainage path analysis in the center and northern areas of the slope show dip-oriented drainage corridors that are repeatedly deflected between strike-oriented folds as they make their way down slope. The drainage pathways are primarily dip oriented and extend unimpeded to the abyssal plain in the southern area of the slope where the folds are lower relief and the topography is partially healed. The shelf displays short, disconnected drainage pathways that are captured by the ponded accommodation.

NW Borneo has a substantially steeper average regional gradient of 1.67° and is generally narrower (50–150 km). Linear grade analysis of NW Borneo shows that the morphology of the slope varies in a complex manner along strike (Fig. 11A). Much of it is a negative residual at or below the regional linear grade. The area above regional grade (positive residual) in the northeastern area is underlain by a Crocker-related nappe. The large positive residual in the western portion of the margin is related to the drowned Luconia Miocene carbonate platform. Offshore NW Borneo's ponded accommodation is generally areally small, strike-elongate and largely restricted to the lower slope between strike-oriented active toe-thrust ridges (Fig. 11C). Ponded accommodation is also found on the shelf between partially buried active folds. Some of these ponded areas are locally thick. Ponded accommodation is rare to non-existent on the middle and upper slope while healed slope accommodation is pervasive throughout the slope (Fig. 11D).

The overall slope morphology can be classified as a stepped profile (in sensu stricto Prather, 2000, 2003). Drainage path analysis in the center and northern areas of the slope show the effects of this stepped profile, where dip-oriented drainage corridors are repeatedly deflected between strike-oriented folds as they make their way down slope (Fig. 12). In the southern area of the slope, where the folds are lower relief and the topography is partially healed, the drainage pathways are primarily dip oriented and extend unimpeded to the abyssal plain. The shelf displays short, disconnected drainage pathways that are captured by the ponded accommodation associated with partially buried folds.

Table 2

Basin	%Ponded[a]	%Healed slope[a]	Average regional dip	Std dev
Central NW GOM	55	45	0.76	0.06
Total NW GOM	11	89	0.79	0.07
Kwanza Basin, Angola	39	61	0.79	0.04
Lower Congo Basin	7	93	1.20	0.12
Steep Areas, Angola			1.73	0.15
Total Angola	5	95	1.03	0.35
Total Nigeria	2	98	1.18	0.29
Total NW Borneo	1	99	1.67	1.06

[a] Percent accommodation (calculated by volume).

4. Comparisons

Comparisons of all four margins reveal important differences between salt-based and shale-based systems (Table 2). Additionally, there are differences between the two shale-based systems that may be attributable to passive vs. active margin settings. These differences are summarized in the following discussion.

4.1. Regional dips

The regional dips associated with the salt-based systems in the Gulf of Mexico and offshore Angola are relatively gentle while the slopes underlain by mobilized shale in Nigeria and NW Borneo are steeper. The steeper dips along NW Borneo are probably the result of it being associated with an active margin tectonic setting.

4.2. Linear grade trends

The upper and middle portions of the salt-based Gulf of Mexico and Angolan slopes are at or below regional grade, bounded by an outboard high in the lower slope region. Most of the shale-based Nigerian slope, however, is above regional linear grade. The Northwest Borneo slope varies along strike with much of its area below regional grade. Again this difference is probably due to its active margin setting.

4.3. Ponded accommodation trends

Ponded accommodation is significantly more prevalent in the salt-based systems compared to the shale-based systems. Additionally, ponded accommodation is significantly thicker in salt-based systems than in the shale-based systems (on average, almost twice as much). Differences do exist, however, between the two salt-based systems of Angola and the Gulf of Mexico. Ponded accommodation in the Gulf of Mexico slope occurs throughout the entire slope but is best developed in the upper and middle regions in association with the large area below regional grade. This is the result of increased subsidence over thick autochthonous and allochthonous salt. Ponded accommodation in Angola, however, is largely restricted in the middle slope of the southern area (Kwanza Basin) probably related to the presence of thick underlying salt (Jackson, 2002). Conversely, the upper slope of the Kwanza Basin has little to no ponded accommodation because of thin autochthonous salt over a paleo-basement high (Jackson, 2002). The prominent lack of ponding in the Lower Congo Basin is probably the result of the salt being grounded and the bathymetry being healed during Late Miocene loading. Ponded accommodation in both salt-based systems tends to be more circular in plan view than in the shale-based systems of Nigeria and NW Borneo. The ponded accommodation in the Gulf also shows a basinward progression from large to small areas, while Angola shows no discernable trend. Ponded accommodation on the slope is areally small and strike-elongate in both shale-base systems and is restricted to the lower slope where it resides between toe-of-slope folds. The origin of this shale-based ponded accommodation is most likely very different than the origin of salt-based ponded accommodation, whereby it results from the upward growth of the toe-thrusts emerging on the lower slopes of Nigeria and NW Borneo.

4.4. Healed slope accommodation trends

Healed slope trends are pervasive in both the salt- and shale-based systems studied. In all four cases, these regional trends mimic the total accommodation distribution trends fairly closely and differ only in absolute thickness. This is because on a regional scale, ponded accommodation is rather limited on these slopes (with the exception of Central Northwest Gulf of Mexico and the Kwanza Basin of offshore Angola). Nigeria's healed slope accommodation is areally more widespread than the salt-based Gulf of Mexico and Angola slopes, but overall, generally thinner. NW Borneo's healed slope accommodation distribution is very complex with no discernable trend and fairly thick in many portions of the slope.

4.5. Drainage pattern trends

Drainage patterns are different as well for the four basins. Long dip-oriented drainage paths dominate the upper and middle slope of Nigeria and NW Borneo. Disconnected, short, intra-slope basin-scale drainage paths dominate large portions of the complexly partitioned slope of Northwest

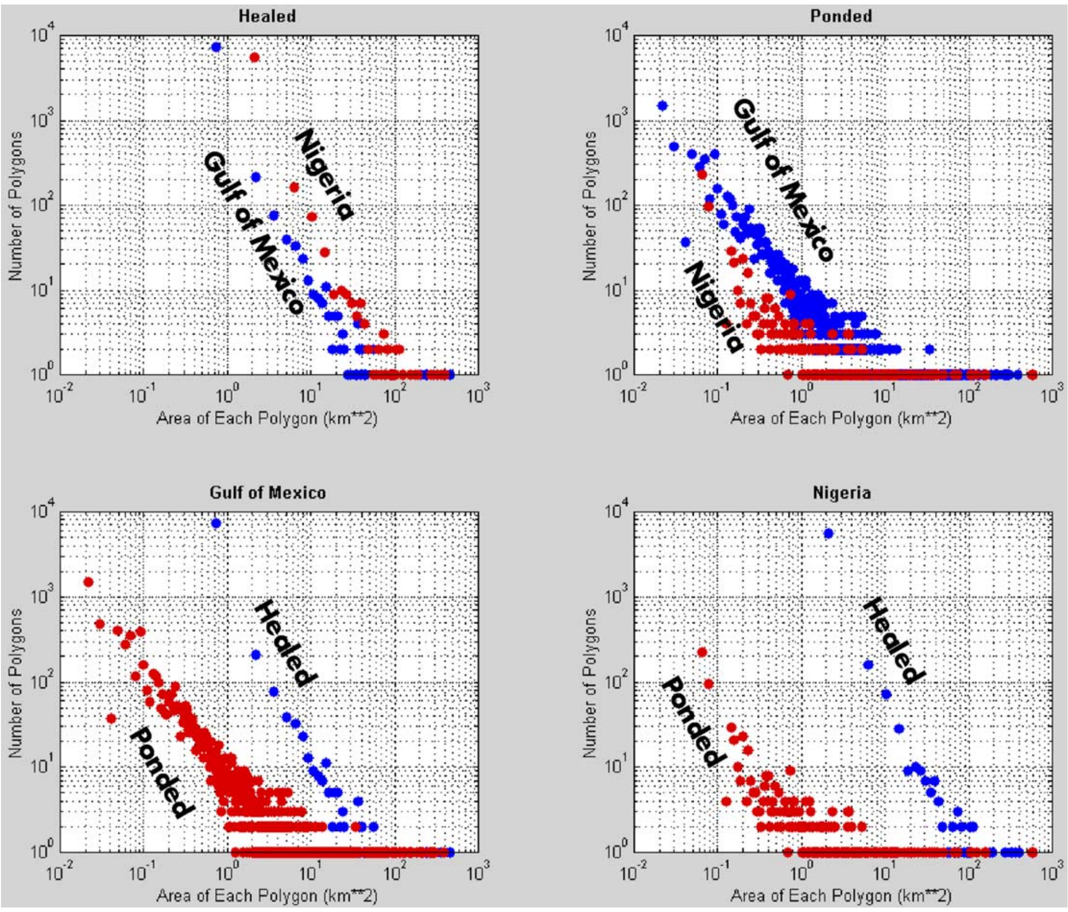

Fig. 13. Statistical comparisons of healed slope and ponded accommodation in Northwest Gulf of Mexico and Nigeria reveal several differences between salt- and shale-based systems. (A) Nigeria healed slope area (polygon areas) are greater than in the Gulf of Mexico. (B) Conversely, ponded polygon areas are greater in the Gulf of Mexico than in Nigeria. (C) Healed slope accommodation areas are an order of magnitude greater than the ponded areas in the Gulf of Mexico. (D) Healed slope accommodation areas in Nigeria are two orders of magnitude greater than the ponded areas.

Gulf of Mexico and the Kwanza Basin of Angola. Additionally, strike-oriented drainage paths controlled by the active toe-thrust ridges are common in the lowermost slope of both Nigeria and NW Borneo.

Preliminary statistical analysis conducted on the shale-based Nigerian margin and the salt-based Gulf of Mexico margin reveals some other interesting comparisons (Fig. 13). Nigeria's healed slope polygons (i.e. intra-slope basins) have a larger area distribution than in the Gulf of Mexico. Conversely, ponded polygons have a larger area distribution in the Gulf of Mexico. The distribution of healed slope areas in the Gulf of Mexico is an order of magnitude greater than the related ponded areas, while Nigeria's distribution of healed slope areas is two orders of magnitude larger than the ponded areas (Fig. 13).

Many of these differences between the four basins are largely due to the physical property variations of mobile shale and salt substrates (viscosity, ductility, rate and duration of deformation, ability to maintain and preserve seafloor bathymetry, etc.). Differences may also be due to the overall tectonic setting, exemplified by the comparison between the active NW Borneo margin and the other three passive margin settings. Sediment load distribution, rate, and volume most certainly play an important role as well.

5. Implications for exploration and development

This study reveals that significant differences exist in deepwater receiving basin configurations between salt-based and shale-based margins as well as between passive and active margin settings. Future studies linking these basin characteristics to near-seafloor fan features residing in these deepwater settings could improve our understanding of the relationships between receiving basin configurations and sediment delivery systems. This approach would also provide additional insights into the potential reservoir distribution and architecture in various fan morphologies. In particular, understanding receiving basin configuration in salt- and shale-based slope settings may lead to predictive models for deepwater reservoir distribution in Greenfield areas. Once calibrated with exploration and/or near-seafloor wells, finer-scale relationships may be discovered between basin configuration and reservoir stacking patterns and architecture.

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