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Research paper

Seafloor morphology and potential gas hydrate distribution in the offshore Niger Delta

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Abstract

Bottom simulating reflectors (BSRs) and seismic pipe features have been used as proxies for defining the distribution of gas hydrate sediments in the offshore Niger Delta. This is the most extensive mapping of gas hydrate sediments in the Delta as of today. The seismic data merge comes from multiple surveys acquired with different parameters and seismic resolutions over the course of decades of oil and gas exploration in the region. Indicated gas hydrate distribution generally follows the structural fabric of the Niger Delta with BSRs occurring along the apexes of the thrust-related ridges that have bathymetric relief on the seafloor. The presence of swarms of seismic pipe features landwards of BSR locations suggests hydrates occur beyond BSR locations. The potential gas hydrates sediment acreage in offshore Niger Delta is 17600 sq-km, representing 20% of the area with a thickness of the gas hydrate stability zone reaching 440 m in the more outboard regions of the Delta. Total gas hydrates sediment coverage likely exceeds this value as BSRs become indistinguishable from sediment strata in regions of flat dips. The presence of double BSRs further suggests the presence of thermogenic gas hydrates in the region and allows to extend the thickness of the potential hydrate zone to 550 m in the outboard regions of the Delta.

Keywords: *Seismic Pipes; Gas Hydrates; Bottom-simulating Reflectors; Continental Slope; Offshore Niger Delta.*

1. Introduction

Natural Gas hydrates are crystalline solids composed of gas molecules (frequently methane) trapped in cage-like water structures. They form under specific conditions involving high pressure, low temperature and high salinity (Sloan and Koh, 2008). They contain huge amounts of energy with one volume of gas hydrates typically yielding 164 volumes of methane gas. They are of interest to several research communities including those studying climate change (Svensen et al., 2004), cleaner energy resources (Collett, 2002), oil and gas exploration (Sami et al., 2013), marine habitats (Katayama et al., 2016: Liu et al., 2022) and seafloor hazards (Rothwell et al., 1998: Sin et al, 2017) among others. Gas hydrates represent a concentrated source of energy, yielding 40-50 SCF/ft^3 of rock compared to 8-10 SCF/ft^3 and 5-10 SCF/ft^3 for coalbed methane and tight gas, respectively (Osadetz et al, 2006). The best-constrained estimates of methane stored in gas hydrate reserves indicate a global resource potential capable of providing for the US energy need for 120,000 years (Klauda and Sandler, 2005; Sloan and Koh, 2008), thus constituting the largest reverse of methane gas in the world (Sloan, 2003: Sloan and

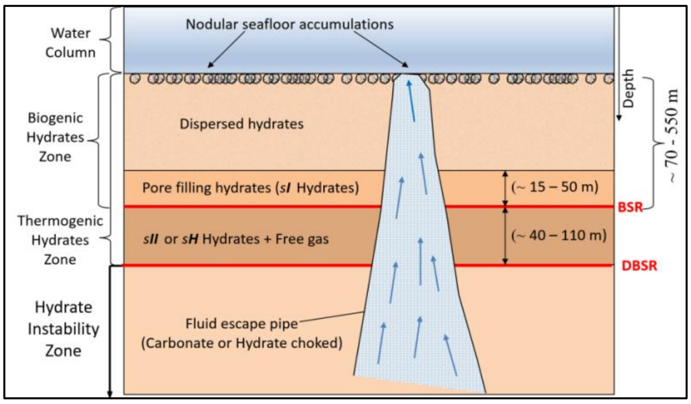

Fig. 1: Gas hydrate occurrence in marine environments. *sI*, *sII*, and *sH* are Structure I, II and H Hydrates systems, respectively. DBSR refers to Double BSR.

Koh, 2008: Boswell and Collett, 2011). In marine environments, gas hydrates may occur as nodules on the seafloor and as dispersed hydrates in shallow sediments. They also occur as pore-fillings in a 15-50 m thick column above the base of what is commonly known as the gas hydrate stability zone (GHSZ - actually represents the stability zone for gas hydrates of biogenic origin), and in conjunction with free gas within the Thermogenic hydrates zone, a column often thicker than 50 m beneath the GHSZ (Fig. 1). Gas hydrates have been retrieved from the seafloor and beneath permafrost grounds from several regions of the globe (Brooks et al., 2000; Osadetz et al, 2006; Collett et al., 2009; Ruffine et al, 2013; Paganoni et al, 2016; Matsumoto et al, 2017). Their presence in marine settings is more often inferred using bottom-simulating reflections (BSRs) and seismic pipe structures in oil and gas exploration seismic data (Zillmer et al, 2005; Popescu et al, 2006; Plaza-Faverola et al, 2012; Paganoni et al., 2018; Aminu and Ojo, 2021). The former, BSRs, are more common. In the Niger Delta, Gas hydrates have been recovered from the seafloor via penetration cores, and have been inferred from infrared thermal core scanning and high-resolution seismic datasets when BSRs are used as proxies (Brooks et al., 2000; Cunningham and Lindholm, 2000; Sultan et al., 2010; Wei et al., 2012; Sultan et al., 2014).

BSRs are typically identified as sub-parallel (compared to the seafloor reflection) that appear in shallow sections below the seafloor (usually less than 500 ms sub-bottom) and exhibit a distinct polarity reversal compared to the seafloor reflections (Shipley et al., 1979; Chi et al., 1998; Bangs et al., 2005; Plaza-Faverolla et al., 2012; Aminu and Ojo, 2021). They are considered to mark the boundary between the gas hydrate stability zone (GHSZ) above and the free gas zone below, where gas hydrates become unstable and dissociate (Sloan and Koh, 2008). The polarity reversal arises due to the acoustic impedance drop in going from gas hydrate-bearing sediments above to free gas sediments in the underlying region (Bangs et al., 2005; Miller et al., 1991; Chi et al., 1998; Zillmer et al., 2005). BSRs generally cut across sediment stratification/bedding (Kvenvolden, 1993; Chi et al., 1998; Zillmer et al., 2005) and are commonly associated with the faulted crests of anticlines, sea mounds, mud volcanoes, fluid pipes and gas chimneys (Chi et al., 1998; Petersen et al., 2010; Paganoni et al., 2018). They therefore are indicative of fluid migration within the subsurface with the base of the GHSZ acting as a barrier to further upward migration of both biogenic and thermogenic fluid in the subsurface (Bangs et al., 2005). This way they encourage the accumulation of free gas in sediments beneath the GHSZ. BSRs may therefore highlight the pathways for fluid migration and provide insights into the complex geological processes that control hydrocarbon movements in the subsurface (Plaza-Faverolla et al., 2012; Paganoni et al., 2018).

In this study, we utilize seismic evidence, specifically, bottom-simulating reflectors and seismic pipe structures to infer the gas hydrates distribution in the offshore regions of the Niger Delta. This represents the most comprehensive and detailed mapping of gas hydrate sediments in the Niger Delta as of now.

2. Study area

The Niger Delta lies between latitudes 3˚N and 6˚N and longitudes 3˚E and 9˚E in southern Nigeria (Fig. 2). It stretches across the southern coast of Nigeria and extends into parts of Cameroon. It is bounded to the west and north by both the Benin Flank and the Abakaliki High, respectively, and to the east by the Calabar Flank. The Dahomey Basin and the Cameroon Volcanic Line define its offshore limits to the west and east, respectively. Its seaward limit is commonly regarded as either the sediment thickness contour of 2000 m or the 4000 m water depth (Weber and Daukoru, 1975; Tuttle et al., 1999). The Delta developed at the site of the triple junction which formed during the opening of the South Atlantic Sea occasioned by the separation of the African and South American continents (Burke, 1972; Whiteman, 1982). Rifting initiated in the Late Jurassic and continued till the end of the Cretaceous (Lehner and De Ruiter, 1977; Tuttle et al., 1999). Five structural provinces are recognized in the Delta (Corredor et al., 2005) and include (Fig. 3) (1) an extensional province characterized by regional and sub-regional growth faulting and downward-cum-seaward movement of the basal shale sequence, (2) a shale diapir province where mobile and buoyant shales take advantage of fault planes to reach shallow sediments, (3) the inner fold and thrust belt whose seafloor expression is a convex-to-sea lobe, (4) a detachment fold province and (5) the outer fold and thrust belt consisting of two convex-to-sea lobes. The initial sedimentation was constrained by the bathymetry of the oceanic crust below (Corredor et al., 2005; Aminu and Ojo, 2018) while subsequent thin-skinned deformation has largely been the result of gravity-driven shale tectonics (Wu and Bally, 2000; Bilotti and Shaw, 2005; Corredor et al., 2005). Stress and strain resulting from the downward and seaward motion of mobile shales beneath the onshore and transitional provinces are transferred seaward along a basal decollement in the upper part of the Akata Formation and manifest in the formation of compressional toe-thrust structures in the more outboard regions of the Delta (Bilotti and Shaw, 2005; Corredor et al., 2005). Fluctuations in sea level and the rate of sediment supply from the hinterland

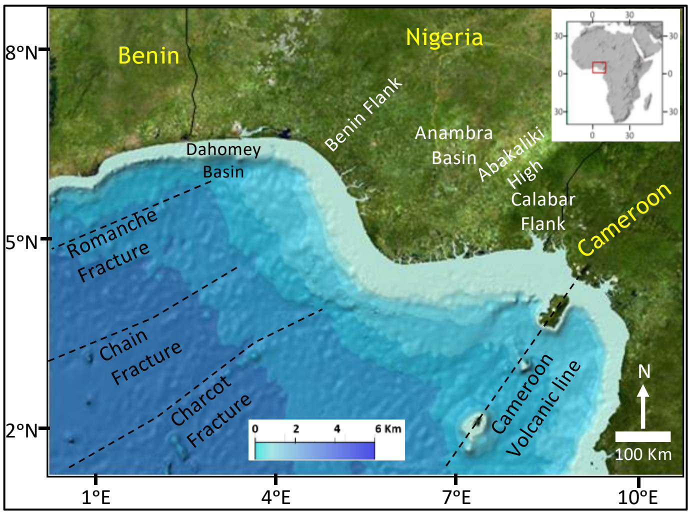

Fig. 2: Bathymetric image of the Niger Delta highlighting major structural elements and province outline (modified after Aminu and Ojo, 2021).

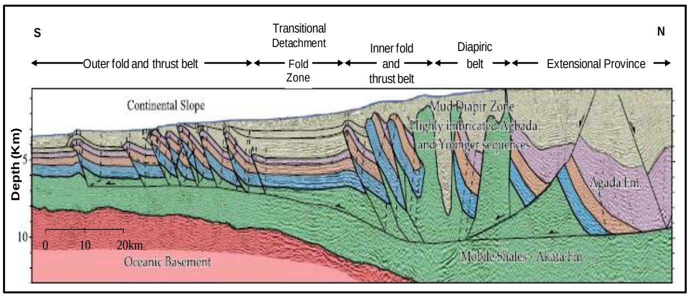

Fig. 3: Interpreted regional seismic profile across the Niger Delta typifying the relationship of its five tectonic provinces. Deformation results from gravity-driven sediment collapse on the continental shelf. The resulting strain is transferred seaward leading to diapiric shale movement near-field and toe-thrust structures in the more outboard regions. (adapted from corredor et al., 2005).

have exerted lesser but significant influences on the development of the Delta (Doust and Omatsola, 1990). The Offshore Niger Delta reaches water depths in excess of 4000 m subsea (Tuttle et al., 1999). Its bathymetric expressions include multiple convex-to-sea thrust-related deformation lobes that define the fold and thrust belts (Connors et al., 1998; Wu and Bally, 2000). The lobes are separated by an intervening plain with little deformation.

The stratigraphic succession of the the Niger consists of three rock units; the Akata Formation, the Agbada Formation and the Benin Formation (Frankl and Cordry, 1967; Short and Stauble, 1967; Avbovbo, 1978; Reijers, 2011). The Akata Formation lies at the base of the succession and is regarded as the principal source rock of the Delta (Fig. 4). It consists of foraminifera-rich marine shales and probably overlies syn-rift clastic fragments of the oceanic basement below (Corredor et al., 2005; Sahota, 2006). The Akata is conformably overlain by the Agbada Formation, a faulted sequence of alternating continentally derived sands and transgressive marine shales (Avbovbo, 1978). The Agbada Formation is the dominant reservoir rock of the Delta. Its shale intercalations are regarded as a potential source of hydrocarbons (Nwachukwu and Chukwura, 1986) and serve as a seal for most reservoir configurations. The Benin Formation overlies the Agbada and completes the stratigraphic succession of the Niger Delta. It consists of massive, porous and usually unconsolidated, fresh-water continental sands (Avbovbo, 1978; Reijers, 2011). The Benin Formation is absent in the most distal deepwater sections of the Delta, rather grading seaward into deepwater clastics of the Agbada Formation (Cobbold et al., 2009; Maloney et al., 2010).

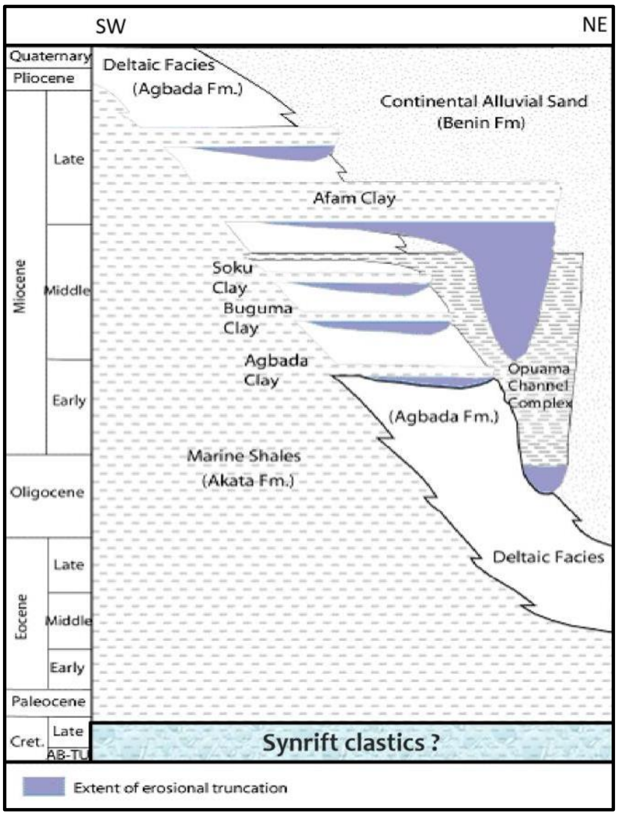

Fig. 4: Stratigraphic column showing the three conformable formations of the Niger Delta; Akata, Agbada and Benin. Syn-rift clastics, fragments of the oceanic crust, possibly underlie the sedimentary succession (Modified from Tuttle et al., 1999).

3. Data and methodology

The data used in this study was a 3D digital seismic data merge from independent oil and gas exploration seismic surveys covering most of the offshore Niger Delta. The data merge was actualized from individual seismic surveys acquired at different times and by different seismic data acquisition vendors over the span of more than 3 decades of exploration. The individual surveys had varying acquisition parameters but earlier surveys had been re-processed over time with updated and improved processing sequences and algorithms. Though there were significant variations in seismic resolution and noise suppression quality within the data merge, the data was generally of high quality except for a few anticlinal structures where the cores of the structures were poorly illuminated. Data was post-stack time migrated, zero-phase and was displayed with normal polarity (North American convention). Data coverage was approximately 79,000 sq km and had an average record length of 8400 ms. The seismic interpretation was carried out in Petrel. The water-bottom reflection was interpreted and gridded to produce a seafloor time map. The seismic-derived chaos attribute was computed to accentuate structural features on the mapped seafloor. BSRs were mapped throughout the data volume following a criteria of reverse reflection polarity closely mimicking the topology of the seafloor and increasing in sub-bottom depth with increasing water depth. Care was taken to identify water-bottom multiples which also mimic the seafloor reflection in shallow waters but possess the same reflection polarity as the seafloor. Further, seafloor terminations of seismic chimneys (pipes) were delineated. Potential free gas volume beneath the delineated BSRs was estimated following Helgerud et al., 1999, and Charbet et al., 2011. The authors propose two models, (1) a uniform distribution of 1 % free gas in the sediments within a 50 m thick column beneath the BSR and; (2) a patchy distribution of 6.5 % free gas in the same column. These saturation levels were estimated for a 50 m thick column beneath the BSRs in this study. As there was no independent porosity information for near-surface sediments in the area, we utilized a porosity range of 40-50 %. Similar porosity ranges have been reported from well logs at depths of 300 m below the seafloor at the Gumusut-Kakap oil field in the middle-upper continental slope of Sabah NW Borneo province (Paganoni et al., 2016). The Sabah province like the Deepwater Niger Delta contains siliciclastic turbidite reservoirs deposited in an environment dominated by anticlines induced by gravity-driven tectonics (Ingram et al., 2004; Hesse et al., 2009; Morley, 2009). Furthermore, BSR depth trends were evaluated for three BSRs earlier identified and discussed in Aminu and Ojo, 2021, using sub-bottom and subsea depth vs water depth plots. These were to highlight the effects of (1) seafloor canyons, (2) pockmarks, and (3) thrust ridges on the stability of gas hydrates. For depth conversion, a velocity of 1480 ms^{-1} (Maloney et al., 2010) and 1500 ms^{-1} (Adeogba et al., 2005: Ruffine et al., 2013) were utilized for the water column and near-surface sediments respectively.

4. Results

4.1. Seafloor morphology of the offshore Niger delta

Within the data merge, water depths reach up to 2960 m (Fig. 5). Overall bathymetric dip of the seafloor is in the southern and southwestern directions. Prominent features on the seafloor include seafloor channels and ridges. The seismic chaos images (Figs. 5b-d) further reveals fluid vents and seafloor fault scars. It is possible to divide the data-merge seafloor image into three regions: a northern region, a western region and an eastern region. The northern and western regions here are a part of what is commonly referred to as the Western Niger Delta (Deptuck et al., 2007) while the eastern region is part of the Eastern Niger Delta.

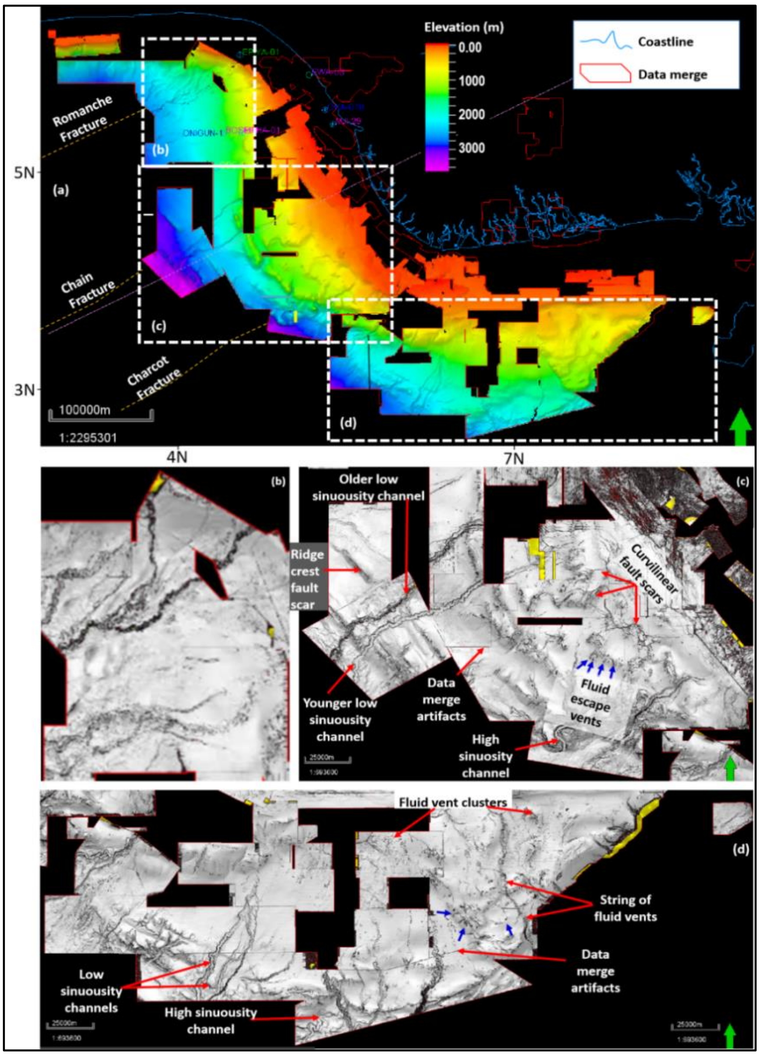

Fig. 5: Bathymetry of the seafloor offshore Niger Delta derived from the seismic data merge used for the study. (a) time map, (b)-(d) are enlarged seismic chaos images of the seafloor in the northern, western and eastern regions defined in this study. Gross bathymetric dip is in the south and southwest direction. The fold and thrust belts have considerable relief on the seafloor and frequently host swarms of fault scars centered on the location of fluid vents.

Ridges defining the surface expressions of the inner and outer fold and thrust belts of the Niger Delta (as described in Corredor et al., 2005) are visible on the seafloor (Fig. 5). Though their full extents are not revealed in the data merge, their arcuate and convex to the sea morphologies are apparent. The inner fold and thrust belt ridge is almost entirely restricted to the western region while the dual lobes of the outer fold and thrust belt ridge are distributed one each between the western and eastern regions of the area (Fig. 5). The break between the two is roughly coincident with the lateral projection of the Charcot fracture. The surface expressions of the two fold and thrust belts come into proximity in the region of this break.

Multiple channels straddle the seafloor and funnel sediments to more outboard regions of the Delta (Fig. 5). Channel trend largely follows the general bathymetric dip of the seafloor with seafloor reliefs associated with thrust ridges exerting further controls on trends. Channel trend varies progressively from roughly east-west in the northern region to north-south in the eastern region (approximate bearing: 066°, 054°, 047°, 027°, 0°). Most channels are linear to slightly sinuous in morphology with the exception of a major channel in the western region. This channel appears to meander strongly around the saddles of thrust-related ridges of the inner and outer fold belts where the convex-to-sea lobes of the seafloor expressions of the two fold belts are in close proximity. In the eastern region, minor channels in the more distal parts of the region show strong sinuosity (Fig. 5c). A few channels run parallel to the folds of thrust ridges. Some channels present with deeper and more chaotic thalwegs with multiple cut and fill sections in the side walls of the channels. Others show much shallower and smoother less-eroded thawlegs. Two major channels, one each in the northern and western regions, appear to be roughly coincident with the lateral projections of the Romanche and Chain fractures (Fig. 5). These channels run in excess of 75 km. The strong sinuosity channel in the western region also appears coincident with the projection of the Charcot fracture.

Multiple fault scars are observed in the seismic chaos image of the Niger Delta seafloor (Fig. 5b). Most fault scars are linear and are associated with seafloor ridges and mounds. Fault scars generally occur on the axial peaks of seafloor ridges and run along or parallel to fold hinges. In several cases, fault scars are curvilinear in morphology, especially when they occur on dome-shaped seafloor reliefs in the western region. In these cases, they may occur in radial patterns centered on the locations of fluid expulsion features (pockmarks). Fault scars and fluid escape features are almost totally absent from the northern region of the study area. They are however common all through the western and eastern regions where bathymetric relief is more variable due to the seafloor manifestations of the inner and outer fold and thrust belts of the Niger Delta. In the eastern region, strings of pockmarks may form along fault scars for more than 70 km in a north-south direction (Fig. 5c).

4.2. Bottom-simulating reflections

A total of 125 BSRs were delineated from the study area (Fig. 6). The BSRs present as reverse polarity reflections (compared to the seafloor reflection) that mimics the topology of the seafloor reflection (Fig. 7). Water depths for which BSRs were identified range from 740 m on the continental slopes to 2960 m sub-sea in the distal outer fold and thrust belt. BSR depths below the seafloor range from 82.5 m on the continental slopes to 440 m in the most distal regions of the outer fold and thrust belt.

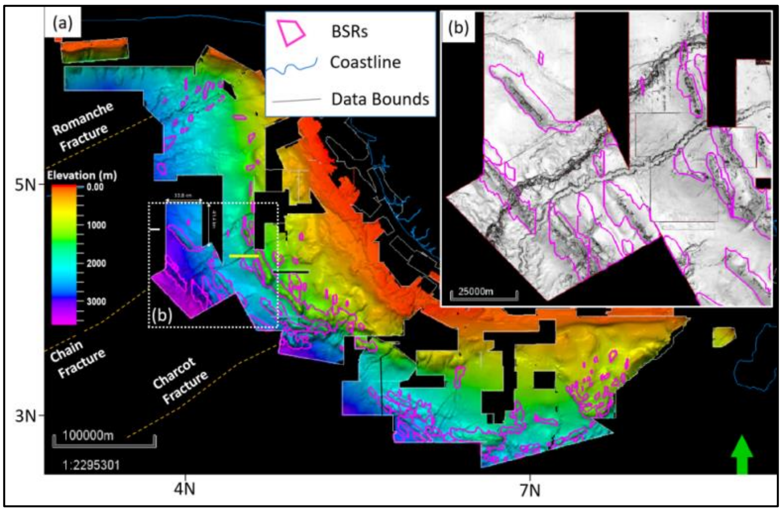

Fig. 6: BSR distribution overlain on (A) Seafloor image, (B) Chaos image of part of the western region (insert). BSRs follow the convex-to-sea lobate trends of the fold belts. They run across more chaotic channels and terminate laterally along the walls of the smoother channel.

Cumulative areal extent of BSRs in the study area is ~ 15,800 sq-km representing approximately 20 % of the seismic acreage. BSRs in the area occur at progressively deeper sub-bottom depths with increasing water depths. This corresponds to thicker GHSZs with increasing water depths/overburden pressure. Exceptions to this trend occur in the crest of thrust-related folds that have bathymetric reliefs on the seafloor. In such scenarios, BSRs may occur at greater sub-bottom depths beneath the crests of folds although such locations represent shallower water depths. At such locations, BSRs often cut across sediment stratification. BSRs in the study area are generally associated with two features: 1) the apexes of thrust-related anticlines which have bathymetric reliefs on the seafloor (Figs. 7 & 8). The thrust anticlines have been active in the recent as to have displaced recent sediments. The thrust-related fold apexes are frequently faulted, often with en-echelon normal fault sets. In some cases, the normal faults may penetrate deep into the core of thrust anticlines. In a specific case, a BSR appears vertically displaced by normal faulting (Fig. 8); and 2) Dome-shaped mounds related to diapiric shale movements and mud volcanoes mostly in the eastern region of the study area (Fig. 8). In several places, sediments above BSRs show markedly dimmed amplitudes (dim amplitude reflections [DAR]) compared to sediments below (Figs. 7 & 8). Away from thrust-related folds and dome structures, the BSRs become essentially flat and generally sole to and become indistinguishable from flat-lying strata. In the western region of the study area, BSRs commonly terminate at the fringes of channels which appear to have smoother or less chaotic thawlegs in the chaos image (Fig. 6). For channels having more chaotic thawlegs, BSRs generally appear to straddle across the channels.

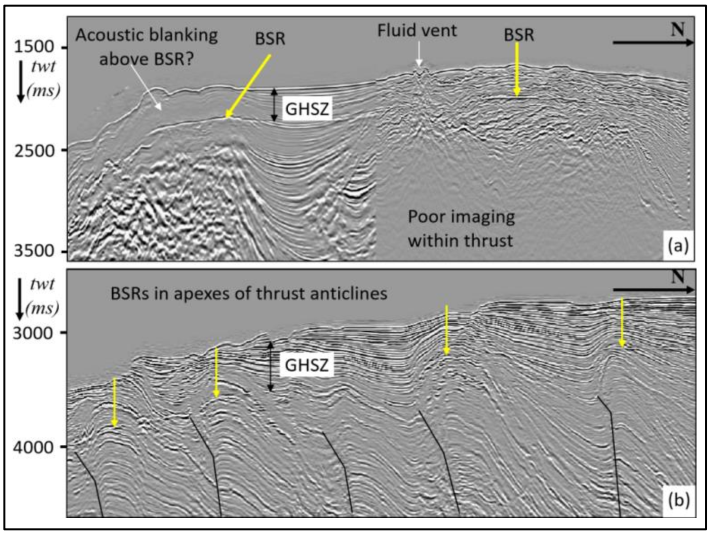

Fig. 7: Typical seismic sections through thrust-related folds in the Niger Delta. (a) BSRs through broad anticlines, one with blanking of the section above the BSR and the second without blanking; (b) BSRs through a series of thrust folds. BSRs have reversed polarity relative to the seafloor reflection and are associated with thrust folds that show bathymetric reliefs on the seafloor:

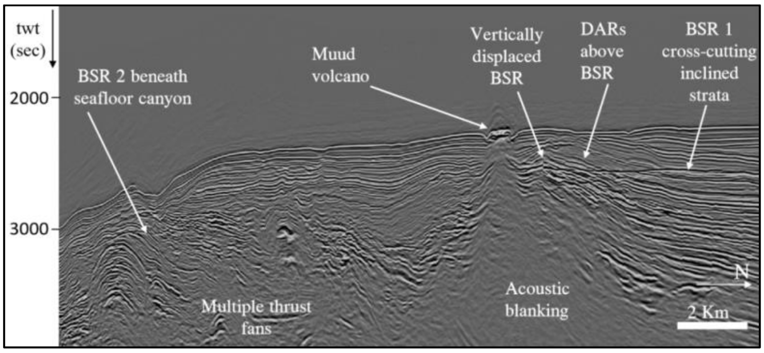

Fig. 8: Seismic section across an anticlinorium hosting BSRs beneath a seafloor canyon and astride an active mud volcano. Dim amplitude reflections (DAR) occur in sediments above a BSRs cutting across inclined strata.

Four cases of double BSRs were identified, two (2) each in the western and eastern regions of the study area (Fig. 9). These are cases where BSRs are stacked vertically one above the other. The two-way time separation between individual BSRs of the double-BSRs ranges on the order of 100-200 ms. The shallow BSR of each pair usually exhibits stronger reflection amplitudes and has greater reflection continuity compared to the deeper BSR. In one instance (Fig. 9b), the lower BSR appears tilted in the hinterland direction relative to the shallow BSR.

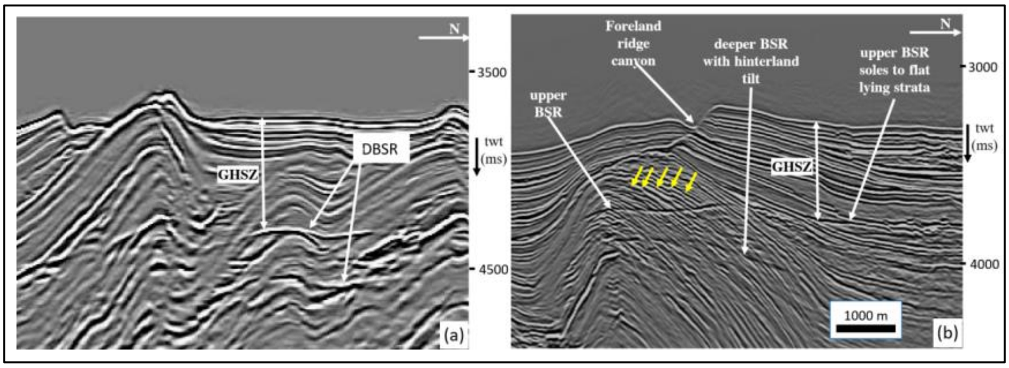

Fig. 9: Two cases of double BSRs from the Niger Delta. (a) flay lying double BSR, (b) lower BSR tilted relative to upper BSR in the landward direction. The lower BSRs have weaker reflection amplitudes and are less continuous.

Numerous pipe structures occur in the study area. These are vertical to sub-vertical elongated inverted conical structures seen on seismic data which lead to pockmarks on the seafloor (Cartwright and Santamarina, 2015; Paganoni et al., 2018). Sometimes referred to as seismic chimneys (Løseth et al., 2009; Bertoni et al., 2017), they act as fluid-escape pathways and may contain elevated levels of gas hydrates or authigenic carbonates. Multiple seismic pipe structures were identified in the study area (Fig. 10). In the western region, the seafloor terminations of pipe structures generally occur landward of delineated BSRs though there is considerable overlap. In the eastern region, the surface terminations of pipe structures are more coincident with the locations of BSRs. Often the surface expressions of these pipes appear to form a terminus from which curvilinear seafloor fault scars diverge in radial patterns (Fig. 5c). In the subsurface, seismic pipe structures in the study area have a chaotic seismic character that disrupts otherwise continuous stratigraphy. Internally, they show strata pull-ups and could be of the order of tens to hundreds of meters in length (Fig. 10).

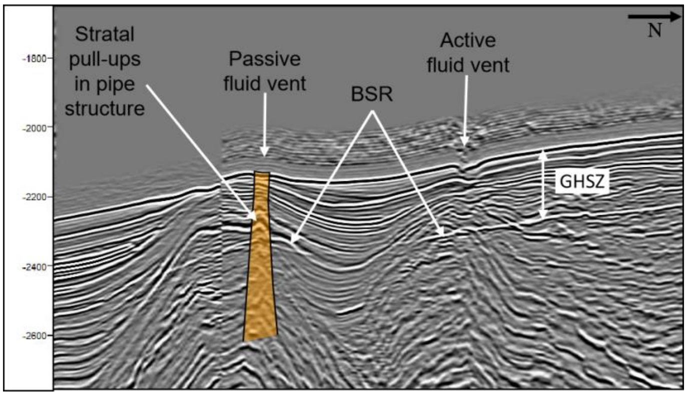

Fig. 10: Seismic section with pipe structure. Reflection pull-ups within pipe structures indicate the presence of higher velocity facies in pipe regions.

5. Discussion

5.1. Gas hydrate distribution

The thickness of the GHSZ in the Niger Delta ranges from 82.5 m on the continental slopes to 440 m in the most outboard regions of the present study. It extends from as shallow as 740 m sub-sea on the continental slopes to as much as 2960 m sub-sea in the distal outer fold and thrust belt. This represents the zone where Structure I (*sI*)nGas hydrates can be expected to be stable and occur. The stability zones for Structure II and Structure H hydrates which involve higher molecular weight hydrocarbons and which are stable at higher temperature-pressure-depth regimes can be expected to be much thicker (Paganoni et al., 2016; Liang et al., 2017). This may extend to the depths of the lower BSRs in cases of double BSRs and be up to 550 m thick considering the one-way time difference between the upper and lower BSRs where double BSRs occur (50-100 ms). For most of the western and eastern regions, seismic evidence indicates that the distribution of gas hydrates in the Niger Delta is strongly influenced by the structural fabric of the Delta. Bottom-simulating reflectors generally follow the bathymetric morphology of the single and dual lobes of the inner and outer thrust and fold belts, respectively, carving out an area with a convex-to-the-sea outboard limit (Fig. 11). In the northern region where the surface expressions of the thrust folds are absent, BSRs cluster along channel fringes and tracts. A few such examples also occur in the eastern region.

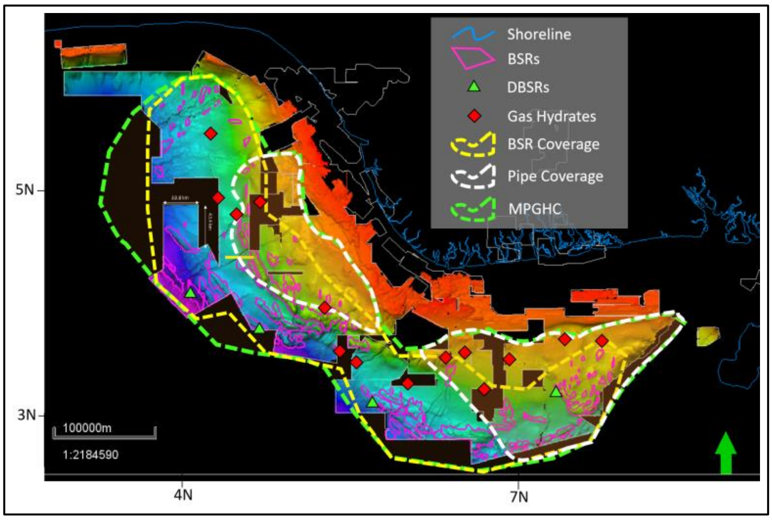

Fig. 11: Interpreted potential for gas hydrate sediment occurrence in the offshore Niger Delta. Core retrieved gas hydrates (red diamond polygons) are replotted from Table 3 in Brooks et al., 2000. MPGHC = Most Probable Gas Hydrates Coverage.

Given the 20 % BSR coverage of the study area, the cumulative areal extent of gas hydrate distribution in the Niger Delta is of the order of 17600 sq-km at a minimum. Occurrence of gas hydrates is likely varied in nature and concentration in the Delta: (1) a part likely occurs within seismic pipes and these may host the highest concentration of hydrates in the region and may involve thermogenic hydrates (Ruffine et al., 2013; Paganoni et al., 2018); (2) a second part occurs as nodules or as massive hydrates on the seafloor and shallow sediments (<50 m below seafloor). These have been retrieved in Piston Cores from the Niger Delta (Brooks et al., 2000; Ruffine et al., 2013); (3) a third part apparently occurs as dispersed occurrences within the GHSZ with elevated concentrations in the lower 15-50 m of the GHSZ. At the base of the GHSZ, this creates a permeability barrier that temporarily halts the migration of free gas to the surface and accumulates gas beneath to generate BSRs detectable in seismic data (Aminu and Ojo, 2021) and; (4) Structure II and Structure H gas hydrates in the intervening depths between the lower and upper BSRs where double BSRs occur. This is possible if the interval between the upper and lower BSRs represents a zone where higher alkane hydrates are stable in the area (Paganoni et al., 2016).

The lateral distribution of gas hydrates most certainly exceeds the limits indicated by BSRs. Further contributions to the gas hydrate acreage in the region likely involve three other sources: (1) the intervening regions between BSR locations where BSRs sole to flat-lying strata. At such locations, the BSRs are indistinguishable from sediment strata and cannot be delineated. These regions, however, lie within the GHSZ and could contain significant amounts of gas hydrates. Many locations from which gas hydrates have been retrieved in piston cores in the Niger Delta fall in regions where no BSRs occur (Fig. 11); (2) the western fringe of the outer fold and thrust belt is not included in our data merge. If we consider that BSRs (and possibly hydrate occurrence) predominantly follow the locations of thrust folds with seafloor relief, this region could hold significant amounts of gas hydrates and; (3) the regions of seismic pipe occurrence which occur landward of BSRs (Paganoni et al., 2018). The presence of pipe structures in these regions implies significant potential hydrate occurrence in this region. The hydrate presence innsuch regions may however be concentrated within pipe structures. The association of BSRs in the study with the apexes of thrust-related anticlines that have bathymetric reliefs on the seafloor likely indicates that focused fluid migration plays an important role in the formation of gas hydrates. Rising biogenic and thermogenic fluids may take advantage of the structural dips in folded strata and normal faults penetrating deep into the cores of thrust anticlines to migrate to shallower levels. These fluids then enter into the GHSZ where they may be incorporated into gas hydrates (Ruffine et al., 2013).

5.2. Gas hydrates and seafloor channels

The smoother appearance of the thalweg of the more easterly channel compared to the westerly channel in the western region indicates less reworking of sediments in the channel thalweg due to the younger age of the channel. Sediments have recently been eroded from the channel path and the thawleg has experienced minimal reworking. Comparatively, the westerly channel thalweg is more chaotic and shows signs of extensive reworking of the thalweg with multiple episodes of cuts and fills, and indications of migration of its gentle meanders. The lateral terminations of BSRs at the fringes of the younger channel are likely due to this young age: apparently, hydrate-rich sediments within the GHSZ have only recently been eroded along the channel course. The incursion of cooler seawater into the thawleg has altered the P-T conditions such as to make gas hydrates unstable at such channel positions. In such a scenario, the base of the GHSZ is forced to migrate to deeper levels beneath the channel bottom where fresh gas hydrates can form (Bangs et al., 2005). While this downward recalibration of the base of GHSZ is ongoing, gas hydrates will remain unstable and not form. Consequently, no BSR will exist at the channel location. This process occurs over a considerable period (order of 5000-7000 years - Bangs et al., 2005) of time and is likely ongoing at the moment beneath the channel. In contrast, channel incision on the westerly channel is much older and the base of the GHSZ apparently has had sufficient time to migrate to deeper strata beyond the channel thawleg to enable gas hydrates to form and generate a BSR. Thus BSRs can be observed straddling across the channel location, just below the channel thawleg.

5.3. Thermogenic hydrates

Brooks et al, 2000, advocate a decoupling of thermogenic gas supply from gas hydrate formation in the Niger Delta. However, Ruffine et al., 2013, provide evidence of thermogenically sourced methane in hydrates retrieved via piston cores from an active fluid vent in the Delta. Thermogenic gas hydrates are often localized by linear structures such as faults (Sloan and Koh, 2008) through which rising petroliferous fluids reach the GHSZ. In the study area, thermogenic hydrates are likely limited to three regions; (1) shallow normal faults that penetrate the core of thrust anticlines and which serve as conduits for rising petroliferous fluids to reach the GHSZ; (2) Seismic pipe structures which often extend deep into the cores of thrust folds and; (3) the intervening depths between the upper and lower BSRs where double BSRs occur. Structure II hydrates have been detected beneath the upper BSR on the continental slope of the Sabah province (Panagoni et al., 2016).

6. Conclusion

In this study, seismic evidence, specifically, bottom-simulating reflectors, have been used to infer the presence of gas hydrates in shallow sediments beneath the seafloor in the offshore Niger Delta. Indicated gas hydrates occurrence follows the structural grain of the Delta occurring principally in active thrust-related folds of the Inner and Outer fold and thrust belts of the Niger Delta. Gas hydrate sediment acreage is up to 17600 sq-km representing 20% of the total offshore Niger Delta acreage. This likely represents the minimum acreage since gas hydrate sediments are seismically indistinguishable in regions of flat bathymetry where BSRs tend to be absent. Thermogenic hydrate occurrence is likely restricted to faults, seismic pipes and the interval between the lower and deeper BSRs where double BSRs occur. Hydrate occurrence is likely varied in mode of occurrence and concentrations.

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