Quest Journals
Journal of Research in Environmental and Earth Sciences
Volume 7 ~ Issue 8 (2021) pp: 24-35
ISSN(Online) :2348-2532
www.questjournals.org

Research Paper

Seafloor Morphology, Pockmark Seismic Character and Fluid Plumbing System in the Offshore Niger Delta

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ABSTRACT: *3D exploration seismic data have been used to describe the morphology of the seafloor, the seismic character of pockmarks and the near-surface hydrocarbon 'plumbing' system of a field in the western region of the outer fold and thrust belt of the Niger Delta. The seabed comprises an intensely deformed northeastern highland, a tectonically quiet central plain and an outboard ridge and basin region. Seven (7) groups of pockmarks including a giant pockmark, sinuous strings of overlapping pockmarks and multiple sets of isolated pockmarks were identified. The pockmarks occur in proximity with near seafloor terminations of shallow normal faults. Pockmark density is high on the tectonically active northeastern highland and they are fed fluids through shallow normal faults which often extend below inferred gas-hydrate seals that trap free gas beneath. Here the pockmarks deflate pressure from within shallow faulted thrust folds and much deeper sections. Overall, the gas supply for pockmarks formation and preservation is likely an admixture of hydrocarbons of biogenic and thermogenic origins sourced chiefly from fluid accumulations beneath gas hydrate sediments and possibly dissociating hydrates. Pockmark clusters within the central plain adjoin channels bounds and are sourced fluids from biogenic sources. Pockmarks in the study area function on three distinct time scales and deflate pressure from either shallow biogenic build-ups or deeper accumulations of mixed-source hydrocarbons beneath a BSR in the apexes of thrust folds or from fractured reservoirs at great depths. The pockmark distribution provides a first-order guide to understanding fluid migration patterns and hydrocarbon potential of the area and to defining potential seafloor hazards.*
KEYWORDS: *Pockmarks, Mud volcano, Gas hydrates, Fluid migration, BSR.*

Received 02 August, 2021; Revised: 14 August, 2021; Accepted 16 August, 2021

I. INTRODUCTION

Pockmarks are concave upwards usually nearly circular depressions on the seafloor which serve as exists for subsurface gas-rich fluids to reach the water column and possibly the atmosphere (Hovland and Judd, 1988; Judd and Hovland, 2007; Petersen *et al.*, 2010). They form due to the accumulation of fluids at shallow levels beneath the seafloor: rising thermogenic and biogenic hydrocarbons accumulate in near-surface sediments until the differential fluid pressure beneath the seafloor exceeds the lithostatic thresholds. The seafloor ruptures and shallow sediments are ejected into the water column in an episodic manner forming crater-like depressions (Hovland, 1989). Such craters may re-erupt in future or may release fluids at low rates between eruptions (Hovland 1989). The existence of pockmarks has multiple implications for hydrocarbon exploration and production activities: when fluids expelled from pockmarks in a field include thermogenic hydrocarbons, pockmarks may indicate: 1) the existence of a working petroleum system (Hovland and Judd, 1988; Carvalho and Kuilman, 2003; Hasiotis *et al.*, 2002; Hood *et al.*, 2002); 2) the breaching of deep-seated and shallow reservoirs and an abundance of migration pathways; and 3) the existence of unstable seafloor (Hovland, 1989). Hence, pockmarks could serve as valuable proxies for locating hydrocarbon reservoirs, understanding the subsurface fluid migration dynamics and could provide valuable information on potential operational hazards which could impact drilling activities and the installation of production facilities (Hovland 1989).

Pockmarks are well documented features in the offshore Niger Delta (Cobbold *et al.*, 2009; Sultan *et al.*, 2010; Babangida, 2015; Riboulot *et al.*, 2019). There often occur in association with thrust fold apexes, and discontinuities in the seafloor such as faults, canyons and channel fringes, seafloor mounds, mud diapirs and mud volcanos (Cobbold *et al.*, 2009; Babangida, 2015). They may also occur in tectonically quiet regions. Core samples taken from hydrate-bearing pockmarks from the Niger Delta indicate a predominance of thermogenically sourced methane through contributions from biogenetically sourced methane cannot be ruled out (Brooks *et al.*, 2000; Sultan *et al.*, 2010; Ruffine *et al.*, 2013). It has been suggested that the dominant source of fluid for pockmark formation in the Niger Delta comes from the dissociation of gas hydrates (Sultan *et al.*, 2010). However, seismic evidence indicates an intricate relationship between near-seafloor terminations of normal faults and the distribution of pockmarks. This suggests a strong causal relationship between the two where the faults likely funnel fluids to shallow levels for the formation and preservation of the pockmarks (Aminu and Ojo, 2021). Fluids funneled for pockmark formation can be either free gas (and other liquids) migrating from deep strata or fluids generated biogenically at shallow levels (Aminu and Ojo, 2021) or from the dissociation of gas hydrates (Sultan *et al.*, 2010).

In this study, we document the seismic character of pockmarks from the offshore province of the western Niger Delta, their structural associations and the inferred fluid plumbing system.

II. REGIONAL GEOLOGICAL SETTING

The Niger Delta is located between latitudes 3˚N and 6˚N and longitudes 3˚E and 9˚E in southern Nigeria (Figure 1). The onshore limits of the Delta comprise the Benin Flank to the west and north, the Abakaliki High to the northeast, and the Calabar Flank to the East-north-east. The offshore extents are defined by the Dahomey Basin to the west, the Cameroon Volcanic line to the east and either of the sediment thickness contour of 2000 m or the 4000 m water depth to the south and southwest (Weber and Daukoru, 1975; Tuttle *et al.*, 1999).

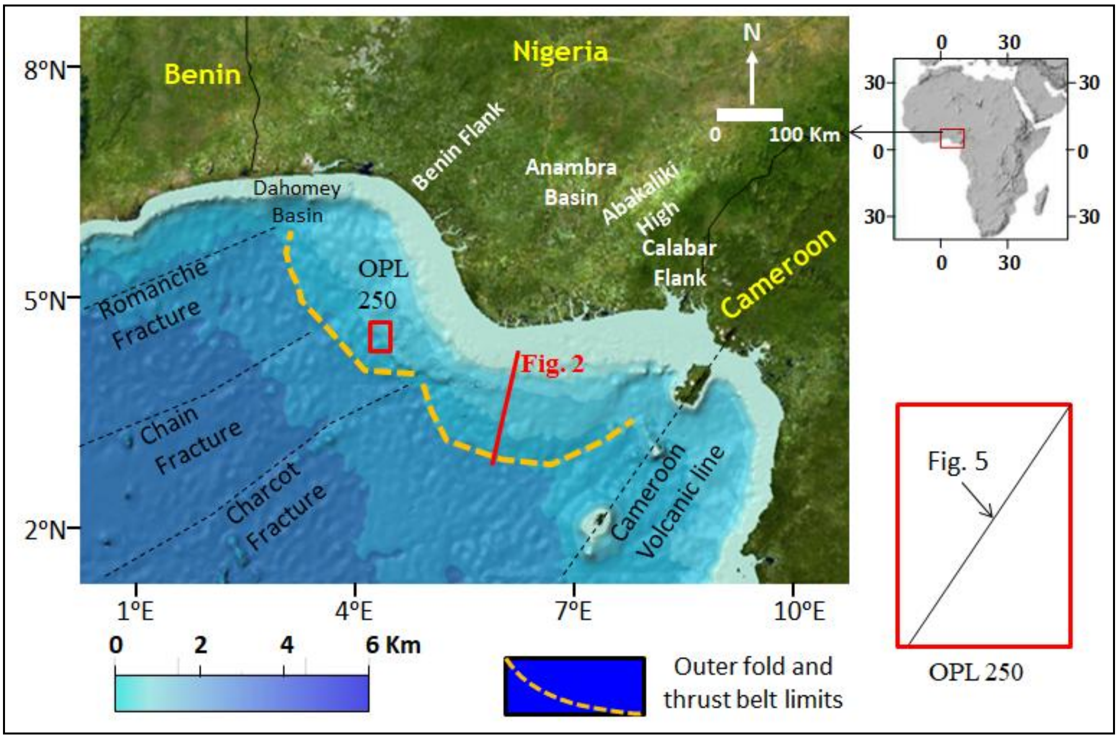

Figure 1. Bathymetric image of the Niger Delta highlighting major structural elements and province outline. The study area (in red polygon), is in the western Niger Delta. Water depth is generally more than 1400 m. The enlarged red polygon indicates the spatial location of Figure 5. Red line indicates the position of the interpreted line shown in Figure 2. (Modified after Aminu and Ojo, 2021)

The Delta sits at the site of the triple junction which formed during the opening of the South Atlantic Sea and the separation of the African and South American continents (Burke, 1972; Whiteman, 1982). Rifting spanned from the Late Jurassic till the end of the Cretaceous (Lehner and De Ruiter, 1977; Tuttle *et al.*, 1999). Five structural provinces characterize the Delta (Corredor *et al.*, 2005): from the hinterland seawards (Figure 2), these include (1) an extensional province, (2) a shale diapir province, (3) the inner fold and thrust belt, (4) a detachment fold province and (5) the outer fold and thrust belt. The initial disposition of the sedimentary succession across these provinces was constrained by the bathymetry of the oceanic crust below (Corredor *et al.*, 2005; Aminu and Ojo, 2018). Subsequent thin-skinned deformation in the Delta has largely been the result of gravity-driven shale tectonics (Wu and Bally, 2000; Bilotti and Shaw, 2005; Corredor *et al.*, 2005): Poorly compacted, pro-delta and delta-slope clays were loaded by denser delta-front sands resulting in the formation of shale diapirs. Further, a lack of lateral support for delta-slope clays encouraged basinward slope instability and allowed the sedimentary pile to glide seawards (Tuttle *et al.,* 1999). Stress and strain resulting from the downward and seaward motion of mobile shales beneath the onshore and transitional provinces were transferred seaward via a basal detachment level in the Akata Formation leading to the development of compressional toe-thrust structures in the more distal portions of the Delta (Bilotti and Shaw, 2005; Corredor *et al.,* 2005). Fluctuations in sea level and the rate of sediment supply from the hinterland have exerted lesser but significant influences on the development of the Delta (Doust and Omatsola, 1990).

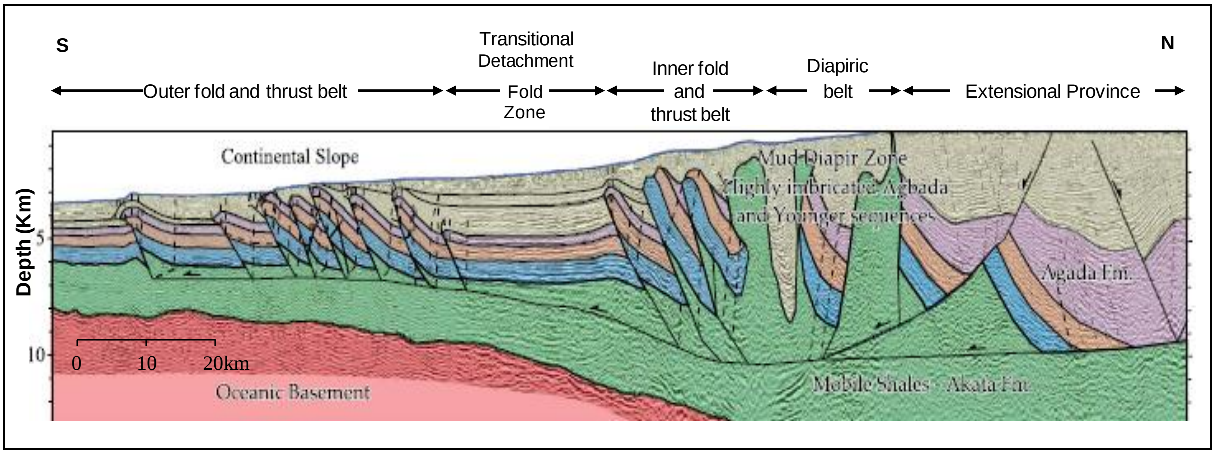

Figure 2. Interpreted regional seismic profile across the Niger Delta typifying the relationship of its five tectonic provinces. Deformation results from gravity-driven sediment collapse on the continental shelf. The resulting strain is transferred seaward leading to diapiric shale movement near-field and toe-thrust structures in the more outboard regions. (Adapted from Corredor *et al.*, 2005).

The deepwater Niger Delta occurs in water depths greater than 1000 m (Corredor *et al.,* 2005). Its bathymetric expressions comprise multiple convex-to-sea thrust-related deformation lobes that define the fold and thrust belts (Connors *et al.,* 1998; Wu and Bally, 2000) (Figure 1). The lobes are separated by an intervening plain with little deformation. The study area is in Oil Producing License (OPL) 250.

Litho-stratigraphy.

Litho-stratigraphically, 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, a foraminifera-rich marine shale lies at the base of the succession and is regarded as the principal source rock of the Delta (Figure 3). The Akata probably overlies syn-rift clastic fragments of the oceanic basement below (Corredor *et al.,* 2005; Sahota, 2006). The Akata is conformably overlain by a faulted paralic sequence of alternating continentally derived sands and marine shales known as the Agbada Formation (Avbovbo, 1978). The Agbada Formation is the dominant reservoir rock of the Delta and its shale intercalations are regarded as a potential source of hydrocarbons (Nwachukwu and Chukwura, 1986) and serve as a seal for most reservoir configurations. Faulting of the Agbada Formation results from both gravity-driven extension in the hinterland and compression in the distal portions of the Delta (Bilotti and Shaw, 2005; Corredor *et al.,* 2005). The Agbada is overlain by the Benin Formation which consists of massive, porous and unconsolidated, usually fresh-water continental sands (Avbovbo, 1978; Reijers, 2011). In the most distal deepwater sections of the Delta, the Benin formation is absent, grading seaward into deepwater clastics of the Agbada Formation (Cobbold *et al.,* 2009; Maloney *et al.,* 2010).

III. DATA AND METHODOLOGY

In this study, we utilized a 3D seismic data volume provided by the Department of Petroleum Resources (DPR) Nigeria. The seismic data was acquired in 1999 by Petroleum Geo-Services. Summary survey details and acquisition/processing parameters can be found elsewhere (Aminu and Ojo, 2021). The subset volume used in this study was zero-phased, post-stack time migrated, displayed with normal polarity (North American convention) and with data coverage roughly of 560 sq Km and a record length of 7400 ms. As data was post-stack and migrated, our analysis was limited to post-stack seismic sections and attributes. Interpretation was carried out in OpendTect 6.0.2. Due to the lack of adequate velocity information for the study area, time-to-depth conversion for the seismic data could not be achieved. Seismic sections are therefore displayed in two-way travel-time (*twt*). For first-order modeling purposes, a velocity of 1480 ms^{-1} (Maloney *et al.*, 2010) was assumed for the water column and 1520 ms^{-1} (Adeogba *et al.*, 2005; Aminu and Ojo, 2021) for near-surface sediments.

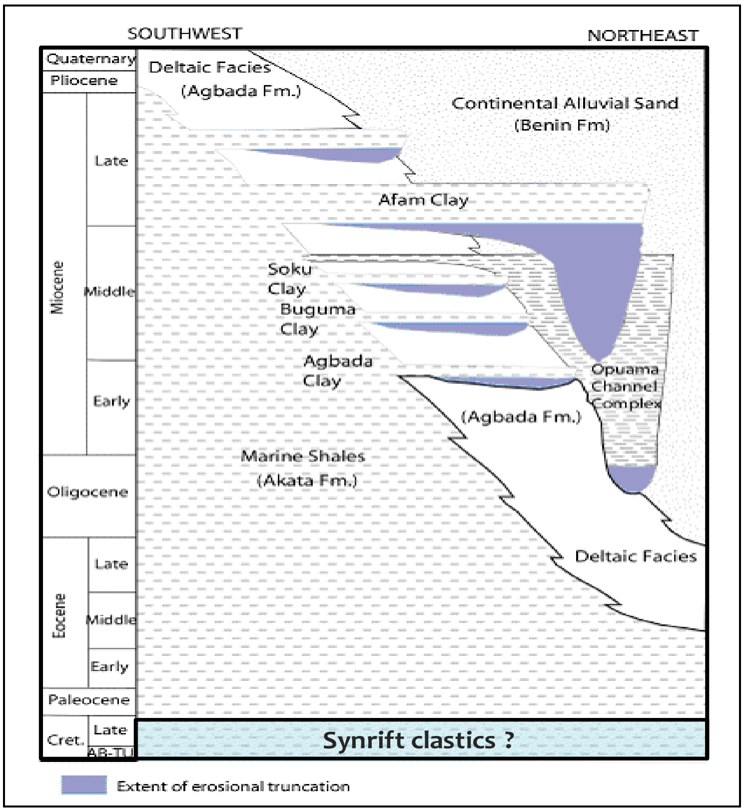

Figure 3. Stratigraphic of the Niger Delta: Akata, Agbada and Benin. Syn-rift clastic fragments of the oceanic crust, likely underlie the sedimentary succession. The marine Akata shale is the source rock while the clastic Agbada serves as the reservoir rock (Modified from Tuttle *et al.*, 1999).

IV. RESULTS

Local Geological Setting

In the study area, the seafloor morphology allows the identification of three distinct regions (Figure 4 & 5); 1) an extensive highland in the northeastern region; 2) a foreland ridge and associated basin in the southwestern limit and; 3) a central low lying plain intervening between the two rises. These regions are described below:

The Northeastern Highland

The northeastern highland is a bathymetric rise resulting from recent (and possibly ongoing) thrust activity on two major thrust systems with multiple fore-thrust fans and thrust duplexes (Figure 5). The highland likely represents an anticlinorium. This bathymetric rise covers an area of approximately 166.3 km^2 in water depths ranging from 1627 m to 2431 m subsea. The leading thrust fold limb of the rise is 25.3 km long within the study area with a strike of 146˚ in the northwest-southeast direction. A saddle exists between the seafloor expressions of the major thrust systems of this rise creating a potential pathway for sediment transport from the hinterland. The northeastern highland host two submarine canyons, two across-strike steep-edged groove-like channels, a slump failure scar, a giant pockmark, and strings of smaller overlapping and isolated pockmarks (Figure 4 – Pockmarks are described in section 4.2).

Canyons: Two canyons (1 & 2) occur on the highland. A major canyon (Canyon 1) consisting of two branches runs in a northwest-southeast direction parallel to the strike of the forelimb of the leading thrust fold of the highland for a total length in excess of 13.6 km (Figure 4). The main branch is approximately 10 km long. The minor leg is roughly 3.6 km long and branches off close to the southern end of the main branch in a northeasterly direction before turning southeastwards. Canyon 1 is approximately 367 m and 431 m wide at its narrowest and widest sections, respectively. Its thalweg deepens from 73 m in the southeastern end to 130 m in the northwest. The thalweg hosts a string of isolated pockmarks (described later in section 4.2). A second canyon (Canyon 2) is approximately 3.1 km long and runs in a slightly actuate northeast-southwest trajectory

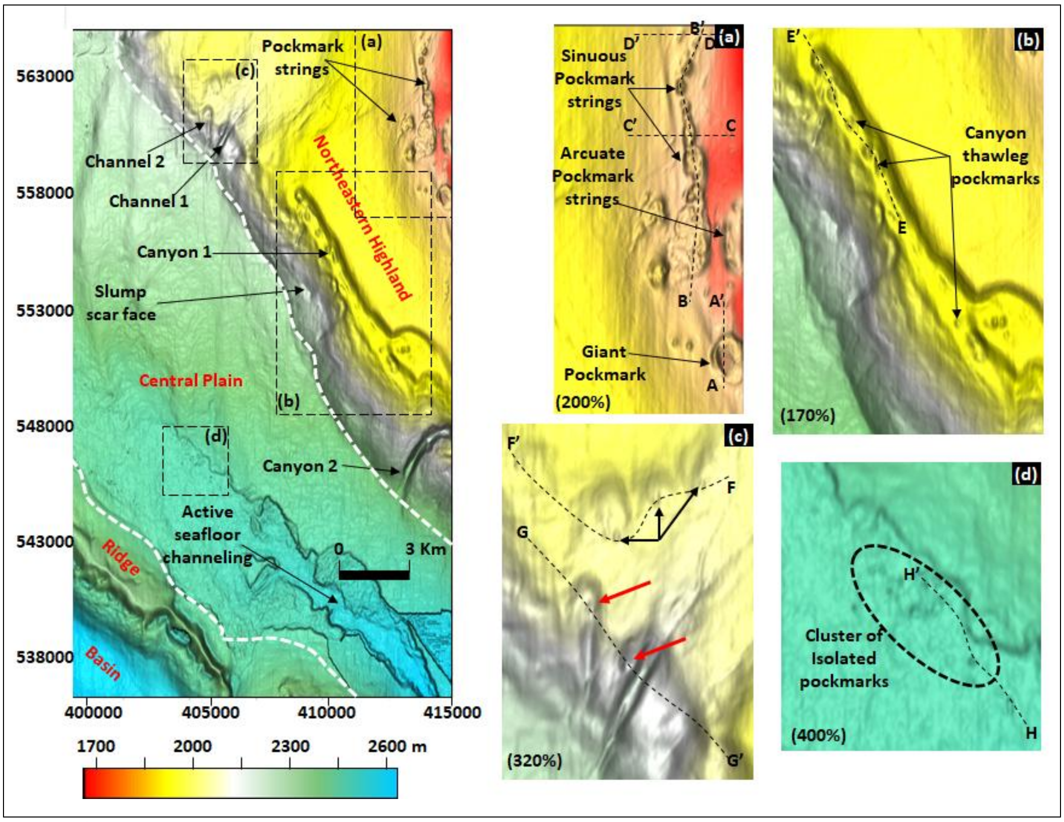

Figure 4. Seafloor relief map of the study area (left). A central low plain separates the two rises, a northeastern highland and a foreland ridge and basin system. The northeastern highland hosts a mud volcano, a slump scar, groove-like channels, strings of oval overlapping pockmarks and seafloor canyons. Irregular yellow polygon represents the lateral extent of the relict BSR_R (shown in Figures 15). Insets are enlarged images of dashed polygons (a), (b), (c) and (d). Zoom levels are indicated in percentages of the original polygons. Dashed white lines represent approximate bounds of the three tectonic regions, while dashed black lines represent seismic transects (A-A´, B-B´, C-C´, D-D´, E-E´, F-F´, G-G´ & H-H´) shown in figures 6 – 10.

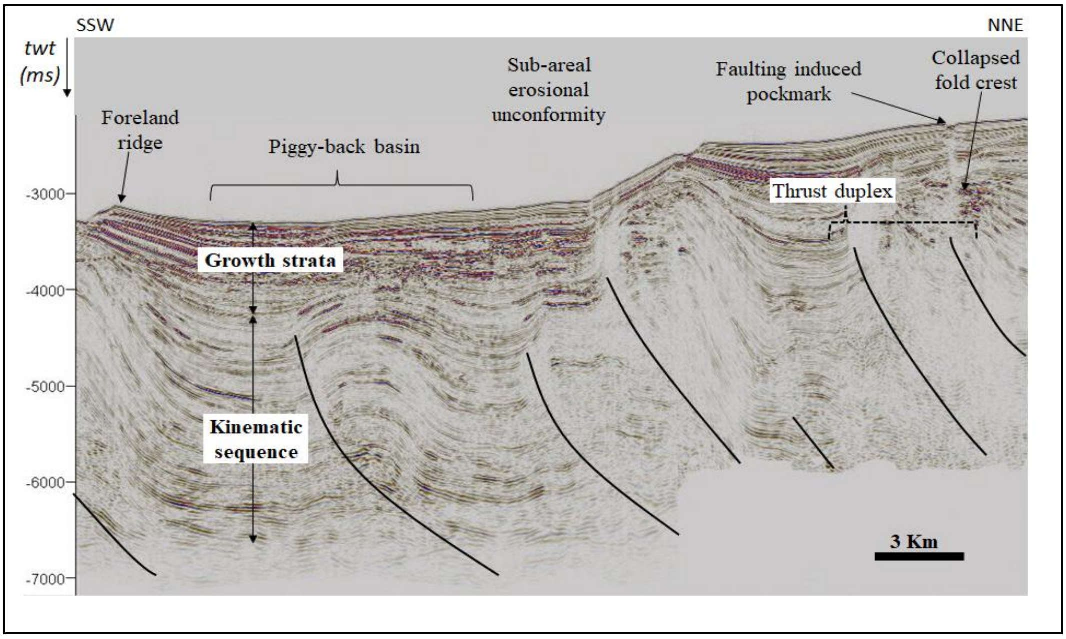

Figure 5. SW-NE across-field seismic line indicating the typical structural configurations in the area (see Figure 1 for location). Deformation resulted from recent active thrusting episodes which produced relief structures such as a foreland ridge and highland in the hinterland. The summits of thrust folds are frequently faulted with faults leading to pockmarks on the seafloor.

beyond the southeastern limits of Canyon 1 (Figure 4). It is roughly 348 m wide at its northeastern end and 223 m towards its southwestern end. It shallows from a thalweg depth of 179 m in the northeast to 25 m at its southwest mouth where it empties seawards.

Groove-like Channels: Two groove-like channels are identified on the highland. The main channel (Channel 1) (Figure 4) has a total length of 2395 m and runs in the northeast-southwest direction across the leading fold of the northeastern highland. It empties in the southwest seaward direction (Figure 4). Channel 1 is approximately 111 m wide at its narrowest sections downstream and 225 m at its widest upstream section. The groove sits within an earlier much wider erosional channel fill with a width up to 3770 m (Figure 9b). This channel is flanked to the north by an isolated pockmark (also described later). A second groove-like channel (Channel 2) runs in the north-south direction also across the leading fold of the highland (Figure 4). It is approximately 190 m wide upstream and 80 wide downstream. It has a total length of 1657m. An isolated pockmark occurs at its upstream end.

Slump scar: The slump scar face has a width roughly 3615 m wide and a length of 2040 m with an estimated total area of 7.37 km^2 (Figure 4). The seismic resolution does not permit an estimation of the thickness of sediments mobilized by the failure but gentle mounds are observed at the base of the slump scar.

The Southwestern Ridge and Basin

The Southwestern Ridge and Basin consists of a pronounced-relief thrust-induced ridge and seaward basin in an area roughly 40.3 km^2 in size (Figure 4). Water depth ranges from 2343 m to 2625 m subsea. The ridge hinge trends on a bearing of 133˚ in the northwest-southeast and has a total length of 10 km. A relay ramp occurs in the middle of the hinge-line, roughly 5.15 km from the western limit of the ridge. The ridge is the result of an active thrust riding on a buried fore thrust (Figure 5).

The Central Plain

The Central plain is a broad area measuring at least 9.1 km across and at least 25.2 km long within the study area with its long axis trending along the regional northwest-southeast strike direction. The Plain measures a total area of 258.7 km^2 (Figure 4). Water depths range from 2213 m to 2606 m subsea with an overall dip in the southeast direction. A submarine channel is active on the seafloor and runs in the southeast direction. The channel is about 1060 m wide at its narrowest sections downstream but reaches up to 4587 m wide, upstream. Incision depth along the channel ranges from 12 m upstream to 100 m at its southeast downstream limits. The Channel runs parallel to the Southwestern ridge and appears to have a branch that flows in a southerly direction around the southwestern limit of the ridge. Small isolated pockmarks (describe in section 4.2) occur on the fringes of the channel (Figures 4d).

4.2 POCKMARK CHARACTER

In the study, pockmarks occur in the Northeastern highland and the Submarine Plains. Pockmarks in the study area vary in size, morphology, cluttering patterns and association with other structures. They further are diverse in the geologic time range over which they appear to function.

Pockmarks in the Northeastern highland

Six groups of pockmarks are identified within the Northeastern highland:

1. **A Giant Pockmark (Nascent Mud Volcano)**: A giant pockmark occurs in the eastern extremes of the Northeastern highland (Figure 4a). This pockmark is elliptical in plan-view with its major axis in the N-S direction. The major axis is roughly 1266 m long while the minor axis is about 970 m long. The pockmark is 61.6 m deep measuring from its base to its rim. It has an emergent pinnacle at its center which rises to 91.2 m above its base indicating ongoing or recent expulsion of mud (Figure 6). This pockmark is fed material through a wide conical section that extends to great depths (>1000 *ms* below seafloor (bsf)) within the sedimentary pile (Figure 6). The conical section is largely acoustically transparent but evidence of stratification can be observed within the section. Reflection push-ups occur within the cone including the push-up of a bottom-simulating reflection (BSR). Enhanced amplitude reflections (EARs) below the BSR terminate laterally against the transparent cone.

2. **An Arcuate String of Pockmarks**: A string of pockmarks arranged in an arcuate fashion in the extreme eastern region of the study area occurs just northwards of the Giant Pockmark (Figure 4a). Individual pockmarks are concave upwards and range from 160 m to 230 m across with smooth internal structures (Figure 6). As a group, they appear to form a N-S semi-continuous depression which includes the Giant pockmark (discussed above). The depression is at least 4.2 km in length (if the Giant pockmark is included)

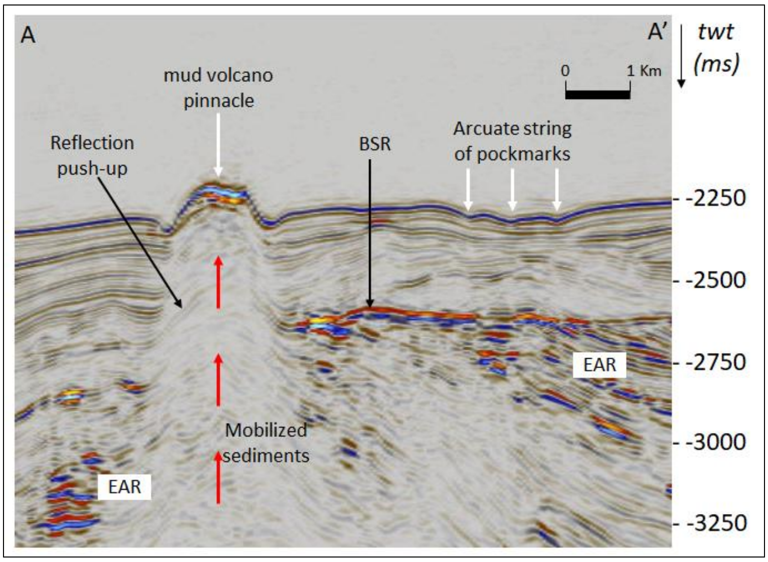

Figure 6. Seismic transect A-A´ through the Giant pockmark (volcano) and the arcuate string of pockmarks (See Figure 4a for location). The Giant pockmark is fed through an acoustically transparent conical section leading to a pinnacle that rises above the seafloor and is not buried by recent sediments. The pinnacle and reflection Push-ups in the conical section indicate active expulsion of sediments. The conical section breaches a regional BSR which has enhanced amplitude reflections below.

and 225–550 m in width. Pockmark depths range from 14.8 m in the north to 34 m and 11 m in the middle and south, respectively. Beneath these pockmarks occur a series of N-S trending conjugate fault systems (not shown–see Figure 7b for typical fault signature). The fault conjugates generally reach the seafloor and form grabens.

2. **A Low Sinuosity String of Pockmarks**: This string consists of closely spaced to overlapping elliptical pockmarks (Figure 4a). The string runs in the N-S direction for a total length of 5.3 km forming an almost continuous depression that is approximately 35 m deep at its deepest point. The depression is 221 m wide at its narrowest in the north and reaches up to 961 m in its southern extremes. Individual pockmarks increase in size from north to south. They are isolated and with smooth internal structures at the northern end of the depression but tend to overlap one another and have chaotic internal structures towards the south. The pockmarks are concave upwards in section view with no pinnacles at their centers (Figure 7b). In the shallow subsurface, the location of this string coincides with the position of N-S trending conjugate normal faults which appear to penetrate to the seafloor and create grabens atop the faulted crest of a thrust anticline (Figure 7c).

4. **Pockmarks in Canyon Thawleg**: These are a set of aligned pockmarks that occur on the thalweg of Canyon 1 (Figure 4b). Individual pockmarks range in size from 550 m at the northern end of Canyon 1 thalweg to151 m at the canyon's southeastern branch. Pockmark internal depths decrease from 28 m in the north to 8 m in the south. They are generally elongated in the direction of the Canyon axis and have smooth internal structures. Inter-pockmark spacing is of the order of 230 m in the north of the Canyon and could be a low as 35 m at its southern end. Beneath these pockmarks, cascades of shallow conjugate normal faults form graben structures (Figure 8). Fault tips generally terminate in proximity to the seafloor location of the pockmarks. The faults penetrate to depths beneath a BSR (~ 450 m bsf) and into the center of a thrust anticline. Enhanced amplitude reflections occur in the region just beneath the BSR.

5. **Pockmarks on the southern end of a dome in the north-central region**: These consist of four isolated pockmarks arranged in an arcuate fashion around the southern end of a dome in the north-central region of

the study area (Figure 4c). These pockmarks are elliptical with their major axes in the N-S direction. They measure up to 130 m wide and 9 m deep. In the subsurface, the seafloor locations of these pockmarks coincide with the tips of shallow normal faults or very shallow acoustic zones where reflection continuity is interrupted (Figure 9a). Faults consist of some conjugates and penetrate beneath the regional BSR. Enhanced amplitude reflections occur beneath the BSR.

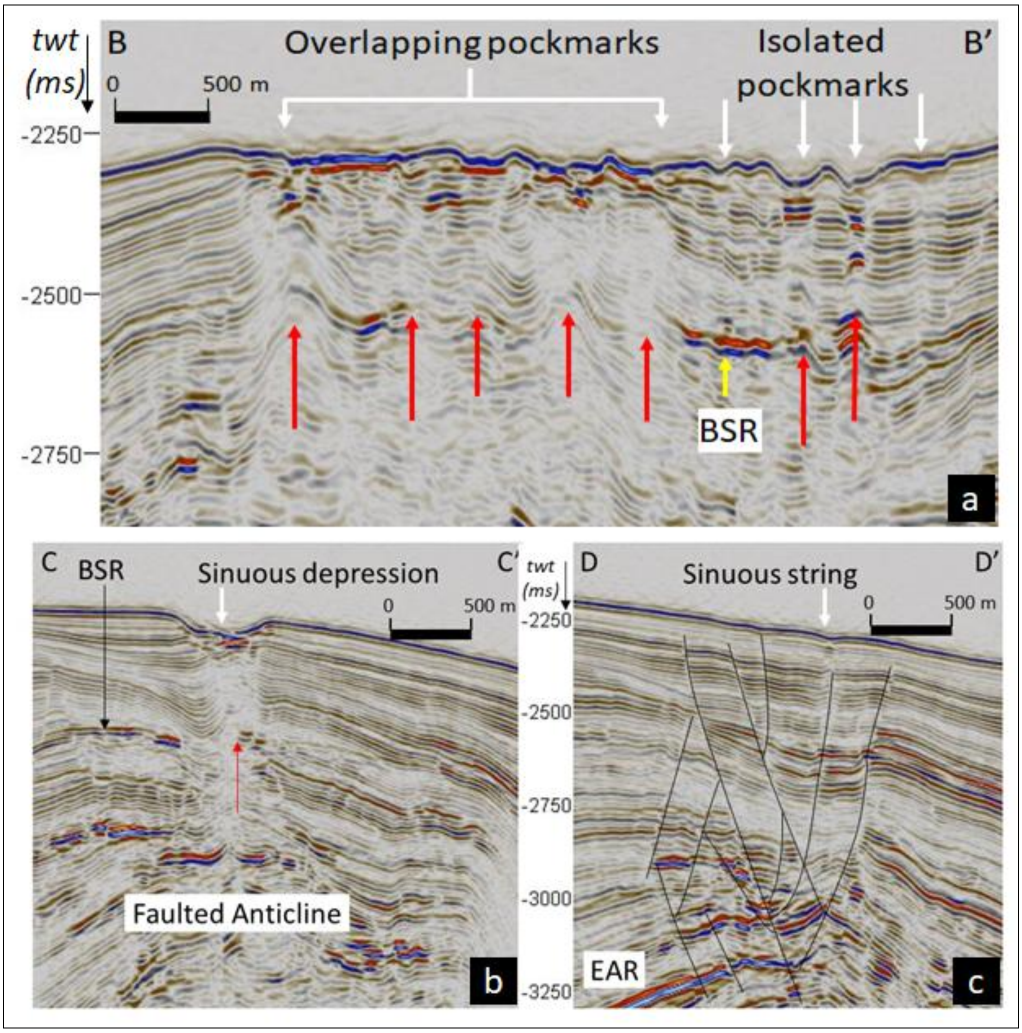

Figure 7. Seismic transects (a) B-B´, (b) C-C´ and (c) D-D´ through the subsurface beneath the sinuous string of oval pockmarks. C-C´ and D-D´ are perpendicular to B-B´ (see Figure 4a for spatial locations). Push-up of reflections beneath the region of overlapping pockmarks is more enhanced than the region of isolated pockmarks along the string. Advection beneath the region of overlapping pockmarks is higher relative to the region with isolated pockmarks. The pockmarks are concave upwards with no pinnacles. The plumbing system involves conjugate N-S trending normal faults that sole out in the crest of a thrust anticline. Individual pockmark depths decrease from south (C-C´) to north (D-D´).

6. **Isolated Pockmarks associated with Groove-like Channels:** Two isolated pockmarks are observed, one in association with the identified groove-like channels that run across the leading fold of the northeastern highland (Figure 4c). A pockmark occurs on the northern flank of Channel 1 while a second pockmark occurs in the upstream end of Channel 2. Each pockmark is roughly 85 m wide and about 11 m deep. They are roughly elliptical in plan-view with the major axis in the direction of the grooves. Along with the grooves, they sit within sediments that drape over the infill of a much wider leveed-channel system (Figure 9b). Beneath these pockmarks are shallow acoustic zones where reflection continuity is reduced.

Pockmarks in the Central Plain

7. **Isolated Small Pockmarks**: Within the Central Plain, numerous isolated pockmarks measuring roughly 45 m across occur on the flanks of the active seafloor channel (Figure 4d). They occur in linear clusters along the fringes of the channel erosion within sediments in the levee region and only in the upstream half of the channel. They sit atop shallow acoustic zones where the continuity of near seafloor reflections is partly interrupted (Figure 10).

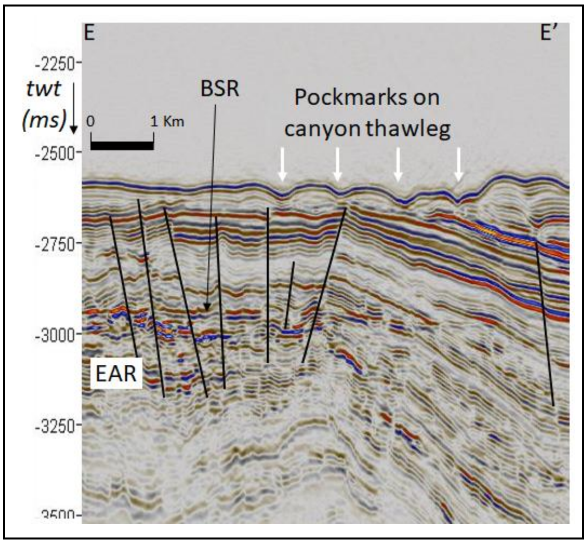

Figure 8. Seismic transect E-E´ through the canyon thalweg (See figure 4b for spatial location). Individual pockmarks frequently occur at the seafloor terminations of shallow conjugate normal faults which penetrate beneath a regional BSR. Enhanced amplitude reflection (EAR) beneath the BSR suggests the accumulation of free gas at these locations.

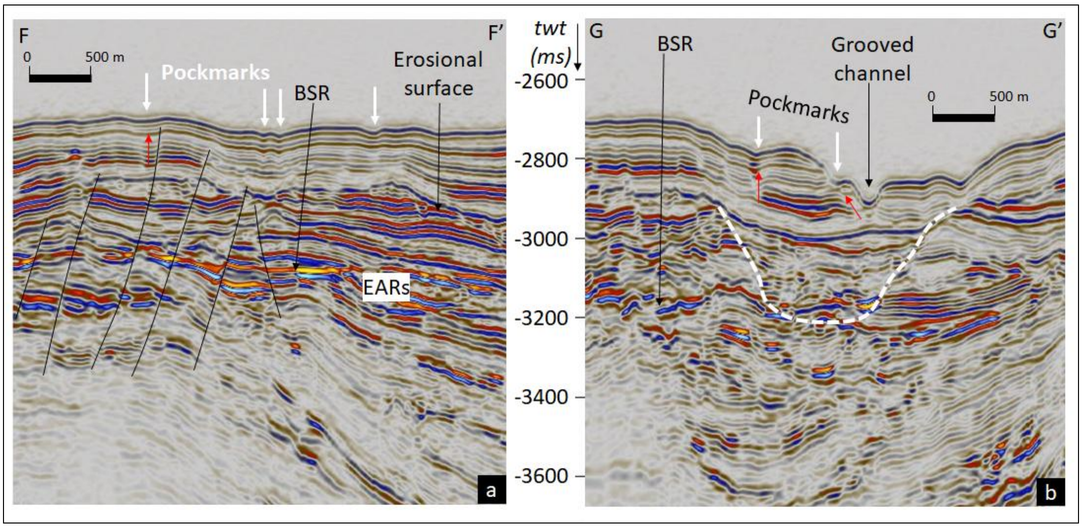

Figure 9. Seismic transects through (a) F-F´ pockmarks on the southern end of a dome-shaped structure in the north-central region and (b) G-G´ pockmarks associated with groove-like channels, respectively (See Figure 4c for spatial locations). Fluid migration is indicated as vertical and sub-vertical chaotic zones (red arrows) which often run adjacent to fault planes.

V. DISCUSSION

We have identified seven groups of pockmarks within the study area. Pockmark distribution in the study area is concentrated in regions of active or recent tectonic activity specifically on the northeastern highland where multiple thrust sheets band together to form an anticlinorium. Spatially, pockmarks are located proximal to the near-surface terminations of shallow normal faults which often penetrate to depths in excess of

500 m bsf well beneath a BSR that represents the base of the gas hydrate zone in the study area and into the summit of thrust anticlines. This suggests a causal relationship between the faults and pockmarks with pockmark formation and preservation considerably dependent on faulting. Beneath the BSR, EARs indicate the accumulation of migrating fluids. The faults apparently act as migration pathways for fluids trapped both within the folds of thrust anticlines and beneath the gas hydrate zone to reach shallow sediments before being exhaled into the water column through pockmarks. This likely implies that rising thermogenically derived hydrocarbons stored either in the crests of thrust folds or beneath the gas hydrate zone source the pockmarks. This is reasonable considering that the formation of an anticlinorium involves much pressure and fracturing of potential reservoirs at depth (Corredor *et al.*, 2005; Twiss and Moores, 2007, Maloney *et al.*, 2010). There is also considerable

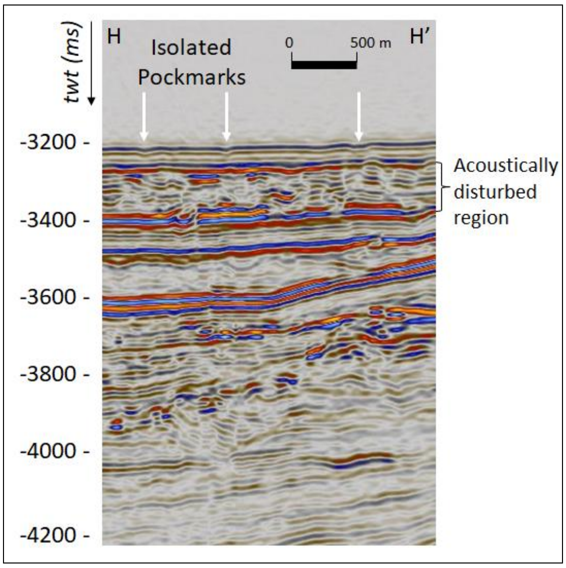

Figure 10. Seismic transect H-H´ through pockmarks on the central plain (See figure 4d for spatial location). An acoustically disturbed zone underlies the area.

seismic evidence of thermogenic gas migration from deep within the basin to shallow levels and the fluid supply can be presumed to be an admixture of both thermogenically and biogenically sourced fluid (Aminu and Ojo, 2021). In a few cases, such as the pockmarks in the central plain, the pockmarks appear to be fed through shallow acoustic zones not exceeding few tens of meters below the seafloor. Fluids sourcing such pockmarks can be expected to be of biogenic origin only. The push-up of seismic reflections beneath the overlapping pockmarks is greater than beneath the isolated pockmarks. This likely implies that advection rates beneath the region of overlapping pockmarks are much higher than beneath the region hosting smooth isolated pockmarks. It is also possible that the overlapping pockmarks are the result of current or at least recent activity and the chaotic internal structure is due to ongoing fluid expulsion (Van Rensbergen *et al.*, 2002). On the other hand, the isolated pockmarks with smooth internal structures have likely been dormant in the recent not expelling fluid or have very low effusion rates which allow seafloor currents to smoothen over the interior of the pockmarks. For the most part, pockmark size increase from N to S, except within Canyon 1 where the converse is true. This N-S trend likely reflects the intensity gradient of tectonic deformation within the area with larger pockmarks occurring in regions of higher tectonic deformation. The pockmarks apparently function over three (3) progressively longer time scales. Small isolated pockmarks such as those on the central plain and within the groove-like channels are sourced with fluids from very shallow strata (usually not exceeding 180 *ms* [120 m] bsf) and therefore function on a '*short*' time scale and respond to pressure build-up within shallow more recent sediments. Pockmarks related to shallow normal faults that penetrate beneath the regional BSR (up to 500 *ms* [375 m] bsf) such as the pockmarks on Canyon 1 thalweg and pockmarks around the north-central dome, function on a much '*intermediate*' time scale. They serve to deflate pressure build-up beneath the BSR and possibly within the apexes of thrust folds. Pockmarks that are sourced fluids from great depths (>1000 *ms* bsf) such as the Giant pockmark and the sinuous pockmark string, function on the '*long*' time scale and apparently serve to deflate pressure resulting from the fracturing of deep-seated reservoirs within the anticlinorium.

The abundance of pockmarks on the northeastern highland and their association with faults, EARs and BSRs have multiple implications: 1) there exists an active petroleum system generating thermogenic fluids; 2) there is an abundance of migration pathways, faults and permeability gateways, from deep sections of the sedimentary sequence to near seafloor strata; 3) the occurrence of shallow fluid accumulations either in the apexes of thrust folds or beneath gas hydrate sediments and; 4) abundance of unstable ground on the northeastern highland. The region thus has a high prospect for hydrocarbon exploration but is also likely beset with multiple geohazard risks to exploration and production facilities on the seafloor.

VI. CONCLUSION

We have identified and detailed seven (7) categories of pockmarks within the study area. Pockmarks are generally associated with the near seafloor terminations of shallow normal faults or shallow acoustic zones and are constrained to elongate in the N-S direction. Gas supply for pockmark formation is likely almost always an admixture of biogenic and thermogenic gas, except for the Isolated small pockmarks in the Central Plain where thrust activity has been dormant for a long period. The pockmarks function over multiple time scales and serve to deflate fluid pressure build-up at progressively deeper/older levels within the sedimentary section.

ACKNOWLEDGEMENT

Special thanks to the Department of Petroleum Resources (DPR), Nigeria, and Chevron, for providing data for this study.

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