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Sequence Stratigraphic Framework, Depositional Settings and Hydrocarbon Prospectivity of the Campanian Section, Tano Basin, Southwestern Ghana

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Abstract

Exploration activities in the prolific Tano Basin of Ghana has gained more momentum and special consideration due to the successes recorded at present. Previous studies have not adequately adopted sequence stratigraphy framework and depositional settings. This study aimed at applying sequence stratigraphy and depositional settings in hydrocarbon prospectivity of the Campanian interval in the Tano Basin. The study made use of data sets i.e. seismic data with well logs and biostratigraphy data. Sequence stratigraphic application revealed that the depositional setting of the Campanian interval is characterised by a lowstand fan system deposited in the middle to lower bathyal, indicated from biostratigraphic data. Also, seismic reflection termination corroborates a slope fan system. Seven mega sequences were delineated on seismic scale in response to the transgression and regression cycle. However, seismic attribute extractions for the Campanian interval revealed that the depositional systems were mainly submarine fans. Spectral decomposition analysis further revealed the architecture of the depositional systems as channel systems (channel-fills, sinuous channel and feeder channel), frontal splays and lobes. Thus, the hydrocarbon prospectivity of the Campanian interval is promising with a high possibility for stratigraphic traps for reservoirs being sands deposited as channel systems, frontal splays and lobes.

***Keywords**: Depositional settings; Campanian; Lowstand, submarine fans; Tano Basin.*

1. Introduction

The Cretaceous Tano Basin belongs to the coastal sedimentary basins of Ghana which is geographically located along the West African Transform Margin (Fig. 1). The Tano Basin has undergone successive hydrocarbon explorational stages since onshore oil seep was reported in 1896 [1-2]. However, this exploration effort gained more momentum following successful and significant commercial discovery made in the Cape Three-Points license, offshore Tano Basin in the year 2007 [3-4]. This economic discovery of hydrocarbon has pulled in more investigation exercises aimed at understanding the petroleum system better, to increase the petroleum reserves in the basin and also extend to other sedimentary basins of Ghana.

Over the last four decades, sequence stratigraphy has been utilized as a predictive exploration tool in the oil and gas industry [5]. This predictability introduces a new look at sedimentary facies component giving it a powerful analytical and correlation tool [6]. Sediment accumulation and preservation trends within a basin fill are important in successful exploration technique [7]. Sequence stratigraphy serves as a guide to uncover potential blend of traps and expand the avenue for deeper exploration in unexpanded sub-fault reservoirs, thereby enabling explorationists to properly place a given sub-basin into a petroleum system framework in a cost-effective manner [8]. This method is known to have been employed to a shallow marine to deeper marine settings with data sets such as outcrops, seismic data, well logs and cores. However, the application becomes more ambiguous in increasing trends from the shallow to deep marine settings [9-11]. Nevertheless, applying sequence stratigraphy in prospectivity endeavor ought to be done in a compelled procedure putting together methodology which depends on the information collection accessible and geologic situation for every specific case [6].

The Tano Basin is one of the prolific sedimentary basins of Ghana. The potential of its deep-water play particularly has attracted global attention [12-13]. The Campanian interval of the Tano Basin is known for its significant clastic sedimentation and identified as an exciting play [14]. This has been corroborated by discoveries in the Campanian aged Odum, Ntome (TEN Field) and the Gye-Nyame field. Thus, this study aims to understand the depositional setting and assess the hydrocarbon prospectivity of the Campanian using seismic attributes in the context of sequence stratigraphic framework in the western part of the Tano Basin. This study is premeditatedly divided into two folds i.e. sequence stratigraphy framework and the hydrocarbon prospectivity assessment of the Campanian interval of the Upper Cretaceous epoch.

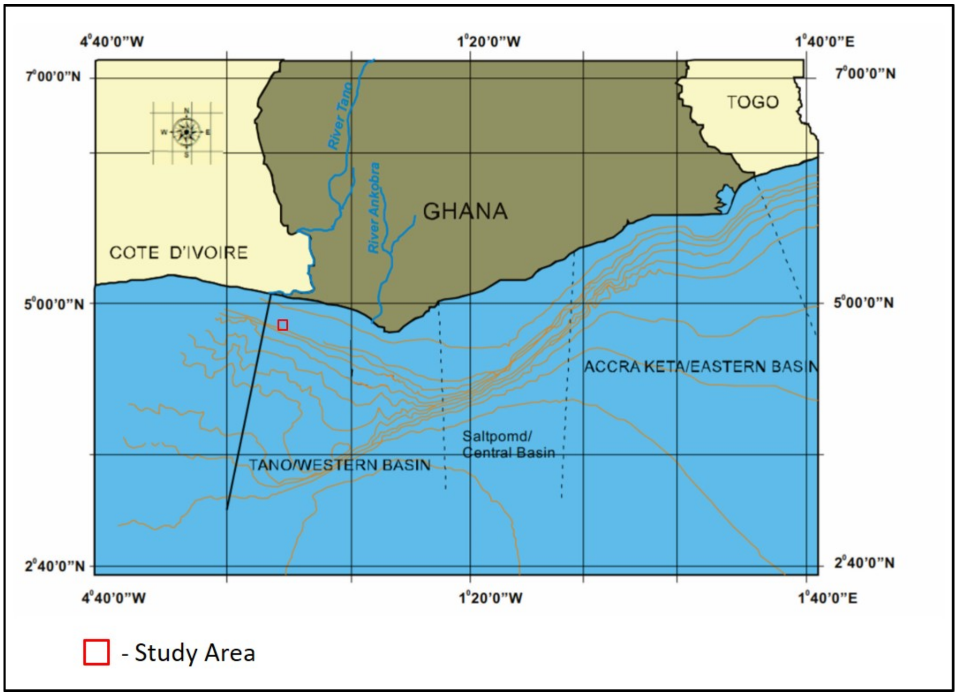

Fig. 1. Location map of the study area (Modified after Atta-Peters and Achaegakwo [15])

2. Geologic setting

The study area is located offshore west in the Tano Basin within the present-day upper continental shelf to mid-slope bathymetry (Fig. 1). The Tano Basin, also referred to as the Western Basin is a coastal sub-basin belonging to the family of the West African Transform Margin (WATM) basins with a larger proportion offshore and a lesser proportion onshore occupying the southwestern part of Ghana [16-17]. The regional tectonic evolution of the WATM is synonymous to that of the Tano Basin [18]. The basin originated from continental rifting in the Mesozoic Era and at the end of Jurassic period it formed a pull-apart basin. Subsequent extension and subsidence of the thinned continental crust of the rift system created accommodation to allow lithic fill into the basin as the South Atlantic Ocean opened up and deepened. However, wrench tectonics in the Cretaceous modified the basin in a grand scale transform fault associated with sagging and fracture [19-21]. The Romanche Fracture Zone (RFZ), one of the prominent structures found in the Tano Basin served as a stable tectonic flow line that reflects sedimentation style and tectonic evolution.

The lithic fill in the basin started from the Aptian age with significant clastics from continental erosion transported into the basin through the major supply of River Tano and River Ankroba [22]. Dailly *et al*., [23] also reported that some submarine canyon system served as clastic sediment delivery into the Tano Basin. According to Garry *et al*., [24], the direct relation between the tectonic phases and its associate sedimentation is marked by three major sequences in the basin as follows:

1. The pre-rift phase which is dominated by Precambrian basement rocks to late Jurassic.
2. The sys-rift phase characterised by Early Cretaceous age sediments with a major unconformity separating the syn-rift from the marine post transform rocks of the Upper Albian and Cenomanian.
3. The post-rift phase with marine sedimentation from Cenomanian to recent.

A detailed stratigraphic division of the Basin has been described [23, 25- 26]. The Basin has a proven working petroleum system with plays identified in the Albian, Cenomanian, Turonian, Campanian and Maastrichtian [14, 27].

3. Data and method

The data sets used in the study included; suit of well logs (GR, Resistivity and Sonic), seismic (i.e. a 2D and 3D) and biostratigraphy. The well Information was obtained from one well (Well A) with total depth equivalent to the Santonian age. The 3D seismic survey covers an area of 200km^2 with some intersecting 2D seismic lines. The 3D seismic survey is a post-stack time migrated (PSTM), recorded two-way time (TWT) and processed to a zero-phase. However, both 2D and 3D seismic data exhibit the normal (American) SEG convention with fair data qualities.

In an attempt to construct a sequence stratigraphic framework, the biostratigraphic data, an extract from previous paleontological studies carried out by Ghana National Petroleum Corporation (GNPC) was first reviewed to recognize and mark key sequence stratigraphic surfaces such as Maximum flooding surface (MFS), Sequence boundary (SB) and Transgressive surfaces (TS) noted in Well A according to Catuneanu *et al*., [28]. These surfaces are marked to the biozone applied by the Oil and Gas industry. This biozone gives information about the fossil (foraminifera, calcareous nannoplankton and palynomorphs) occurrence with their abundance and diversity at sampled depth. Also, paleobathymetry indication of some of the sampled sediment succession was noted from the biostratigraphy data. For this study, combination of the Haq *et al.* [29] format i.e. ('80') Ma and Hardenbol *et al.* [30] format i.e. Cam1 SB (meaning the first sequence boundary within the Campanian age) was adopted for the nomenclature for key sequence stratigraphic surfaces.

Using the Petrel Well template, the well log profile was displayed with the paleobathymetry incorporated into the templates. The lithofacies were then interpreted from the well logs by applying specific cut-offs with calibrated colour codes to indicate sands, silts and mud/shales on the Gamma-ray (GR) logs. Catuneanu *et al*. [11] model-independent framework approach was applied in the study as the genetic and bounding surfaces present in the Cretaceous succession. Following, the Well sequence stratigraphy was then constructed by interpreting the well logs patterns, paleobathymetry and the marked key stratigraphic surfaces. Also, the stacking patterns were drawn, systems tracts identified and constrained by the stratigraphic surfaces. Subsequently, the intersecting 2D survey was interpreted to capture the seismic facies based on the seismic reflection pattern and geometries in response to the stratigraphic transgression and regression cycles.

To assess the prospectivity of the Campanian, Well A was tied to the 3D seismic volume using the appropriate time-depth relation. The Top and Base of the Campanian was mapped on the 3D seismic section to generate time surface maps. Seismic surface attribute analysis was carried out with the mapped surfaces (horizons) to recognize the depositional elements spatially. Furthermore, spectral decomposition was applied to the surfaces to understand the trends of the depositional elements.

4. Results and discussion

Although the main focus of the study was on the Campanian, the stratigraphic interval ranges from the Upper Santonian (88 Ma) to Lower Maastrichtian about 71 Ma. The results obtained will be discussed in sections in line with the aim of the study.

4.1. Well stratigraphy

The lithofacies successions identified (Fig. 2) on the log template made use of Gamma-ray (GR) cut off values to represent likely lithology associated with colour grade i.e. 0-30° API (Yellow) represents sand, 30- 40° API (Dark grey) for silts and > 40°API (Black) for shale/mudstone.

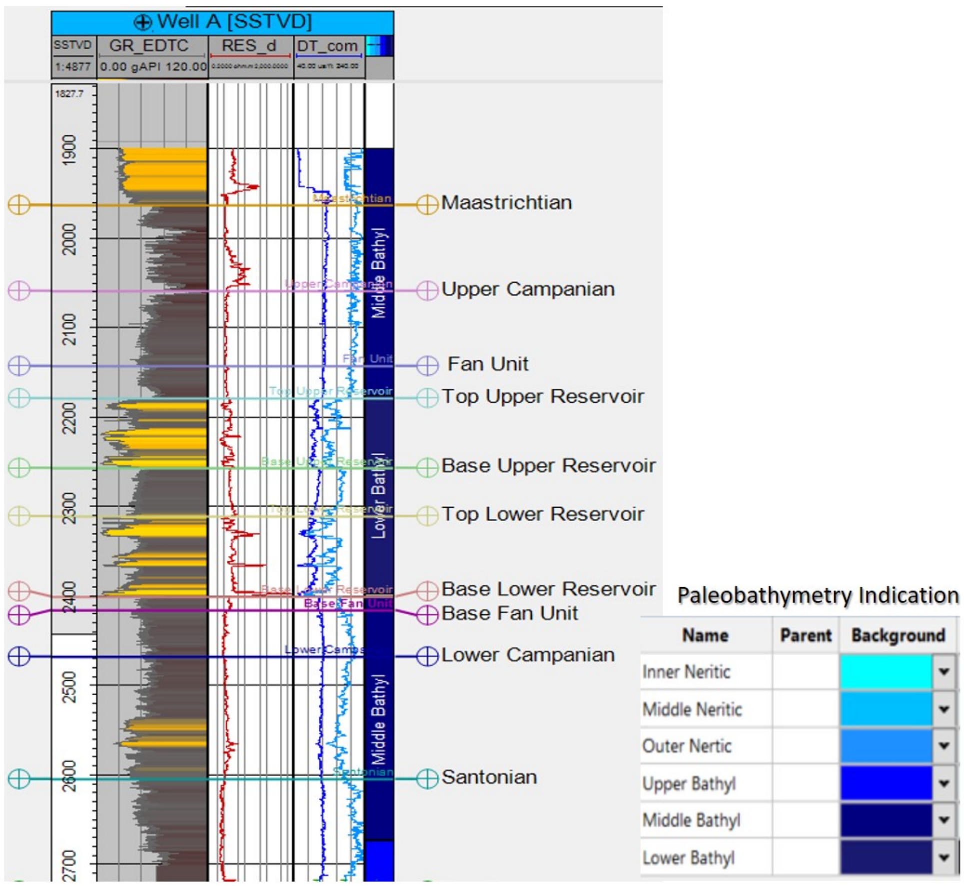

Fig. 2. Lithofacies succession of Well A showing the ages of marked Formations tops in the Upper Cretaceous and their paleo bathymetry indication

The lithofacies succession represents a period of mud/shale with intercalations of sand units. The Campanian interval is characterized by a higher sediment thickness about 410 m compared to others. Biostratigraphy data indicated a fan system in Well A with about 270 m sediment thickness deposited in the middle to lower bathyal. The Top of the fan unit was picked at depth 2150 m while the base of the fan at 2470 m. According to unpublished paleontological reports of GNPC, the presence of the fan unit in Well A was confirmed and supported by significant recoveries of *Palaeocystodinium species* noted throughout this interval (1,965 m to 2,405 m). Also, a high incidence of freshwater algae (*Pediastrum specie*s) between 2,205 m and 2,424 m is a positive indication of a lowering of erosional base level due to a fall in sea level during the Campanian. This therefore suggests that the Campanian interval as a lowstand system tract. The low stand systems tracts encompass sediments that accumulate during the onset of relative sea-level rise which is characterized predominantly by clastic sedimentation [28]. Lowstand systems tracts have been reported worldwide to contain sand prone reservoir lithofacies largely dominated by sediment gravity flows, including turbidites [31].

The Campanian interval bears two reservoir units which are stacked i.e. Upper reservoir and a Lower reservoir unit (Fig. 2) which were deposited in the marine environment. However, comparing to Rider [32] model which uses the GR signatures to infer the possible deposition elements, the Upper reservoir unit mimics a slope channel while the Lower reservoir unit is more of a supra fan depositional lobes.

The stacking pattern on the log template (Fig. 3) is constrained by the GR log shape. It is also paramount to note that stacking pattern relates to changes in shoreline trajectories on the shelf [33].

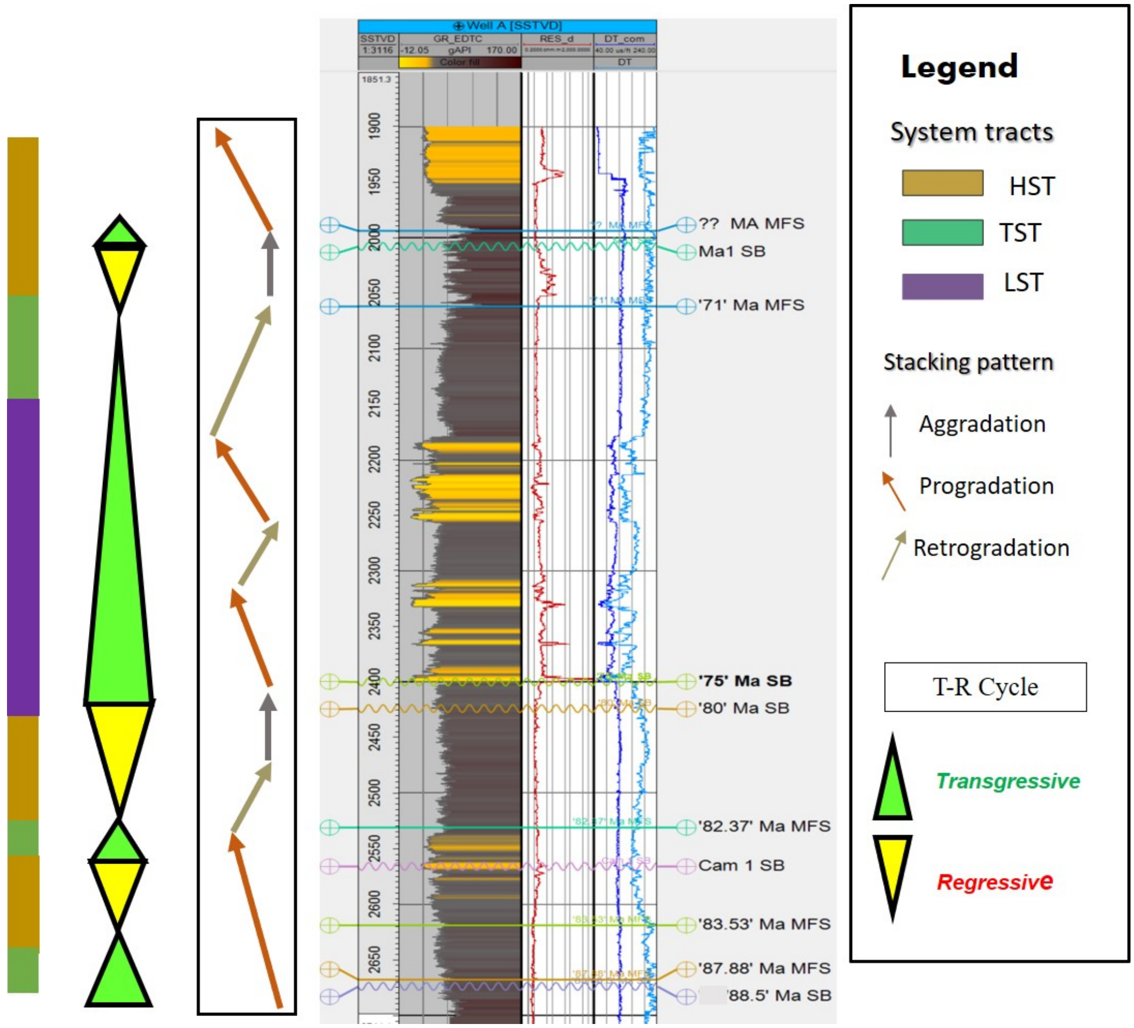

Fig. 3. Well A Sequence stratigraphy showing the stacking pattern, systems tracts and the Transgressive and Regressive (T-R) cycle

The stacking pattern drawn on Well A represents an alternate period of progradation (coarsening upward) and retrogradation (fining upward) with minor aggradation. The Upper reservoir unit on the log showed more of progradation stacking character with a short period of retrogradation in between while the Lower reservoir unit appeared progradational but with some evidence of a short period of retrogradation, generally having the appearing as multi-story upward finning stacking pattern.

According to Baum and Vail [34], sediments successions would be put into a sequence stratigraphic framework only when the key stratigraphic surfaces have been identified. In Well A, five (5) SBs and four (4) MFSs were the prominent stratigraphic surfaces picked from the biostratigraphic data. These surfaces assisted in the sequence model division of the candidate well. Using the Genetic sequence [35] and based on the MFSs, three complete and distinct genetic sequences were recognized;

i. Sequence one ('87.88' Ma MFS to '83.53' Ma MFS)
ii. Sequence two ('83.53' Ma MFS to '82.37' Ma MFS)
iii. Sequence three ('82.37' Ma MFS to '71' Ma MFS)

Also, four compete and distinct depositional sequences constrained by the SBs were also recognized i.e.

i. Depositional sequence one ('85/88.5' Ma SB to Cam 1 SB)
ii. Depositional sequence two (Cam 1 SB to '80' Ma SB)
iii. Depositional sequence three ('80' Ma to '75' Ma)
iv. Depositional sequence four ('75' Ma to Ma1 SB)

4.2. Seismic stratigraphy

The analyses of stratal termination patterns on the seismic profile in the study area have assisted in the identification of seismic mega sequences (packages). According to Emery and Myers [36], these stratal terminations relate to relative sea-level fluctuations and a combination of eustatic sea-level change and tectonic subsidence allows an understanding of why sediment packages develop where they do on the seismic scale.

Seven mega sequences were recognized in the study area as bounded by possibly Maximum flooding surfaces, Sequence boundary or transgressive surfaces and incised valley fill (Fig. 4). This observation made was based on seismic reflections pattern and knowledge of the regional stratigraphy with sedimentation processes been inferred.

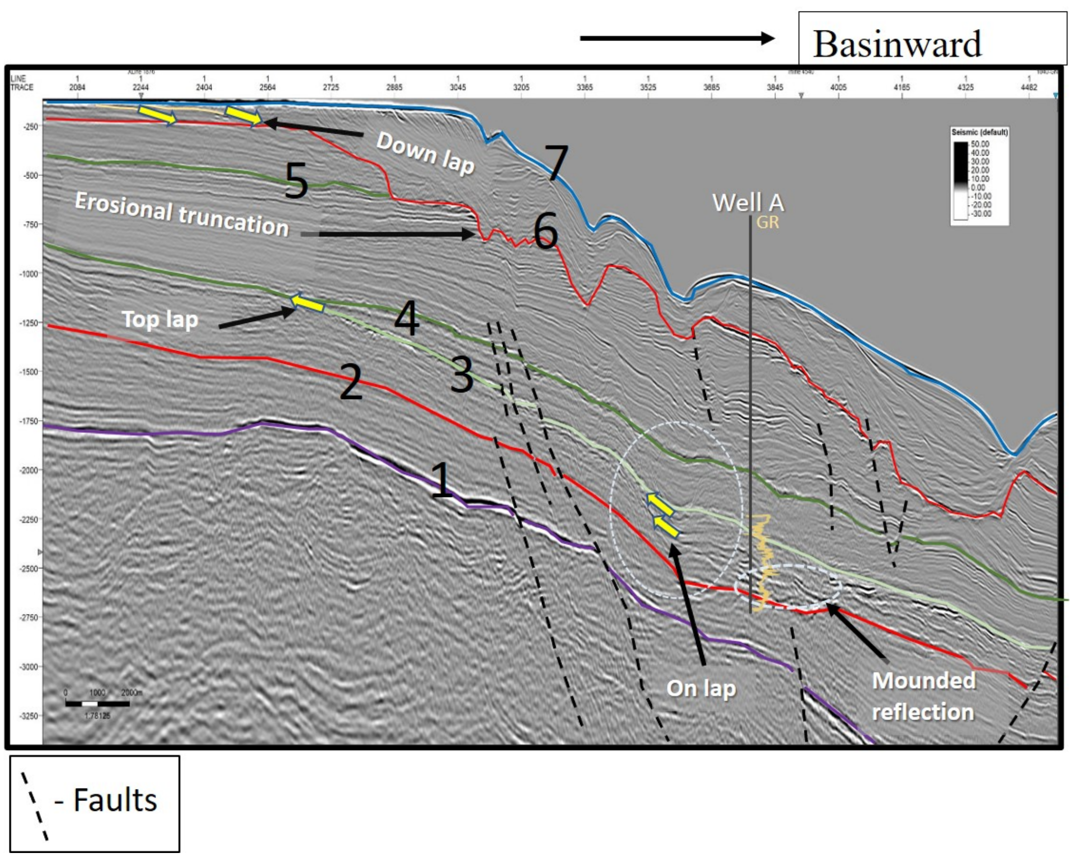

Fig. 4. Seismic stratigraphic framework showing the marked bounding seismic stratigraphic surfaces annotated in numeric figures and colours, some faults, reflection terminations such as top laps and onlaps in the study area and the position of Well A with the GR log response

Surface 1 is possibly the Albian unconformity, the oldest unconformity encountered in the study area. This surface appears as an arc and terminates basinward. It is marked by a strong bright contrast in seismic reflection amplitude in the study area. The Albian unconformity is a regional event in the Tano Basin that denotes a period of non-deposition during the Albian age [26]. A new sequence was built on surface 1 and it is characterised by parallel to sub-parallel seismic events which slopes gradually basinward and capped by surface 2.

In the study area, surface 2 appears as a sequence boundary reflector cutting into older reflector basinward and this created a depression in the vicinity of Well A. The sequence built on surface 2 shows a transgressive character confirmed by top lapping to surface 4. However, some 3 km in the vicinity of Well A towards basinward, the reflections appeared mounded which is diagnostic to confirm the presence of a channels or fan system. Mounded reflections on seismic could infer deposits formed by higher velocity turbidity currents which are characterized by their three-dimensional fan shape and internal reflection [37]. Also, the seismic events about 2km radius of Well A show onlapping low angle reflections terminating against a steeply dipping surface. A close examination of the onlap termination gives a strong indication of subaerial paleo shelf exposure to allow the subsequent on lap events on the slope. Thus, the paleo slope position must have been close to the area of Well A.

Subsequently, the sequence built on surface 3 appear as nearly parallel seismic events were capped by surface 4. The surface 4 is the Base Tertiary surface, an unconformity surface appearing as a strong and bright continuous event basinward. It is important to note that the Base Tertiary is a regional marker that differentiate the Cretaceous systems from the Cenozoic systems in the Tano Basin [26]. An entirely different sequence was built on surface 4 and capped by surface 5 as conformable parallel to sub-parallel seismic reflections in the proximal area away from the basinward direction. This could mean shelf environments, commonly characterized by general parallelism of seismic reflections [37].

Thereafter a distinct sequence then followed on surface 5. However, a new surface 6 emerged as cutting across into older seismic reflectors showing some erosional truncation features. Based on the knowledge of the regional stratigraphy of the Tano Basin, surface 6 is the regional Miocene-Oligocene Unconformity. The surface (Miocene-Oligocene Unconformity) is associated with a system of numerous erosional features which is related to the development of the unconformity. A look at Haq *et al.,* [29] chart shows that the Miocene and Oligocene epoch was marked with frequent rise and fall in sea level (base level). This reoccurring base-level rise and fall could have led to this system of repeated erosional features expressed as unconformity surface. Other propositions have expressed that the Miocene-Oligocene Unconformity is associated with some regional Pan African uplift event in the Tano Basin. However, the validity of this uplift hypothesis has not been supported scientifically.

Laying on surface 6 are seismic events appearing as a highstand prograding lobes which shows down lap termination. Thus, the incisions created by the Miocene-Oligocene Unconformity surface was subsequently filled and capped by surface 7. Surface 7 is the sea bed which represents the current sedimentation.

4.3. Prospectivity assessment of the Campanian interval

To assess the prospectivity of the Campanian interval, it is important to first recognize and understand the depositional elements in the study area. Seismic attributes help to capture sensitive geological feature (e.g. channel system, splays and lobes) to allow the proper definition of some depositional elements [38-39]. The Root Mean Square (RMS) attribute extraction for the interpreted Campanian surfaces showed the possible reservoir sand distribution in the study area (Fig. 5). The RMS is a seismic attribute that shows the strength of amplitude over a given volume interval, and high-amplitude anomalies are indicative of probable sands (potential reservoirs) while the low amplitude anomalies correspond to mud or shale sediments [40-41]. According to Tyler [42], the higher the contrast in acoustic impedance, the higher the RMS values and thus the indication of possible reservoir. Fig. 5 reveals a conspicuous trend of the possible sand fairway appearing as a large fan system from the northeast to the south-west direction. The occurrence of the large fan system suggests that some favourable conditions such as base-level fall, significant clastic inputs from continental sources or shelf exposure to facilitate erosion may have, existed in the Campanian period. However, in the far north-west corner, a localized possible sands deposits appearing as a frontal splay were observed. The frontal splay occurred as a nucleated patchy deposit which showed some lateral relation down south. The frontal splay is associated with flaring out of sands, mostly controlled minimal sand loss as sediments flow due to high density in a preformed channel system [43].

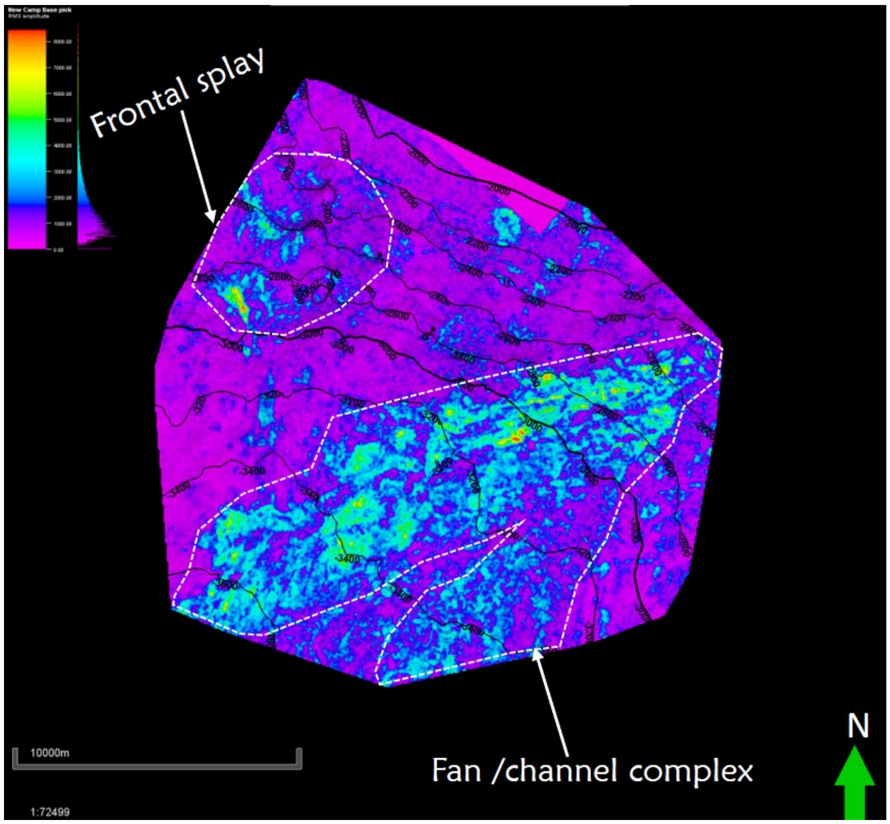

Fig. 5. RMS surface attribute map of the Campanian displaying the channel complex and a frontal splay in the study area.

Spectral decomposition application provided additional useful information about the architecture of the submarine fans/ channel complexes. This method facilitated a better understanding of the individual depositional elements to the channel complexes which the RMS amplitude map could not resolve. The spectral decomposition map was generated by blending the frequencies derived from the RMS amplitude map. The spectral decomposition stratal slices show sinuous channel, channel fill, feeder channels and depositional lobes (Fig. 6-7). The channels appear with a low degree of sinuosity and trends in the northeast to the south direction which conforms to the trend of the fan complex. The recognised feeder channel is isolated and located at the southwestern portion of the study area (Fig. 6). The feeder channel trends down south. This southward trend is characterised by a sharp anomalous frequency contrast and resembles an ancient hourglass that funnels sediments delivery down south.

The depositional lobe (Fig. 7) observed in the study area is seen as a very strong contrast in frequency anomaly and located to the south western corner of the study area. It appears localised and pitch-out in the northwards direction. According to Posamentier and Walker [44], lobe element or frontal splay are depositional elements that are formed at the terminal end of the channel. The location of lobes are often basinward of a submarine channel and are composed of sediments that are eroded and transmitted through the channel. The erosion associated with lobes could improve reservoir quality through sorting.

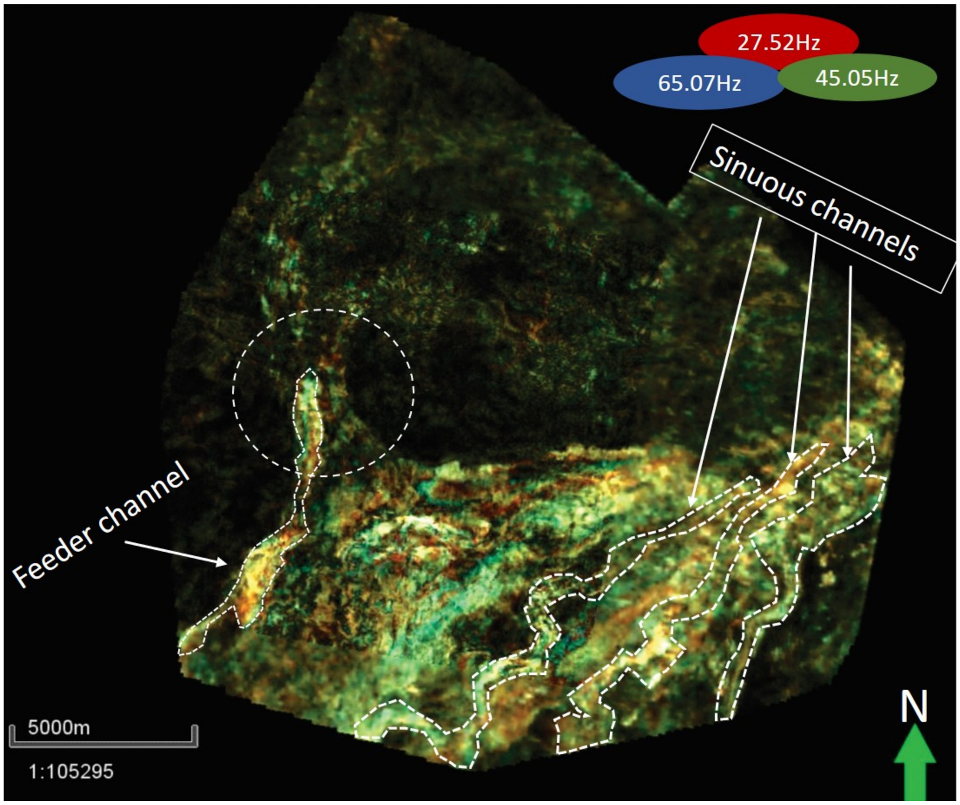

Fig. 6. Colour blended (RGB) spectral decomposition map (at 27.52, 45.05 and 65.07Hz) showing the sinuous channel and crevasse splay within the Campanian

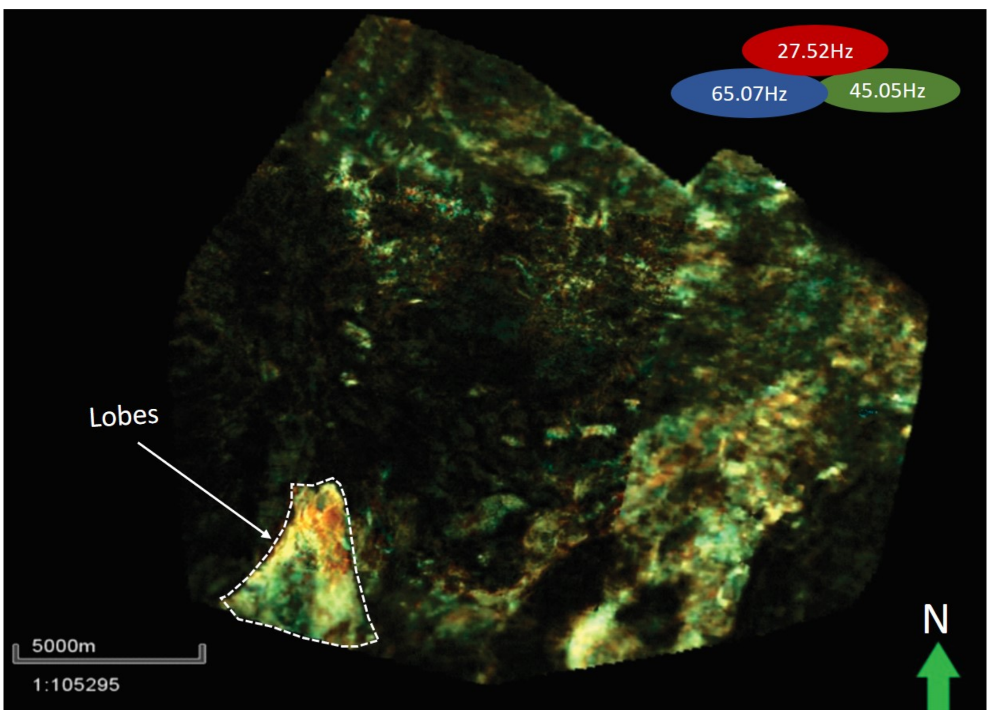

Fig. 7. Colour blended (RGB) spectral decomposition map (at 27.52, 45.05 and 65.07Hz) showing the depositional lobe in the Campanian

The depositional elements recognized (channel, lobes and fan system) indicate the presence of possible reservoir sands with a fair spread in the study area. The Campanian interval in the study area is generally structureless. The possible trapping system is more likely to be a stratigraphic trap. However, the possibility of fault assisted traps cannot be eliminated because some faults were observed in the study area though with minor trends and localized with less penetration in the Campanian interval. The seal potential is more of intraformational shales (as evident on the well log section).

5. Conclusion

An assessment of the prospectivity of the Campanian section in the West Tano Basin has been carried out using 3D seismic, well logs and biostratigraphic data. The study showed depositional elements as submarine fans systems bearing reservoir sands deposited in the lower and middle bathyal paleodepth. The fan system was deposited as lowstand systems tracts based on the significant recovery of *Palaeocystodinium species* and high incidences of freshwater algae *Pediastrum* spp. The presence of these microfossils is an indication of freshwater run off into the fan system. The seismic reflection terminations within the Campanian interval further corroborates a slope fans deposit in a lowstand system. The sequence boundary (SB), Transgressive surfaces (TS) and Maximum flooding surfaces (MFS) were the main stratigraphic surfaces that bounded the system tracts both on seismic and well scale. Seismic stratigraphy revealed seven (7) mega sequences in response to the transgression and regression cycle of the Tano Basin. However, the Campanian system is straddled in the third (3) mega sequence. Also, the sequence model division of well A shows three genetic sequences and four depositional sequences.

The RMS attribute revealed that the Campanian interval is characterized by a fan system. The large fan system dominantly trends in the northeast to south-west direction. In addition, spectral decomposition analysis further resolved the architecture of the depositional elements of the fan system as channel system (sinuous channel, channel fill, feeder channel), frontal splay and depositional lobes. No major structural traps were mapped within the interval of focus. Stratigraphic traps are, however, dominant and should be the main target during future exploration campaigns.

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