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Palynofacies and source rock potential of the ST-7H well, offshore Tano basin, Western Region, Ghana

D. Atta-Peters*, C. A. Achaegakwo, D. Kwayisi, P. Garrey

Department of Earth Science, University of Ghana, P. O. Box LG 58, Legon, Accra, Ghana

Email address:
dattapeters@gmail.com (D. Atta-Peters), chrisach007@yahoo.com (C. Achaegakwo), dkwayisi@gmail.com (D. Kwayisi), pgarrey@yahoo.com (P. Garrey)

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Abstract: Samples from ST-7H well offshore Tano basin in western region of Ghana have been subjected to palynofacies, palynological and geochemical analysis. Five palynofacies associations (I – V) have been identified based on the percentage relative abundances of the sedimentary organic matter (SOM). Palynofacies type I and type IV reflects deposition in a distal dysoxic-anoxic shelf (nearshore) environment, palynofacies type II suggest distal dysoxic to anoxic shelf to deep basin environment with abundant AOM, palynofacies type III is indicative of distal dysoxic to oxic shelf (fluvio-deltaic) environment of deposition and palynofacies type V, a mud –dominated oxic distal shelf (open marine) environment. Based on marker palynomorphs, an Aptian to Maastrichtian age, have been assigned to the sediments in the ST 7H well, with an unconformity between the Cenomanian and Campanian sediments. Geochemical data indicate that the samples from ST 7H well have fair to very good petroleum potential. Most of the samples, however, fall out of the hydrocarbon generating zone because of the low (< 0.10) Production Index (PI). Kerogen types show type II, II/III and III which are oil prone, oil-gas prone and gas prone respectively. Thermal maturity from within the well indicates immature to early mature hydrocarbons.

Keywords: Kerogen, Palynofacies, Palynology, Organic Geochemistry, Hydrocarbon, Tano Basin

1. Introduction

The Tano Basin is situated close to Ghana's western border with Ivory Coast and is the eastern extension of much larger Ivory Coast Basin. It is developed between the Coastal Fault System, St Paul's and Romanche Fracture Zones. The Tano Basin occupies an area of at least 3000 km^2, with the onshore component estimated at about 1165 km^2 [1]. The Tano structure is located approximately 39 km from the Ghana coast in the Gulf of Guinea and approximately 24 km east of the Ghana-Ivory Coast border, with a water depth in the area ranging from 91 m to 125 m.

The Tano Basin began its tectonic-sedimentary life as an extensional rift basin modified by wrench tectonism. This rifting was initiated by complex movements due to the separation of the continents of South America and Africa. This was most likely initiated in the Barremian and Aptian times. It is thought that movement along a series of transform faults including faults in the Romanche Fault Zone during this continental separation led to the development of the large rift basin in the Tano area [2]. As a result of these movements, by Aptian - early Albian time, a large rift basin had developed in the Tano Basin area. This was followed in middle - late Albian times by widespread deposition of shallow marine sandstones and shales with minor limestone in the area. General evidence suggests that final separation on the continents took place in latest Albian [2]. It is speculated that, a thermal anomaly with subsequent uplift occurred at the margin of the newly created African and Brazilian continental plates in the Tano area. This uplift occurred in late Albian time and may be the plate tectonic model for the development of the Tano structural trend.

The aim of the present study is to use palynomorph assemblages to determine the geological age of sediments from the well, to integrate it with palynofacies to interpret environment of deposition and to examine the hydrocarbon potential of the sediments using geochemical data.

2. Materials and Methods

Sixty four (64) samples from ditch cutting samples from ST-7H well (Fig. 1) obtained from the GNPC Core Laboratory were analyzed for study using standard palynological processing techniques. Each sample was digested using hydrochloric (35-38%) and hydrofluoric (40%) acids to remove carbonates, silicates and fluorides from the sediments. The residue after centrifuging in Zn Br_2 was mounted on slides for light microscopy and microphotography.

The Automatic Point Scan was used to count a total of 350 particulate organic matter and palynomorphs to determine their relative abundance in percentages at each depth (Appendix 1) (Fig. 2). To identify the divisions of the studied succession in the well using palynofacies, cluster analysis (Q-mode) was performed using SPSS software and IrfanView to generate a dendogram based on the discrete grouping characteristics (relative percentages) of the objects (Fig 3).

Data for organic carbon and Rock – Eval pyrolysis was also obtained from Ghana National Petroleum Corporation (GNPC) (Appendix3) and this was used to determine the maturity and type of organic matter in the sediments and their hydrocarbon potential.

About 100 mg of each sample was analyzed by using Rock Eval II instrument. The output from this sensor provides the peak data for the S_1 and S_2 indices. At low temperatures kept isothermally at 300 º C for 4 minutes the free hydrocarbons in the sample were volatilized and S_1 measured with a Flame Ionization Detector (FID). At increasing temperatures by programmed pyrolysis in an inert helium atmosphere at 25 ºC/min to 600ºC, hydrocarbons are expelled from the kerogen itself by cracking. This peak was measured as the S_2. The temperature at which the maximum generation of cracked hydrocarbons occurred at S_2 peak is termed Tmax. Tmax is a maturation parameter that is kerogen-dependent. The S_3 peak which is a result of CO_2 produced from the kerogen cracking and trapped between 300-390 ºC, was detected with a thermal conductivity detector (TCD).

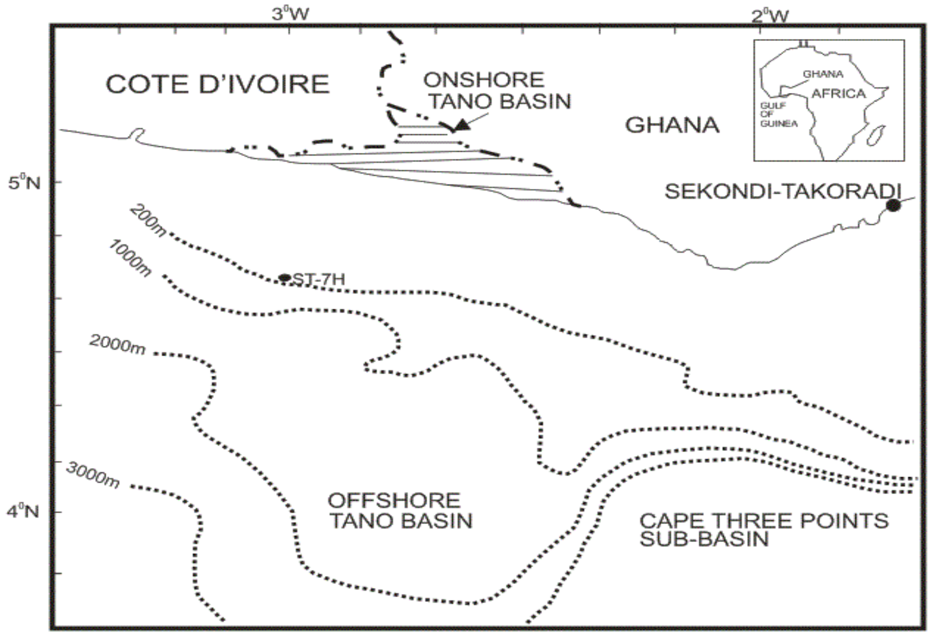


Fig 1. *Map showing ST-7H well in the offshore south Tano Basin {modified after [3]}.*

3. Results

3.1. Palynofacies Analysis

The concept of palynofacies was first introduced by [4] to describe acid-resistant organic matter in sediments. Various authors have demonstrated its usefulness in palaeoenvironmental and depositional interpretation. {[5], [6], [7], [8], [9]}.

The palynofacies classification terms used here follows [10]: amorphous organic matter (AOM), phytoclasts, opaque phytoclasts (black debris) and palynomorphs (spore and pollen, dinoflagellates).

- Palynomorphs include all spores, pollen, dinocysts, acritarchs, chitinozoans, microforaminiferal lining, prasinophytes, and marine algae.
- Phytoclasts include structured terrestrial plant fragments such as cuticles, wood tracheid and cortex tissue;
- Opaques (black debris) comprises oxidized or carbonized brownish black to black coloured woody tissues including charcoal;
- AOM includes all particulate organic components that appear structureless at the scale of light microscopy, including bacterially-derived AOM, resinous and amorphous products of the diagenesis of macrophyte tissues.

3.1.1. Palynofacies Types

Cluster analysis based on the percentage and composition of kerogen elements revealed two superclusters A and B (Fig 3). Supercluster A is subdivided into four subclusters (A1, A2, A3 and A4) (Fig 3; Table 1). The AOM group dominates supercluster A and it is concentrated in the deeper sections of the well with the palynomorph group dominating supercluster B in the shallower sections of the well (Fig. 2)

3.1.2. Palynofacies Type I (P-I). Dominance of AOM and Palynomorphs (Plate III; A, B)

This palynofacies type is found in sample depths 5410ft, 5490ft, 5130ft, 5590ft, 8660ft, 8580ft, 8920ft, 8120ft, 5230ft, 7100ft, 8380ft, 8840ft, 8480ft, 8740ft, 8220 ft and 8300ft. It is characterized by AOM with relative abundance of 49% of total kerogen, palynomorphs 33% with opaques and phytoclasts having low relative abundance of 11% and 7% respectively (Table 2). The palynomorph group is dominated mainly by terrestrial palynomorphs contributing up to about 28% of the palynomorph group.

3.1.3. Palynofacies Type II (P-II).AOM Dominant with Palynomorphs (Plate III; C, D)

Palynofacies type II occurs at sample depths 6310ft, 5050ft, 6130ft, 5850ft, 6030ft, 5770ft, 6210ft, 5690ft, 9000ft, 6760ft, 6920ft, 6680ft, 6730ft, 6510ft, 6550ft and 6700ft. It is characterized by abundant AOM with few palynomorphs, opaques and phytoclasts. Relative abundance of AOM, palynomorphs, opaques and phytoclast are 67%, 16%, 13% and 4% respectively (Table 2). The palynomorph group is dominated by terrestrial palynomorphs with little to no marine palynomorphs.

3.1.4. Palynofacies Type III (P-III). Equal Amounts of AOM and Palynomorphs with Opaques (Plate III; E, F)

Palynofacies type III is represented at sample depths 7150ft, 7940ft, 7180ft, 7340ft, 7400ft, 7580ft, 6610ft and 4580ft. Relative abundance of AOM, palynomorphs, opaques and phytoclasts are 36%, 35%, 20% and 9% respectively (Table 2). Palynofacies type III has the highest record of opaques. The palynomorphs group has nearly equal contributions from terrestrial and marine palynomorphs (18.5% and 16.5% respectively).

3.1.5. Palynofacies Type IV (P- IV). AOM Dominant, Palynomorphs and Opaques (Plate IV; A, B)

Palynofacies type IV is found in sample depths 7020ft, 7760ft, 7240ft, 6800ft, 7860ft, 6830ft, 4850ft, 6410ft, 4770ft, 4950ft, 6470ft, 6900ft, 6970ft, 7160ft, 5050ft, 7680ft, 7400ft, 7260ft and 8020ft. High amount of AOM of relative abundance 51%, palynomorphs 26%, opaques 15% and phytoclasts 8% occurs in this type (Table 2). The palynomorph group is dominated by terrestrial palynomorphs with little marine palynomorphs.

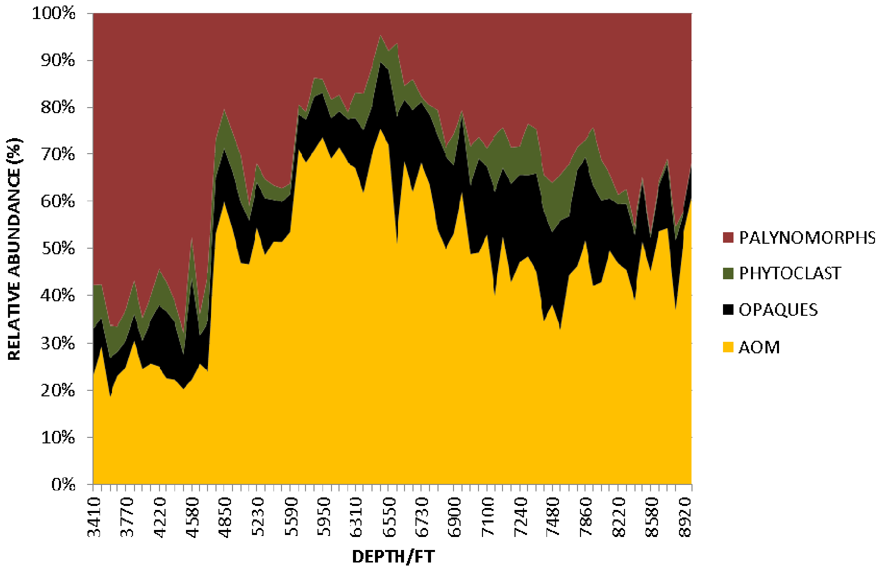


Fig. 2. *Percentage relative abundances of palynomorphs, phytoclasts, opaques and AOM.*

3.1.6. Palynofacies Type V (P-V). Dominant Palynomorphs with AOM and Few opaques (Plate IV; C, D)

This type of palynofacies is represented in sample depths 3500ft, 3860ft, 3680ft, 3950ft, 4640ft, 3770ft, 4490ft, 3590ft, 3410ft, 4730ft, 4220ft, 4310ft, 4130ft and 4400ft. It is characterized by abundant palynomorphs of relative abundance 62%, AOM 19% and few amounts of opaques and phytoclasts with almost equal relative abundances of 9% and 10% respectively (Table 2). The palynomorph group is dominated by marine palynomorphs which contributes about 48% of the palynomorph group.

Table 1. *Palynofacies associations identified after cluster analysis.*

Palynofacies type	Description	Cluster	Supercluster
P-I	Dominance of AOM and palynomorphs with few phytoclasts	A1	
P-II	Dominance of AOM with palynomorphs	A2	A
P-III	Equal dominance of AOM and palynomorphs with opaques	A3	
P-IV	Dominance of AOM with palynomorphs and opaques	A4	
P-V	Dominance of palynomorphs with AOM and few opaques	B	B

Table 2. *Clusters, palynofacies types and percentages relative abundance of total kerogen.*

Clusters	Palynofacies types	AOM	Opaques	Phytoclasts	Palynomorphs
A1	P(I)	49	11	7	33
A2	P(II)	67	13	4	16
A3	P(III)	36	20	9	35
A4	P(IV)	51	15	8	26
B	P(V)	19	9	10	62

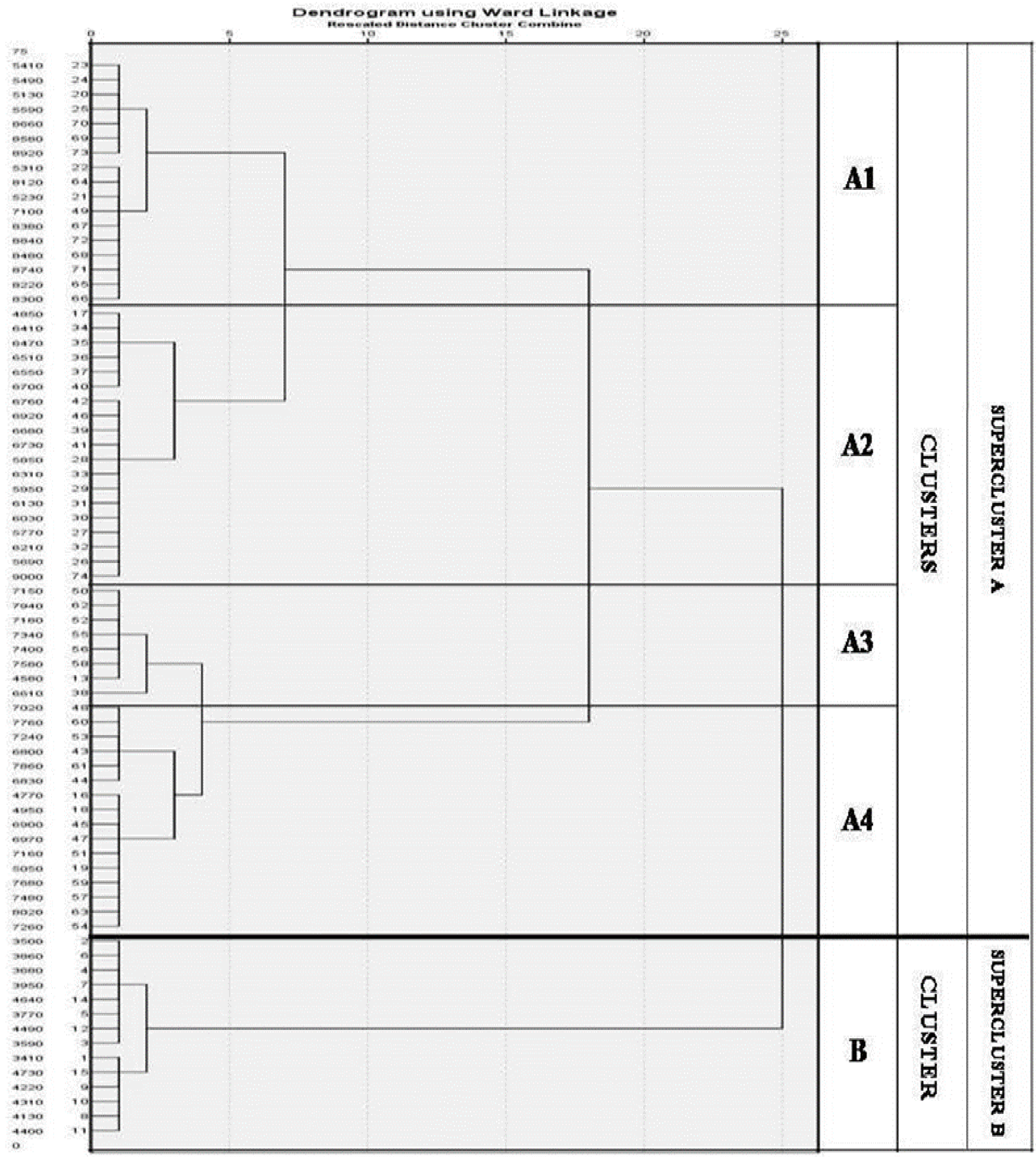


Fig. 3. *Dendrogram (Q-mode) of ST-7H well shows the grouping of samples.*

4. Discussion

4.1. Palynofacies and Palaeoenvironmental Analysis

Palynological and palynofacies data retrieved from ST-7H well indicate that the samples plot within the fields V, VII, VIII and IX on the AOM - phytoclasts - palynomorphs (APP) ternary diagram (Fig. 4), representing suboxic- oxic shelf to distal shelf, distal dysoxic-anoxic shelf, distal dysoxic-oxic shelf, and distal suboxic-anoxic deep basin with abundant AOM respectively [10]

Palynofacies type I (P-I) and palynofacies type IV (P-IV) plots in field VII of Tysons APP ternary diagram which indicates deposition in a distal dysoxic-anoxic shelf condition. It is characterized by moderate to good AOM preservation, moderate abundance of palynomorphs. The palynomorph group of P-I and P-IV are dominated by terrestrial palynomorphs with little to no marine palynomorphs. [11], [12], [13], have intimated that the large amounts of AOM may be the result from a combination of high preservation rate and low energy reducing depositional environment. According to [10], [12], [14], [15], the preservation of AOM is related to dysoxic or anoxic conditions and can be, but not necessarily correlated with high primary productivity. [16] interpreted their Unit A-24 (415-383 m) based on palynofacies elements which is comparable to palynofacies P-I and P-IV of the present study as transitional (brackish lagoonal).

Palynofacies type 1 (P-1) of [17] from samples of the Neuquen Basin, Argentina is comparable to P-I and P-IV of this study. This palynofacies type is suggestive of a proximal marine environment with moderate oxidizing conditions and energy. This assemblage is comparable to Palynofacies type 5 of [18], who suggested a deltaic environment.

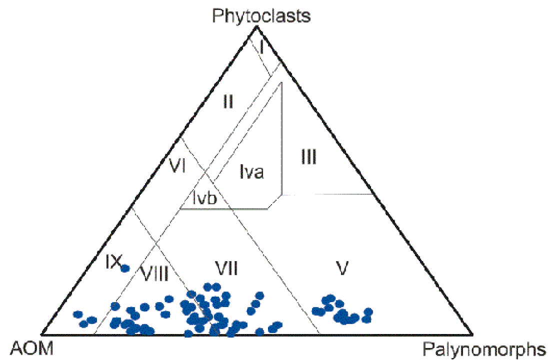
Palynofacies type II plots in the field IX representing a distal suboxic-anoxic deep basin which is dominated by AOM assemblages with low occurrence of palynomorphs. In oxygen-deficient basins, with high AOM preservation, allochtonous terrestrial material is dominant in the immediate vicinity of fluvio-deltaic sources or within turbidites [12], [19]. [20] reported similar palynofacies association (PF-1) from the well 16/U-1 onshore basin in eastern Yemen, and interpreted an open marine environment with the presence of the terrestrial palynomorphs indicating input from a river or transport from a nearshore environment. The palynomorphs present are mostly terrestrial palynomorphs (spores and pollen grains) with little to no marine palynomorphs.

[13] recorded high AOM (58-72%) and common palynomorphs (10 – 30%) in their Palynofacies IV, comparable to that of the present study. They contended that high AOM in organic rich sediments suggests reducing conditions and increased water column stability, resulting in dysoxic or anoxic bottom conditions. [21] reported a similar palynofacies association (PF-2) from the Jurassic basal Cretaceous Sulaiy formation, southern Iraq, and suggested a distal suboxic –anoxic basin environment for the assemblage.

Palynofacies type III (P-III) plots in the VIII field which reflects distal dysoxic-oxic shelf and has the highest percentage relative abundance of opaques (about 20%) in the well, with almost equal percentage abundances (35%) of AOM and palynomorphs and little phytoclasts. Relatively high percentages of terrestrial palynomorphs indicate varied and abundant vegetation associated with shoreline. [19] suggested that the high values of opaques indicate oxidizing conditions and proximity to terrestrial sources or re-deposition of organic matter from fluvio-deltaic environment of deposition. The presence of relatively equal amount of AOM and palynomorphs (predominantly spores/pollen) is suggestive of a nearshore environment of deposition [18]

Palynofacies type V (P-V) plots in the field V and is indicative of a mud-dominated oxic shelf (distal shelf) and is composed of low to moderate phytoclasts and AOM. The palynomorph group is dominated by diverse marine palynomorphs (dinocysts) which contributes about 48% out of the total of 62% (Table 2). [15] inferred that their palynofacies characteristics of PF-3 and 4 with low numbers of small spores and pollen grains and much greater percentages of dinoflagellate cysts (gonyaulacoids) was an offshore environment, which is comparable with palynofacies type V (P-V).The Palynofacies Association B of [22] has a lot in common with P-V of the study. They are both characterized by high number and diversity of dinocysts (gonyaulacoids) and other terrestrial materials which reflect a neritic or open marine environment. According to [22], depending on the type of microplankton, more specifically, gonyaulacoid dinocysts, and the ratio of sporomorphs to phytoplankton reflects the proximal-distal trends. In the palynofacies type V (P-V), the microplankton (dinocysts) (Appendix 2) dominates the palynomorphs and may be indicative of a distal shelf.

[23] examined samples from Western Southland, New Zealand and suggested an inner-shelf environment of deposition to samples characterized by high proportion of mostly well preserved dinoflagellates and a low abundance of land-derived palynomorphs. [18] examined samples from northeastern Tierra del Fuego, Argentina and suggested that their palynofacies type 6 with relative abundance (56-93%) and high diversity of marine organic-walled phytoplankton (gonyaulacoid) as having open marine neritic to outer neritic conditions of environment of deposition.



Palynofacies fields	Environment of deposition
I	Highly proximal shelf or basin
II	Marginal dysoxic-anoxic basin
III	Heterolithicoxic shelf ('proximal shelf')
IV	Shelf to basin transition
V	Mud-dominated oxic shelf ('distal shelf')
VI	Proximal suboxic-anoxic shelf
VII	Distal dysoxic-anoxic 'shelf'
VIII	Distal dysoxic-oxic shelf
IX	Distal suboxic-anoxic basin

Fig. 4. *APP ternary palynofacies diagram used for palaeoenvironmental interpretation [10].*

5. Palynology and Age Assessment

5.1. Campanian- Maastrchtian Age

The terrestrial palynomorphs within the interval (3410-5590ft) include *Proteacidites dehanni, Echitriporites trianguliformis, Deltoidspora minor, Spinizonocolpites* spp. *Longapertites* spp, *Proxapertites* spp. These forms have been reported extensively in Campanian-Maastrichtian sediments {[24], [25], [26], [27], [28], [29], [30], [31]}. Some selected marine palynomorphs found in the interval which support this age include, *Senegalinium bicavatum, Cerodinium* spp, *Phelodium magnificum, Spiniferites* spp, *Cordosphaeridium* spp, *Areoligera* spp, *Palaeocystodium australinum*, and *Andalusiella* spp. These species have been reported extensively in Campanian - Maastrichtian sediments in tropical/subtropical regions {[32], [33], [34], [35], [36]}.

Typical Turonian – Santonian pollen species are absent in the section. Notably among them are *Droseridites senonicus, Cretacaeisporites* spp, *Zlivisporis blanensis, Hexaporotricolpites* spp. Their absence suggests an unconformity between sample depths 5690ft to 6760ft.

5.2. Albian- Cenomanian Age

The interval between 6900ft-8550ft is characterized by the elaterate pollen, *Elaterosporites* spp, *Elaterocolpites* spp, *Galaecornea* spp, and also *Ephedripites* spp, *Classopollis classoides, Reyea polymorphus, Afropollis jardinus*, and *Cicatricosisporites* spp. The elaterate pollen are reported to be restricted to the Albian – Cenomanian Elaterate Province in Africa – South America (ASA) region. These species have been reported from Albian - Cenomanian sediments by [28], [37], [38], [39], [40], [41], [42], [43].

5.3. Aptian Age

The age occurs in sample interval, 8660ft-9000ft. The interval is characterized by absence of elaterate pollen, and the occurrence of *Afropollis jardinus, Deltoidspora* sp, *Reyea polymorphus, Ephedripites* sp, *Cicatricosisporites, Perotriletes pannaceus, Cyathidites* spp.

A. jardinus has been reported on the world record as a stratigraphic marker for the early Aptian age for regions in equatorial Africa [44]. Elater pollen first appears in the stratigraphic sequence during the early Albian – middle Albian sediments {[28], [39], [40], [41], [45], [38]}. The absence of any elater–bearing pollen which is a stratigraphically important element of the Albian – Cenomanian, delimits the age of the interval to pre-Albian and suggests an Aptian age. Dinocysts common here are *Subtilisphaera* sp, *Oligospaeridium complex*.

6. Source Rock Evaluation

Conditions necessary for hydrocarbon formation is the presence of a reducing environment in a subsiding basin where POM in sediments are subjected to enough time and temperature for thermal maturation [46]. In geochemical analysis the first step in hydrocarbon investigation is the measurement of total organic carbon (TOC %) content of the potential source rock. Other important parameters obtained from Rock-Eval pyrolysis are S_1, free hydrocarbon; S_2, pyrolyzed hydrocarbon resulting from the cracking of kerogen; S_3, quantity of CO_2, and Tmax, the temperature at which the maximum generation of hydrocarbon (S_2) is observed and measures the thermal maturation [46]. These parameters are used to calculate the following:

OI, oxygen index [OI = (S_3/TOC) x 100)] which is related to the amount of O_2 in the kerogen [47]; HI, hydrogen index [HI = (S_2/TOC) x 100] which indicates the potential of kerogen in a rock to generate petroleum; PI, production index [PI = S_1 / (S_1 + S_2)] indicating the level of thermal maturation and also the presence of migrated hydrocarbons; Hydrogen richness in the kerogen = S_2/S_3 which indicates the potential of the rock to generate hydrocarbon and Genetic Potential of the source rock = S_1 + S_2 which indicates the total amount of petroleum that might be generated from a rock.

6.1. Organic Carbon Richness and Hydrocarbon Potentiality

For a rock to be a source of hydrocarbon it must contain sufficient organic matter for generation and expulsion [14]. Carbonate and shale rocks are viewed as source rocks if TOC is in excess of 0.3 and 0.5 % respectively [50], [53].

[47], however, put the minimum organic content of a source rock to be between 1-2%, while [14], [46], [53] put it at 0.5%. Sediments from ST-7H well have generally TOC (% of rock) ranging from 0.51-3.45 % with an average of 1.4% which is above the minimum and are thus of good potential (Table 3).

Table 3. *Guidelines for interpreting source rock quantity, quality and maturation, and commonly used Rock-Eval parameters. {[47], [48], [49], [50], [51], [52]}.*

Quantity	**TOC**	**S_1(mg HC/g rock)**	**S_2(mg HC/g rock)**
Poor	<0.5	<0.5	<2.5
Fair	0.5-1	0.5-1	2.5-5.0
Good	1-2	1-2	5-10
Very Good	2-4	2-4	10-20
Excellent	>4	>4	>20
Quality	HI (mg HC/g TOC)	S2/S3	Kerogen Type
None	<50	<1	IV
Gas	50-200	1-5	III
Gas and Oil	200-300	5-10	II/III
Oil	300-600	10-15	II
Oil	>600	>15	I
Maturation	Ro (%)	Tmax (^{0}C)	TAI
Immature	0.2-0.6	<435	1.5-2.6
Early Mature	0.6-0.65	435-445	2.6-2.6
Peak Mature	0.65-0.9	445-450	2.7-2.9
Late Mature	0.9-1.35	450-470	2.9-3.3
Post Mature	>1.35	>470	>3.3

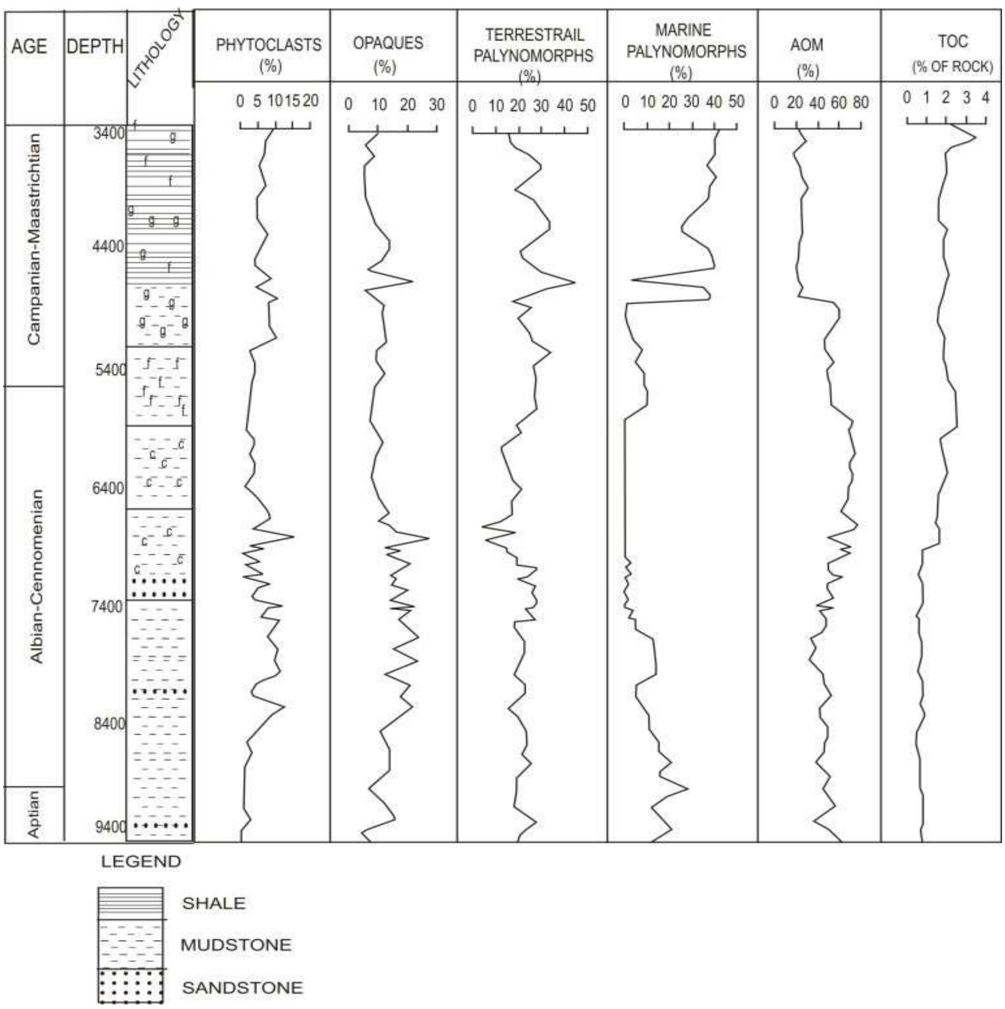


Fig. 5. *Distribution of relative abundances of sedimentary organic matter (SOM), palynomorphs and total organic carbon (TOC) against depth for ST-7H well.*

The highest recorded TOC value (1.34-3.45%) occurred within the interval [(3140-230 ft.) – (6570-650ft)] (Fig. 5), (Appendix 3) with rich AOM indicating a superabundance of organic matter preserved under adequately reducing conditions. This observation is in agreement with [10], [16] [19] who indicated that the percentage values obtained for TOC correlated well with variations in AOM abundance. 54% of the samples have TOC values of more than 1% needed to estimate the hydrocarbon potential of ST-7H well. Most of the samples studied have 'fair' to 'very good' petroleum potential on plots of Rock-Eval S_2 versus TOC (Fig 6a). According to [47], S_2 measures the existing potential of a rock to generate hydrocarbon, and thus is regarded as a more practical measure of source rock potential than TOC. This is because TOC takes into account inert or dead carbon that is not able to produce hydrocarbons. Therefore data from ST-7H well with S_2 values (0.61– 7.83; average of 2.97) is a fair potential source rock.

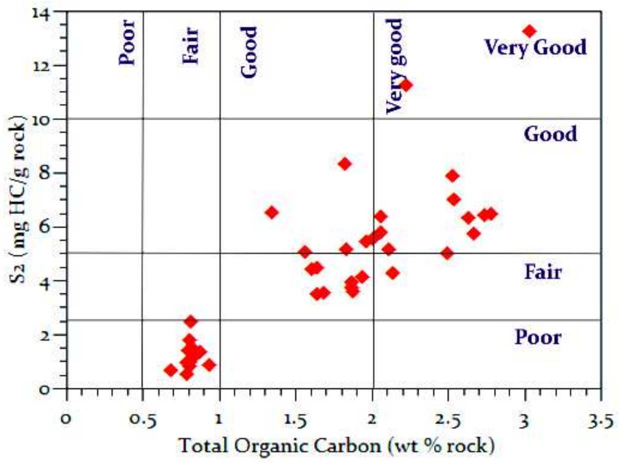


Fig. 6a. *Plot of S_2 versus TOC indicating hydrocarbon potential and source rock efficiency.*

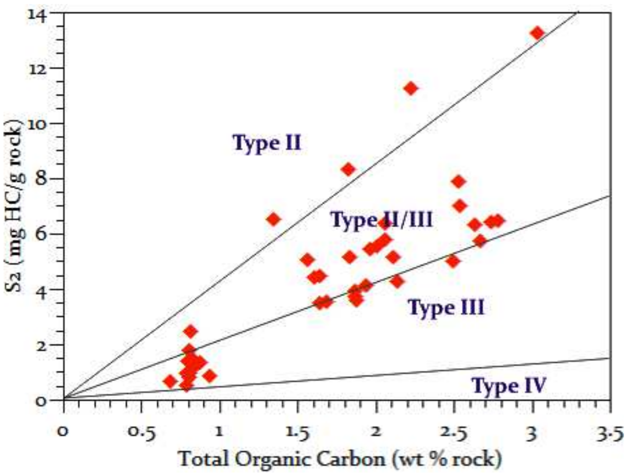


Fig. 6b. *Plot of S_2 versus TOC indicating kerogen type.*

The cross plot of S_2 versus TOC and determining the regression equation according to [54], is the best method for analyzing the true average HI and measuring the adsorption of hydrocarbon by the rock matrix. HI values from analyzed samples range from 64-504 mg HC/g TOC (ave. 234 mg HC/g TOC) indicating a kerogen of mixed type II, II/III and III [46] and yielding oil, oil/gas and gas respectively, but with II/III and III dominant (Fig. 6b).

6.2. Kerogen Type and Maturity

Organic geochemical method can be used to identify kerogen types. The type of organic matter is an important factor in evaluating source rock potential. It is very important to determine the kerogen types due to the variation of the chemical structure of organic matters and hydrocarbon products. Four types of kerogen (I, II, III and IV) are identified and values of elemental analysis of C, O and H plotted on the Van-Krevelen diagram [55] can define these kerogen types. Kerogen types can also be identified by plotting HI versus OI on a modified Van-Krevelen diagram [53], [56]. The kerogen designation is based entirely on HI [46], but the kerogen quality and maturity are determined by plotting HI versus Tmax rather than HI versus OI. This eliminates the use of OI as a kerogen type indicator (comparable to O/C in the Van-Krevelen diagram). Raw data plotting on the modified Van-Krevelen diagram (HI versus OI) (Fig. 7) indicate kerogen of mixed type II, II/III and III (oil, oil/gas and gas prone) respectively. The HI values ranging from 64-504 mg HC/g TOC (av. 234 mg HC/g TOC) also suggests mixed kerogen type II and III. 26% of the samples have HI of between 50-200, 51% (200 – 300) and 23% (300 – 600). This indicates mixed kerogen type II, II/III and III with the type II/III and III dominant (Fig. 7).

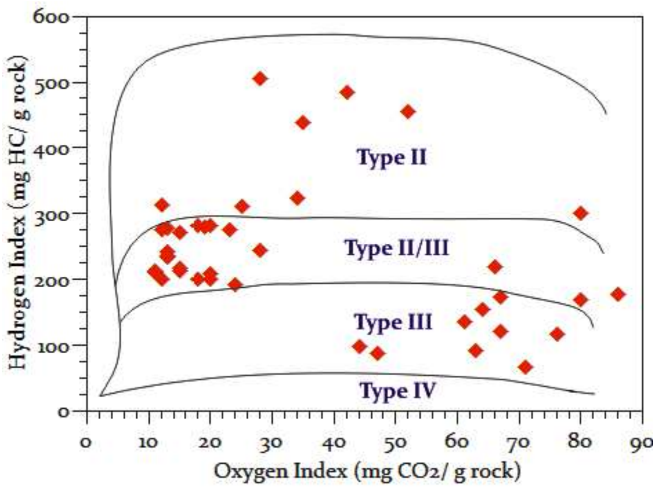


Fig. 7. *Plot of Hydrogen Index versus Oxygen Index for ST-7H well showing kerogen types II, II/III and III.*

Thermal maturity was evaluated from Rock-Eval Tmax. This is the maximum temperature (°C) reached at the greatest hydrocarbon production (S_2) when kerogen undergoes thermal cracking between 300 – 600 °C. It is used together with Thermal Alteration Index (TAI) and Vitrinite Reflectance (Ro) to evaluate thermal maturation [46], [57]. The Tmax values obtained for the samples range from 409 – 442°C (average 431°C), indicating immature to early mature kerogen. The thermal maturation of the organic matter was additionally deduced from the Tmax versus HI plot from Rock-Eval pyrolysis (Fig. 8).

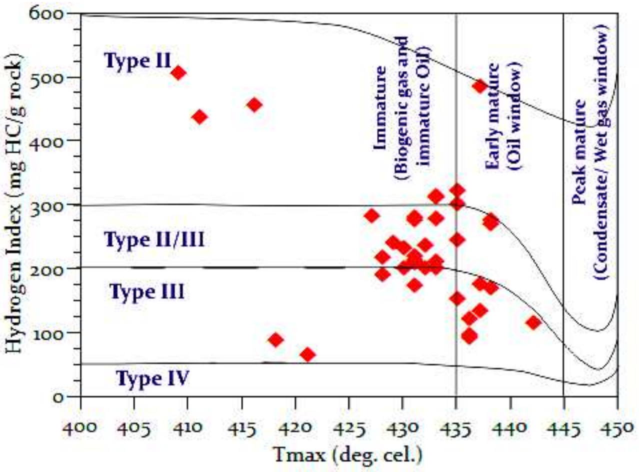


Fig. 8. *Plot of Hydrogen Index versus Tmax for ST-7H well indicating thermally immature and early mature kerogen.*

The relationship between Tmax and Production Index (PI), is a valuable method for indicating the thermal maturity of organic matter. The following relations between Tmax and PI are observed:

- Immature organic matter has Tmax and PI values less than 430°C and 0.10, respectively;
- Mature organic matter has a range of 0.1– 0.4 PI. At the top of oil window, Tmax and PI reach 460°C and 0.4, respectively;
- Mature organic matter within the wet gas-zone has PI values greater than 0.4; and
- Post-mature organic matter usually has a high PI value and may reach 1.0 by the end of the dry-gas zone [47], [50], [58].

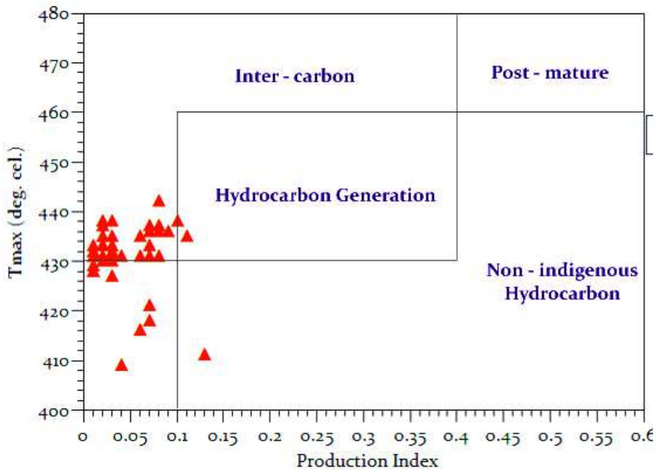


Fig. 9. *Plot of Tmax versus Production Index for ST-7H well showing that nearly all samples fall outside the hydrocarbon generating zone.*

[53] put the oil generation zone between Tmax temperature of 435°C - 460°C and between PI values 0.1 – 0.4. With the Tmax of the samples between 409 – 442°C (average 431°C) and PI values for most of the samples less than 0.1 (Fig. 9), (Appendix 3), it indicates that the in-situ generated hydrocarbons from the samples in the well are low. Most of the samples plot out of the hydrocarbon generation zone and are concentrated in the inert carbon zone (Fig. 9).

7. Conclusions

1. Five Palynofacies types have been identified in the ST-7H well based on sedimentary organic matter associations.
   - Palynofacies type I and type IV reflects deposition in a distal dysoxic-anoxic shelf (nearshore) environment.
   - Palynofacies type II suggest distal dysoxic to anoxic shelf to deep basin environment with abundant AOM.
   - Palynofacies type III is indicative of dysoxic to oxic shelf (fluvio-deltaic) environment of deposition.
   - Palynofacies type V indicates mud-dominated oxic distal shelf environment. The dominance by marine palynomorphs (gonyaulacoid dinocysts) suggests an open marine environment.
2. Palynostratigraphic interpretations assigns sample interval (3410-5590ft) to Campanian - Maastrichtian age, sample interval 6900ft-8550ft to Albian-Cenomanian age. An Aptian age is assigned to sediments within intervals (8660ft-9000ft). The Campanian - Maastrichtian age found directly above the Albian - Cenomanian age suggests an unconformity between the interval 5590 ft. and 6900 ft.
3. From geochemical interpretation, most of the samples from ST-7H well show:
   - ‘fair’ to ‘very good’ petroleum potential
   - kerogen typing from the modified van-Krevelen diagram indicate the presence of mixed kerogen types; Types II, II/III and III kerogens which are oil prone, oil-gas prone and gas prone respectively.
   - with regards to thermal maturity, Tmax temperature range of 409 – 442°C indicate immature to early mature hydrocarbons.
   - most of samples from the ST-7H well have low Production Index (<0.10) indicating low in-situ hydrocarbon generation.

Acknowledgement

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Explanation of Plates

PLATE I

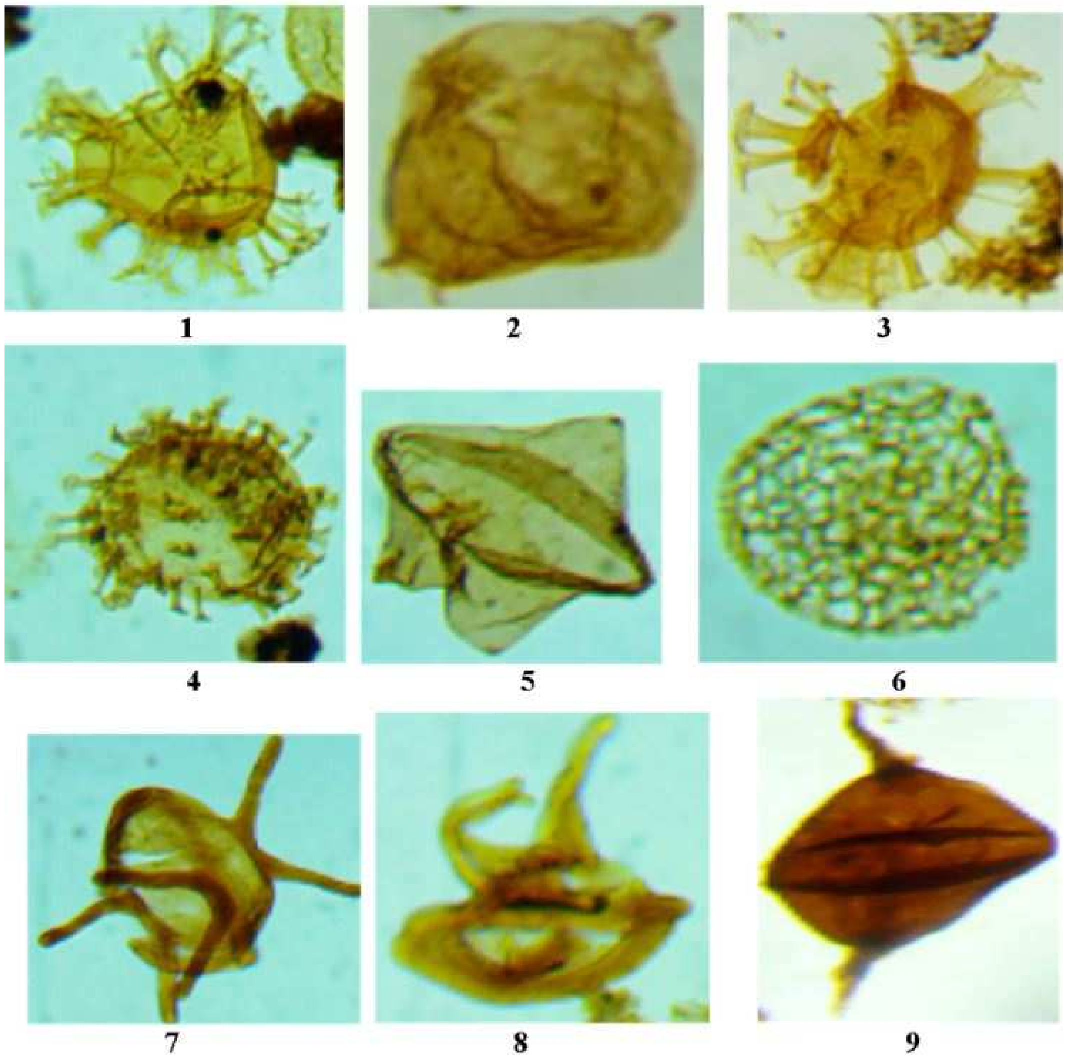

Plate I

All figures ×550
Figure
1. *Oligophaeridium complex* (Whyte) Davey and Williams, 1966
2. *Senegalinium laevigatum* (Malloy) Bujak and Davies, 1984
3. *Cordosphaeridium inodes* (Klumpp) Eisenack1963b emend. Morogenroth, 1968
4. *Spiniferites* sp
5. *Phelodium magnificum* (Stanley) Stover and Evitt, 1978
6. *Afropollis jardinus* (Brenner, 1968) Doyle et al., 1982
7. *Elaterosporites klaszii* (Jardiné et Magloire, 1965) Jardiné, 1967
8. *Elaterosporites verrucatus* (Jardiné et Magloire, 1965) Jardiné, 1967
9. *Palaeocystidinium australinium* (Cookson) Lentin and Williams, 1978

PLATE II

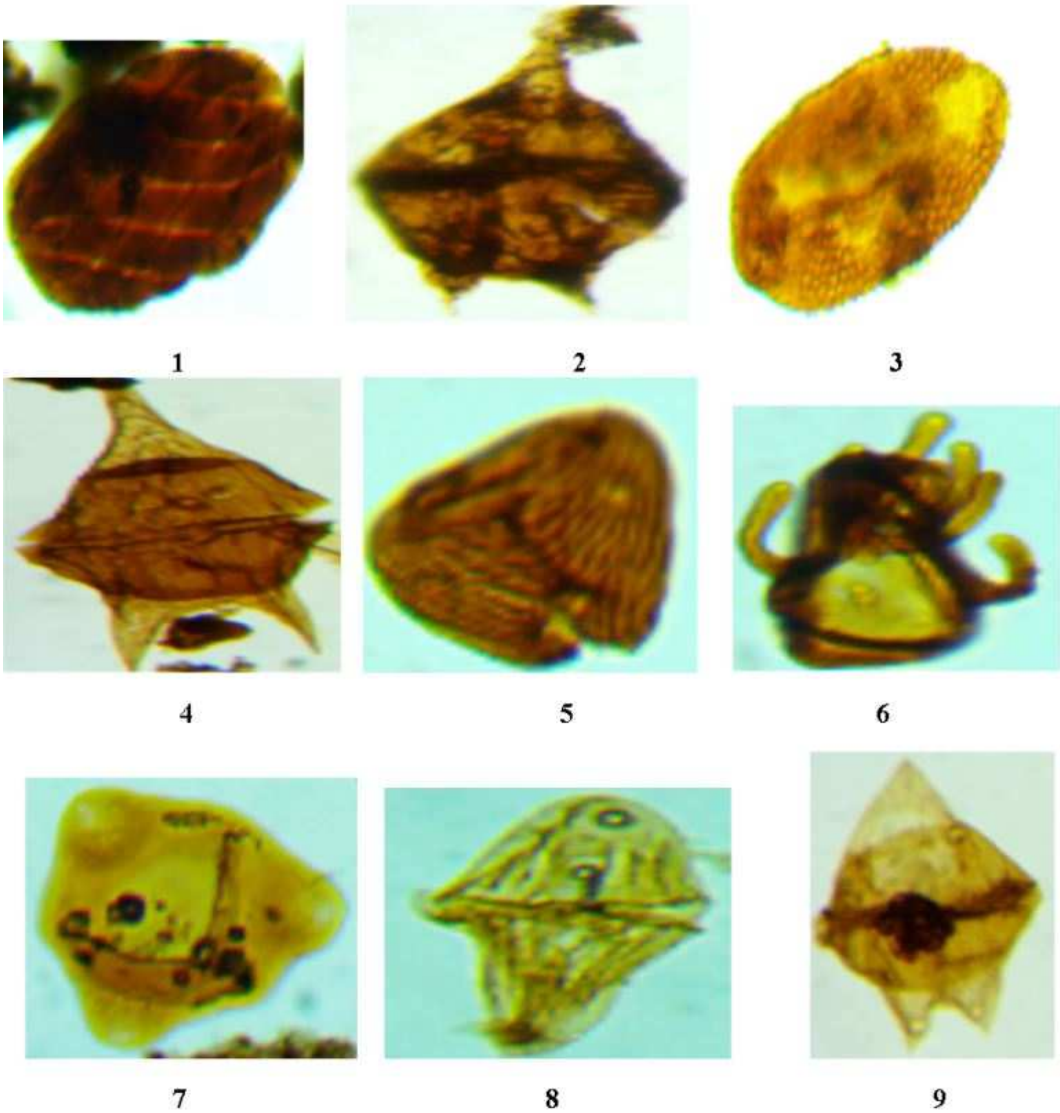

Plate II

All figures × 550

Figure

1. *Ephedripites* sp
2. *Cerodinium boloniense* (Riegel) Lentin and Williams, 1989
3. *Longapertites vaneendenburgi* Germeraad, Hopping and Muller, 1968
4. *Cerodinium boloniense* (Riegel) Lentin and Williams, 1989
5. *Cicatricosisporites australiensis* (Cookson) Potonié, 1956
6. *Elaterosporites verrucatus* (Jardiné et Magloire, 1965) Jardiné, 1967
7. *Triporites* sp.
8. *Dinogymnium undulosum* Cookson and Eisenack, 1970
9. *Cerodinium obliquipes* (Deflandre and Cookson) Lentin and Williams, 1989

PLATE III

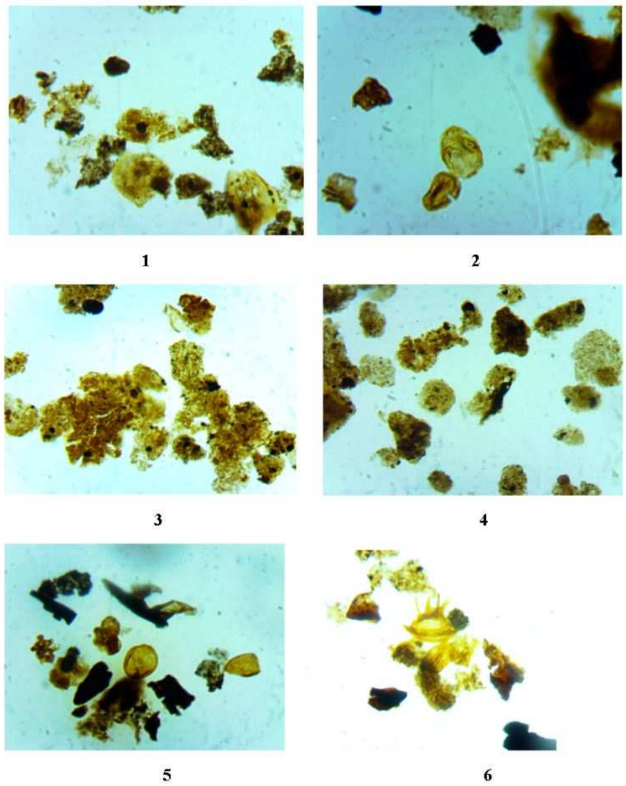

Plate III

All figures × 400

Figure

1, 2. Palynofacies type I and IV (P-I and P-IV). Dominance of AOM with some palynomorphs;

3, 4. Palynofacies type II (P-II). Abundant AOM with little phytoclasts;

5, 6. Palynofacies type III (P-III). Equal dominance of AOM and palynomorphs with high opaques.

PLATE IV

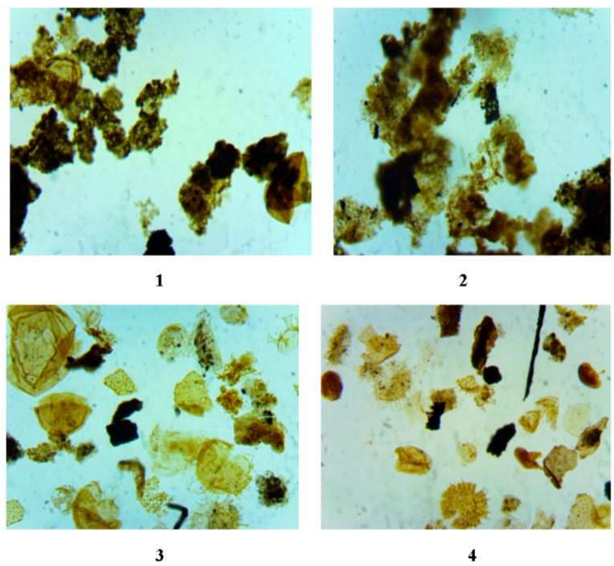

Plate IV.

All figures ×400

Figure

1. 2. Palynofacies type IV (P-IV). High amounts of AOM with some palynomorphs and opaques;

3. 4. Palynofacies type V (P-V). High amounts of palynomorphs dominated by marine palynomorphs.

Appendix 1. Relative Percentage Abundance of SOM and Palynomorphs

Depth/Ft	AOM	Opaques	Phytoclasts	Palynomorphs
3410	23.1	10.0	9.20	57.7
3500	29.3	6.00	7.10	57.6
3590	18.6	8.30	6.90	66.3
3680	23.1	5.10	5.40	66.4
3770	24.9	5.70	6.30	63.1
3860	30.6	5.40	7.20	56.8
3950	24.6	6.00	4.60	64.8
4130	25.7	9.10	5.10	60.0
4220	25.1	12.9	7.70	54.3
4310	22.6	14.0	6.30	57.1
4400	22.3	12.0	4.30	61.4
4490	20.3	7.40	4.60	67.8
4580	22.3	21.4	8.70	47.6
4640	25.7	6.00	4.30	64.0
4730	24.0	10.6	10.6	54.8
4770	53.1	12.0	8.00	26.8
4850	60.0	11.4	8.30	20.3
4950	54.0	12.3	8.30	25.4
5050	46.9	12.9	10.0	30.3
5130	46.6	9.30	3.10	41.0
5230	54.4	9.70	4.00	31.9
5310	48.6	12.1	4.00	35.3
5410	51.4	8.90	3.10	36.5
5490	51.4	8.60	2.90	37.2
5590	53.5	8.00	2.30	36.2
5690	71.1	7.40	2.00	19.4
5770	68.3	9.10	1.70	20.9
5850	70.9	11.4	4.00	13.7
5950	73.8	9.40	2.90	14.0
6030	69.1	8.60	4.00	18.3
6130	71.5	7.70	3.40	17.4
6210	68.3	9.10	1.40	21.1
6310	67.1	10.6	5.40	16.9
6410	61.7	13.4	7.70	17.1
6470	70.0	10.3	8.30	11.4
6510	75.4	14.3	5.70	4.60
6550	72.0	16.0	4.00	8.00
6610	50.9	27.1	15.7	6.30
6680	68.5	13.1	2.90	15.4
6700	62.0	17.4	6.60	14.0
6730	68.3	12.9	1.10	17.7
6760	63.7	14.9	1.90	19.6
6800	54.0	20.0	5.40	20.6
6830	49.7	20.0	1.70	28.6
6900	53.2	14.6	6.60	25.7
6920	62.0	16.3	1.10	20.6
6970	48.8	14.6	8.30	28.3
7020	49.1	20.0	4.60	26.3
7100	53.0	14.4	3.90	28.7
7150	40.0	22.0	12.0	26.0
7160	52.6	14.6	8.60	24.3

Depth/Ft	AOM	Opaques	Phytoclasts	Palynomorphs
7180	42.8	20.9	7.70	28.5
7240	47.1	18.6	6.00	28.3
7260	48.3	17.3	10.9	23.5
7340	45.1	20.9	9.40	24.6
7400	34.5	23.4	7.70	34.3
7480	38.1	15.4	10.5	36.0
7580	32.9	23.1	9.70	34.3
7680	44.3	12.6	11.1	32.1
7760	46.2	20.5	4.80	28.5
7860	51.7	17.7	3.70	26.9
7940	42.0	21.4	12.3	24.2
8020	42.8	17.4	8.60	31.1
8120	49.5	11.1	5.10	34.2
8220	46.8	12.6	2.00	38.6
8300	45.4	14.0	3.10	37.4
8380	38.9	14.0	1.70	45.4
8480	51.4	12.9	0.90	34.8
8580	45.1	7.10	0.90	46.8
8660	53.7	9.70	0.90	35.8
8740	54.3	13.7	1.10	30.9
8840	36.9	14.9	2.90	45.4
8920	52.9	5.10	0.30	41.7
9000	60.9	7.10	0.30	31.7

Appendix 2. Relative Percentage Abundance of Palynomorphs

	Terrestrial	Marine			Total palynomorphs
Depth/ft	Spores/ Pollens	Gonyaulacoids	Peridinoids	Total marine	
3410	16.0	40.3	1.40	41.7	57.7
3500	17.6	37.3	2.70	40.0	57.6
3590	26.3	37.3	2.70	40.0	66.3
3680	29.4	33.1	3.90	37.0	66.4
3770	22.7	33.7	6.70	40.4	63.1
3860	19.3	29.4	8.10	37.5	56.8
3950	28.1	25.0	11.7	36.7	64.8
4130	33.7	13.4	12.9	26.3	60.0
4220	28.0	14.0	12.3	26.3	54.3
4310	21.1	12.9	23.1	36.0	57.1
4400	22.6	13.1	25.4	38.5	61.1
4490	28.9	8.00	30.9	38.9	67.8
4580	44.1	1.60	1.90	3.50	47.6
4640	29.1	10.3	24.6	34.9	64.0
4730	18.0	13.7	23.1	36.8	54.8
4770	25.1	0.00	1.70	1.70	26.8
4850	20.0	0.00	0.30	0.30	20.3
4950	24.0	0.00	1.40	1.40	25.4
5050	26.6	0.06	3.10	3.70	30.3
5130	33.3	3.10	4.60	7.70	41.0
5230	26.9	3.00	2.00	5.00	31.9
5310	27.1	6.90	1.30	8.20	35.3
5410	27.7	7.70	1.10	8.80	36.5
5490	26.9	9.40	0.90	10.3	37.2

	Terrestrial	Marine			Total palynomorphs
Depth/ft	Spores/ Pollens	Gonyaulacoids	Peridinoids	Total marine	
5590	27.4	7.70	1.10	8.80	36.2
5690	19.4	0.00	0.00	0.00	19.4
5770	20.9	0.00	0.00	0.00	20.9
5850	13.3	0.00	0.00	0.00	13.7
5950	14.0	0.00	0.00	0.00	14.0
6030	18.3	0.00	0.00	0.00	18.3
6130	17.4	0.00	0.00	0.00	17.4
6210	21.1	0.00	0.00	0.00	21.1
6310	16.9	0.00	0.00	0.00	16.9
6410	17.1	0.00	0.00	0.00	17.1
6470	11.4	0.00	0.00	0.00	11.4
6510	4.60	0.00	0.00	0.00	4.60
6550	8.00	0.00	0.00	0.00	8.00
6610	6.30	0.00	0.00	0.00	6.30
6680	15.4	0.00	0.00	0.00	15.4
6700	14.0	0.00	0.00	0.00	14.0
6730	17.7	0.00	0.00	0.00	17.7
6760	19.6	0.00	0.00	0.00	19.6
6800	18.6	1.10	0.90	2.00	20.6
6830	27.6	0.80	0.20	1.00	28.6
6900	23.7	1.00	1.00	2.00	25.7
6920	20.0	0.30	0.30	0.60	20.6
6970	27.0	1.00	0.30	1.30	28.3
7020	26.0	0.30	0.00	0.30	26.3
7100	27.7	0.70	0.30	1.00	28.7
7150	25.7	0.00	0.00	0.00	25.7
7160	23.4	0.90	0.00	0.90	24.3
7180	25.1	3.10	0.30	3.40	28.5
7240	26.4	1.60	0.30	1.90	28.3
7260	18.7	3.90	0.90	4.80	23.5
7340	19.1	4.00	1.50	5.50	24.6
7400	22.3	6.60	5.40	12.0	34.3
7480	22.9	7.10	6.00	13.1	36.0
7580	20.6	6.30	7.40	13.7	34.3
7680	18.3	6.90	6.90	13.8	32.1
7760	22.9	4.80	0.80	5.60	28.5
7860	21.7	4.60	0.60	5.20	26.9
7940	16.0	7.10	1.10	8.20	24.2
8020	20.3	9.70	1.10	10.8	31.1
8120	23.2	8.60	2.40	11.0	34.2
8220	23.7	12.9	2.00	14.9	38.6
8300	21.7	14.0	1.70	15.7	37.4
8380	25.1	18.6	1.70	20.3	45.4
8480	19.4	15.1	0.30	15.4	34.8
8580	19.1	26.3	1.40	27.7	46.8
8660	18.3	16.6	0.90	17.5	35.8
8740	18.6	11.7	0.60	12.3	30.9
8840	27.4	16.9	1.10	18.0	45.4
8920	21.4	19.4	0.90	20.3	41.7
9000	19.3	11.7	0.70	12.4	31.7

Appendix 3. Rock-Eval pyrolysis/TOC Data for the ST-7H Well

SAMPLE DEPTH	TOC % OF				PYROLYSIS				
(Feet)	ROCK	S1	S2	S3	HI	OI	PI	Tmax	S2/S3
3140-230	0.88								
	1.16								
	2	70	5480	460	274	23	0.01	431	11.91
3230-320	1.87	50	3540	440	189	24	0.01	431	8.05
	2.4								
3320-410	2.66	70	5720	390	215	15	0.01	428	14.67
3410-500	2.13								
	2.63	50	6280	350	239	13	0.01	426	1794
	1.64								
3500-590	1.95								
	2.78	110	6410	360	231	13	0.02	430	17.1
3590-680	3.45								
	2.73	60	6390	360	234	13	0.01	432	17.75
3680-770	1.86								
	2.49	70	4960	310	199	12	0.01	433	16
	0.92								
3770-950	1.68	90	3480	330	207	20	0.03	431	10.55
3860-950	1.58								
3950-4040	2.05	150	5750	360	280	18	0.03	427	15.97
4040-130	1.86	100	3710	370	199	20	0.03	430	14.54
4130-220	1.82								
4220-310	1.93	150	4070	280	211	15	0.04	431	14.54
4310-400	2.13	140	4230	380	199	18	0.03	432	11.13
4400-490	1.97								
440-580	1.86	250	3870	210	208	11	0.06	431	18.43
4580-670	1.73								
4670-730	1.64	240	3440	180	210	11	0.07	433	19.11
4770-850	1.6								
4850-930	1.87								
4930-5010	1.96	110	5420	380	277	19	0.02	433	14.26
5010-090	1.86								
5090-170	2								
5170-250	2.11	130	5130	600	243	28	0.02	435	8.55
5250-330	2.45								
5330-410	2.53	120	6980	320	276	13	0.02	433	21.81
5410-490	2.49								
5490-570	2.52	140	7830	300	311	12	0.02	433	26.1
5570-650	1.71								
5650-730	1.83	100	5110	360	279	20	0.02	431	14.19
5730-810	1.87								
5810-890	2.05	170	6330	510	309	25	0.03	433	12.41
5890-970	1.86								
5970-6050	1.59								
6050-130	1.56	170	5000	530	321	34	0.03	435	9.43

SAMPLE DEPTH	TOC % OF				PYROLYSIS				
(Feet)	ROCK	S1	S2	S3	HI	OI	PI	Tmax	S2/S3
6130-210	1.53								
6210-290	1.48								
6270-370	1.6	120	4380	190	274	12	0.03	438	23.05
6370-450	1.64	80	4410	240	269	15	0.02	438	18.38
6490-570	1.58								
6570-650	1.34	100	6470	560	504	42	0.02	409	11.55
6650-730	0.74								
6730-810	0.81	150	2420	650	299	800	0.06	435	3.72
6810-890	0.79								
6890-970	0.77								
6970-7050	0.65								
7050-130	0.82	100	1090	500	133	61	0.08	437	2.18
7130-210									
6700-780	0.61								
6780-860	0.75								
6860-940	0.8	80	910	610	114	76	0.08	442	1.49
6940-7020	0.81								
7020-100	0.83	150	1390	660	167	80	0	438	2.11
711-180	0.7								
7180-260	0.68								
7260-340	0.51								
7340-420	0.66								
7420-500	0.58								
7500-580	0.65								
7580-660	0.8	160	1740	530	218	66	0.08	431	3.28
7660-740	0.73								
7130-20	0.58								
7210-290	0.79	100	1380	680	175	86	0.07	437	2.03
7290-370	0.79								
7740-820	0.7								
7820-900	0.87	160	1320	560	152	64	0.11	435	2.36
7900-980	0.56								
7980-8060	0.43								
8060-140	0.56								
8140-220	0.68	50	610	430	64	63	0.08	436	1.42
8220-300	0.69								
8300-380	0.66								
8380-460	0.8	60	760	350	95	44	0.07	436	2.17
8460-540	0.78								
8540-620	0.82	100	1410	550	172	67	0.07	431	2.56
8620-700	0.7								
8700-780	0.72								
8780-860	0.78	90	930	520	119	67	0.09	436	1.79
8860-940	0.76								
8940-9000	0.65								

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