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Palynofacies analysis and organic geochemical characterization influence on the hydrocarbon generation of the subsurface Devonian rocks in Siwa Basin, north Western Desert, Egypt

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ABSTRACT

The Devonian sediments in the Western Desert of Egypt are promising source for hydrocarbons. Productive samples from the Devonian succession in Sifa-1 well were examined in this study. Distribution of the liptinite content of hydrogen rich organic matters from these sediments is investigated. Study of the liptinite depended on observations from both incident and transmitted light microscopical modes. There are a diverse and abundant liptinite macerals in the studied sediments that include both terrigenous and marine organic matters. The palynological investigations include statistical analysis of the miospores assemblages and palynofacies categories in addition to calculation of the sedimentation rates. These analyses signify four miospores biotopes and three palynofacies biotopes. These biotopes assess the ramps of paleoclimatological and paleoenvironmental changes during the sedimentation and used to define a model of the liptinite distribution in the Devonian. The model includes two phases that witnessed essential changes in the basinal dynamics in climate, sea level and sedimentation rates. The redox conditions were confirmed by inorganic geochemical analysis of trace elements. The high oxygen level affected both the quantity and quality of organic and greatly reduced the preservation of the amorphous organic matters. The quality of the organic matters ranges between kerogen type II/III and kerogen type III that are supported by organic elemental and pyrolysis gas chromatography analysis. The sediment generated hydrocarbons with consideration that the whole Devonian succession is in oil window as observed from the miospore thermal coloration index.

Keywords: Palynofacies, Organic Geochemistry, Hydrocarbon Generation, Devonian, Western, Desert, Egypt.

1. Introduction

The Devonian rocks cover the entire North Africa from Mauritania in west to Egypt in the east (Boote *et al*., 1998). The subsurface Devonian in the Western Desert of Egypt was well prosperous and full of life in a dynamic and constantly changing world. In the sea, the marine life flourished with large microplankton productivity and sea animals. On the continent, the floral life grew in dense vegetation cover (Makled *et al*., 2018). These biological rich ecosystems produced diverse and abundant amounts of the organic matter that were preserved in the nearby deltaic and shallow marine environments. They represent exclusive hydrocarbon sources rocks in many locations in the North African region. However, only lean hydrocarbon source rocks are detected in these sediments in Egypt (Ghori, 1991; Makled *et al*., 2018; Abd El–Gawad *et al*., 2019). The reasons behind the existence of these lean sources in this region are investigated in the present study. Despite the diversity and abundances of the organic matters deposited in the Western Desert area, there are many other factors that control quality of the source rock and its hydrocarbon generation potentiality

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(Tyson, 1995, 2005; Katz, 2005). In the present study, the types and abundances of organic matters that are known for their potentiality to generate oil are determined. The "liptinite" is a term that used to describe the hydrogen–rich macerals in the kerogen or polished whole rock samples by the International Committee of Coal Petrology. The present study aims also to recognize the paleoenvironmental conditions that existed during the deposition of the liptinite and which controlled its distribution, productivity and preservation. The results are used to delineate an environmental model for the deposition of the organic matters that gathers both the paleoclimatological and sea–level changes. The examinations of organic matters are supported with organic geochemical analysis that contributed to the interpretation of paleoenvironmental conditions and hydrocarbon generation potentiality.

Geologic Settings

Sifa–1 well was drilled by ARCO Company in 1990 (Long. 29° 59' 14.9" and Lat. 25° 04' 05.2"), and it was bottomed in Basur Formation at a total depth of 10398 ft. (Fig. 1). This well is located near the Egyptian–Libyan border in the Western Desert of Egypt. The well location is in the middle of common basin and tectonic elements extend in both of Egypt and Libya. The entire area is a part of the Sirt Basin and the structural high Cyrenaica Platform that extends through Libya and Egypt. The Devonian rocks are recorded in northern part of the Western Desert of Egypt in many wells (Hallett and Clark–Lowes, 2012; Makled *et al*., 2018). In both the Faghur Basin (Egypt) and Cyrenaica Platform (Libya), the Devonian rocks are mainly clastics that include predominantly sandstones and siltstones with shale intercalation (Makled *et al*., 2018; Abd El–Gawad, *et al*., 2019). These clastics were deposited mainly in marine environments (shallow marine, deltaic and fluvial).

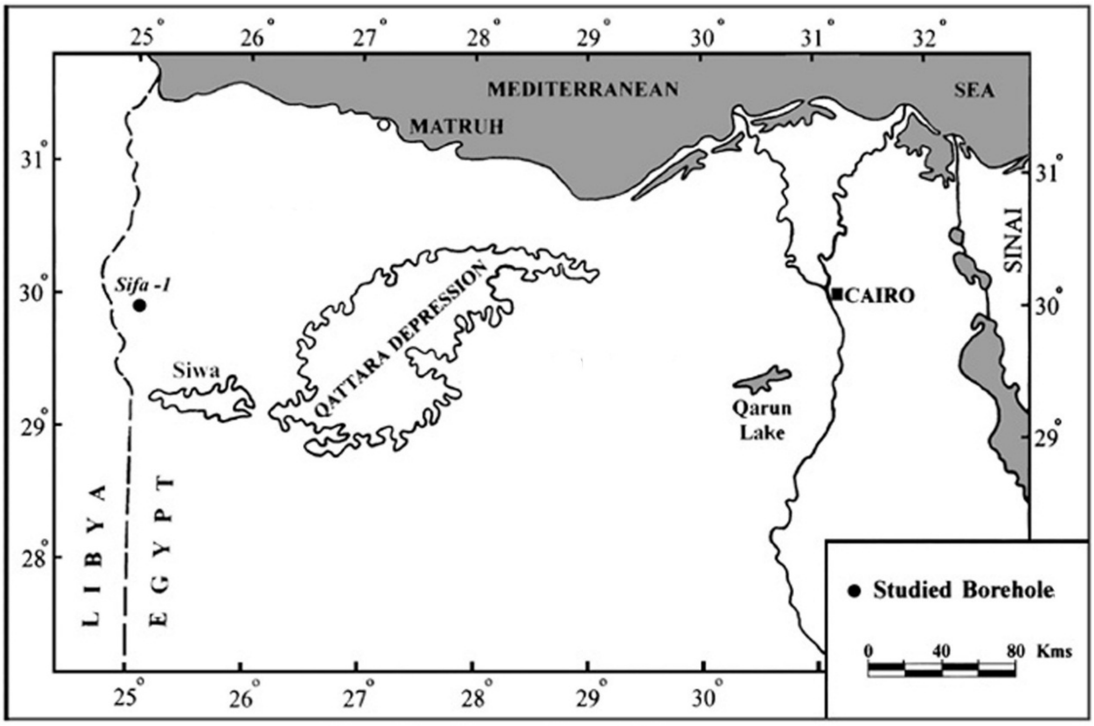


Fig. 1: Location map of the studied Sifa–1 well

The Devonian succession in the subsurface Western Desert comprises two rock units; the Zeitun Formation (thickness 2293 ft.; 10000–7707 ft.) and the basal part of Desouqy Formation (thickness 207 ft.; 7707–7500 ft.) (Fig. 2). Lithologically, the Devonian rocks are composed mainly of fine clastic sediments in the Lower Devonian (Lochkovian, Pragian and Emsian) with some sandstone and siltstone intercalation (Fig. 2). In the Frasnian there are some large thick beds of sandstone with some shale interbeds that increase in the upper part. In the Famennian, the lithology is mainly sandstone with shale intercalation in the middle part (Fig. 2). The Lower Devonian is a part of large transgression that reached the boundaries of the Cyrenaica Platform in the west, and it reached its peak in the Emsian with siltstones and dark shales. The rocks are similar in their thickness and composition to these found in the Sifa–1 well. They were deposited during the transgression in shallow marine conditions and show evidence of the condensed sedimentation in both Egypt and Libya (Hallett and Clark–Lowes, 2012; Makled *et al*., 2018). The thickness and composition of the sediment above the maximum flooding surface (Eifelian to Famennian) are also similar to the succession in Sifa–1 well. They were deposited in the shallow water littoral to deltaic to upper shoreface. The upper part of the Frasnian contains dark calcareous shale in the Zeitun Formation that is equivalent to the "Hot Argile Radioactive" of the Murzuq or Ghadamis Basins in west of Libya (Abd El–Gawad *et al*., 2019). In general, the Devonian sources in both Cyrenaica Platform and its extension in Egypt are of low potentiality for oil generation (Ghori, 1991, Makled *et al*., 2018). However, the condensed sedimentation is recorded in both of Libya and Egypt and it was targeted in the present study to evaluate its potentiality.

2. Material and Methods

2.1 Palynofacies analysis

Forty two samples are examined in this study from Sifa–1 well. The samples were prepared according to the standard palynological procedures which include wet sample treatment by HCl 10 % and HF 40 % to remove the carbonate and clay minerals. The residue is sieved at 10 µm nylon mesh. The oxidation process was excluded to avoid removing of surplus organic matter particles. The concentrated organic matters are collected after heavy liquid separation to store in distilled water. A small fraction of the concentration is mounted to glass slide by glycerin gel for the microscopic examination, palynofacies countings and spore color observations. For statistical analysis of palynofacies categories 500 palynomorph particles were randomly counted from all categories. The examination included photographing with Leica microscopic systems in transmitted light mode (attached to DFC280 digital camera). The miospores and palynofacies are recorded in Plates (1–3). The statistical analysis is used later to interpret paleoenvironmental conditions during the deposition and to evaluate their kerogen type. The organic particles are classified into seven palynofacies categories. The classification followed the schema of Tyson (1993) using ternary plot of palynofacies main categories, which are AOM, palynomorphs, phytoclasts.

2.3 TOC, CHNSO elemental analysis, and pyrolysis gas chromatography

The total organic carbon (TOC) is measured after removing the carbonate mineral from the bulk sediment by 1 NHCl heated to 80°C in LECO SC 632. Other organic geochemical analyses are used to support the results of the organic matter quality from the microscopical observation. 18 samples were analyzed by the CHNSO elemental analysis using the Elementar analyzer. The atomic H/C and O/C ratios are used in the van Krevelen, 1961 (Tissot *et al*., 1974) to determine the kerogen types. Four kerogen samples were selected for pyrolysis gas chromatography (PyGC). The PGC is carried out using the Chromatec–Crystal 5000 apparatus. The resulted gas chromatograms reveal valuable information about the environment, kerogen type and maturity. Several indices can be calculated from these gas chromatograms. The Pristane/Phytane (Pr/Ph) ratio, isoprenoid/n-*alkane* (Pr/C_{17} and Ph/C_{18}) ratios are used in cross plot to explain the redox conditions and maturity.

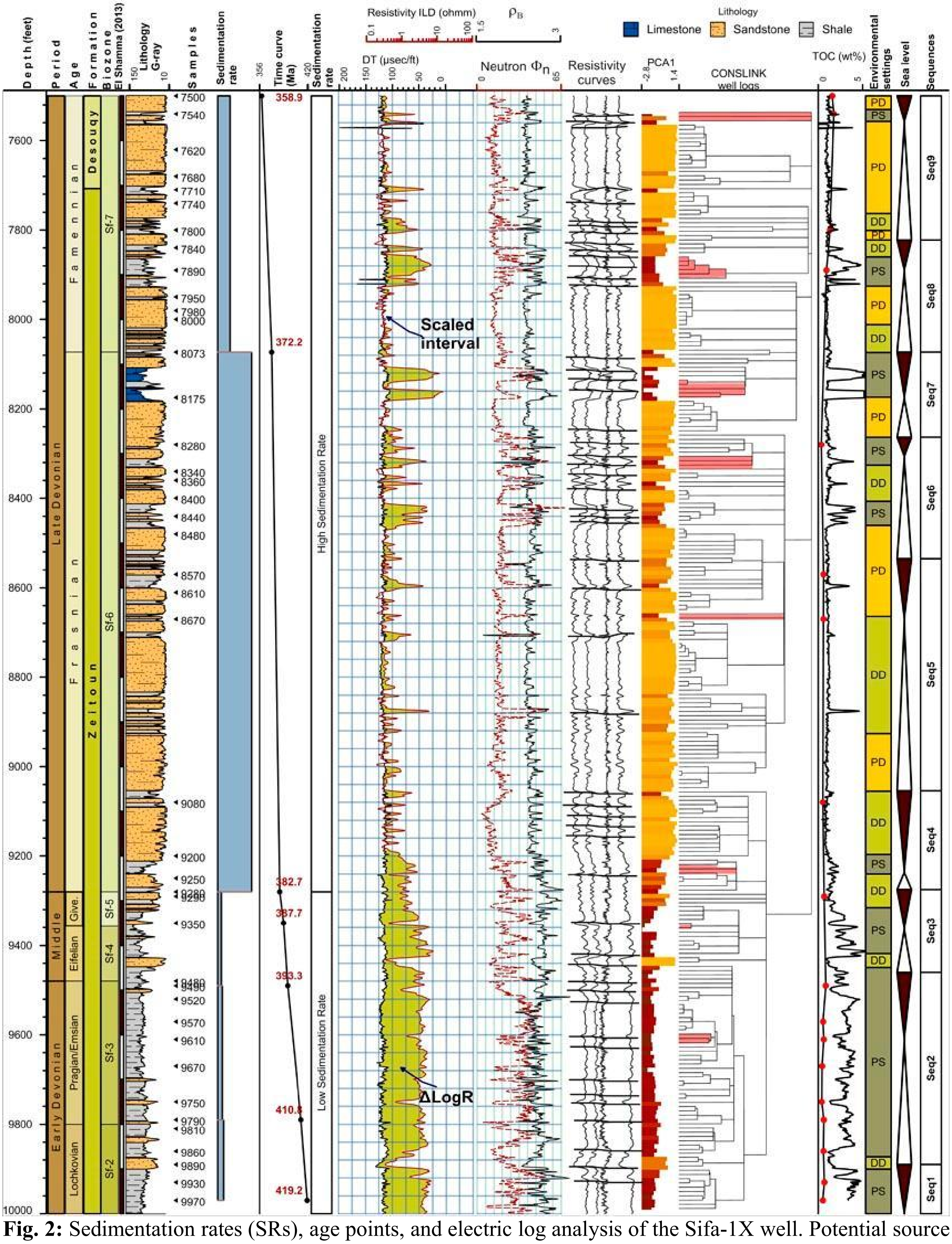


Fig. 2: Sedimentation rates (SRs), age points, and electric log analysis of the Sifa-1X well. Potential source enrichment (TOC wt %) is presented with both measured and calculated TOC values. The gamma ray (gAPI), density ($\Delta\rho$; g/cm^3), neutron (ϕn; p.u.), electric resistivity (ILD, ohm. m) and sonic logs (ΔT; μsec/ft) are represented. The electric log facies of principal component analysis is represented against the environmental settings with resistivity electric beds and CONSLINK analysis. The identified sequences are represented and the maximum flooding surfaces are marked with red color.

3. Results and Discussion

3.1. Sedimentation rates (SRs)

In the present study, the age for the studied section from Sifa–1 well is based on the studies of El–Shamma *et al*., (2011). They discriminated seven miospores assemblage biozones in the in the interval extending from the Silurian and Devonian Periods (lettered abbreviations Sf–1 to Sf–7). Six of these biozones were encountered in the present study excluding one biozone that distinguish the Silurian Period for with total thickness 2470 ft. (7500–9970 ft.; Sf–2 to Sf–7). The studied Devonian section in Sifa–1 well is distinguished with diverse and abundant miospore assemblages through its history as well as marine component (Fig. 3). However, the correlation of El–Shamma *et al*. (2011) biostratigraphic scheme with Richardson and McGregor (1986) of Western Europe establish the base for the age identification of the different bioevents in Ma (Becker *et al*., 2012). These age points are used to calculate the sedimentation rates (SRs) in studied section (Fig. 2). In the Early and Middle Devonian (9970–9280 ft.), the SRs are extremely low (0.25 inch/kyr in Lochkovian; 0.20 in Pragian/Emsian; 0.29 inch/kyr in Eifelian; 0.16 inch/kyr in Givetian). This section is composed mainly of dark shales and may represent a composite of condensed sections of Early and Middle Devonian times. The condensed section developed in the area between the shelf/slope break landward to the distal edge of inner neritic–sand deposition at the times of maximum transgression of shoreline. The SRs increased significantly in the Late Devonian (9280–7500 ft.).

It reaches 1.37 inch/kyr in Frasnian; 0.51 inch/kyr in Famennian. The sediments in this part are mainly sandstones occasionally intercalated with shales. However, although the SRs are in general low in the Lochkovian and Pragian, they become inverted in the Givetian (high 2.66 inch/kyr in Faghur–1 and 2.22 inch/kyr in NWD–302–1), Frasnian and Famennian (low 0.07–0.34 inch/kyr in Faghur–1) (Makled *et al*., 2018). This inversion is probably because of the development of the inter–basinal barriers between the Devonian Ghazalat Basin in the east (Egypt) and Cyrenaica Basin in the west (Libya) during and after Givetian time. So, this indicates that tectonic elements (subsidence and uplift) had a stronger influence on the sedimentation than the eustatic changes in this area (Keeley, 1994).

3.2 Paleoclimatological affinity of the Miospores biotopes

The miospore assemblages preserved in the rock reflect the nature and density of the vegetation cover in the nearby land area in any basin. In the studied Devonian section from Sifa–1 well, the miospore assemblages reflect the constant terrestrial floral evolution that accompanied with paleoclimatological changes and development of differentiated floral ecosystems. There is a large influence of the vegetation cover on many of the aspect of sediments and depositional settings. These aspects are like quantities of sediments, erosion of sediment, soil profile thickness and land flows. Vegetation nature and density also control the production of clays and development of meandering river style (Davies and Gibling, 2010). Throughout the Early Paleozoic, some dramatic changes took place in the nature of the alluvial and fluvial processes and deposits in addition to the landscape in general that triggered primarily by evolution of the land plants. Davis and Gibling (2010) divided the Devonian Period into two vegetation stages that are VS5 for Lochkovian to Emsian and VS6 for Eifelian to Famennian. The VS6 is further divided into VS6a for Eifelian and Givetian and VS6b for Frasnian and Famennian. These vegetation stages are well presented in the Devonian section in Sifa–1 well. The development of the root system and its evolution enhanced the weathering, enlarged the coarser grained sediments retention time and increased the production of the mud during the VS5 and VS6a (Davis and Gibling, 2010 and discussion therein). The development of arborescent vegetations and carbon plant remains litter on the forest ground increased the potentiality of wildfire and charcoal production (opaque phytoclast) in the Late Devonian which can be washed into fluvial and marine facies (Stein *et al*., 2007). The miospores morphology and assemblages are discriminated through time using constrained single linkage cluster analysis into four stratigraphical miospore biotopes (Fig. 3). These biotopes are matched with the vegetation stages (VS5–VS6). The study depended on the relative abundances of 34 genera.

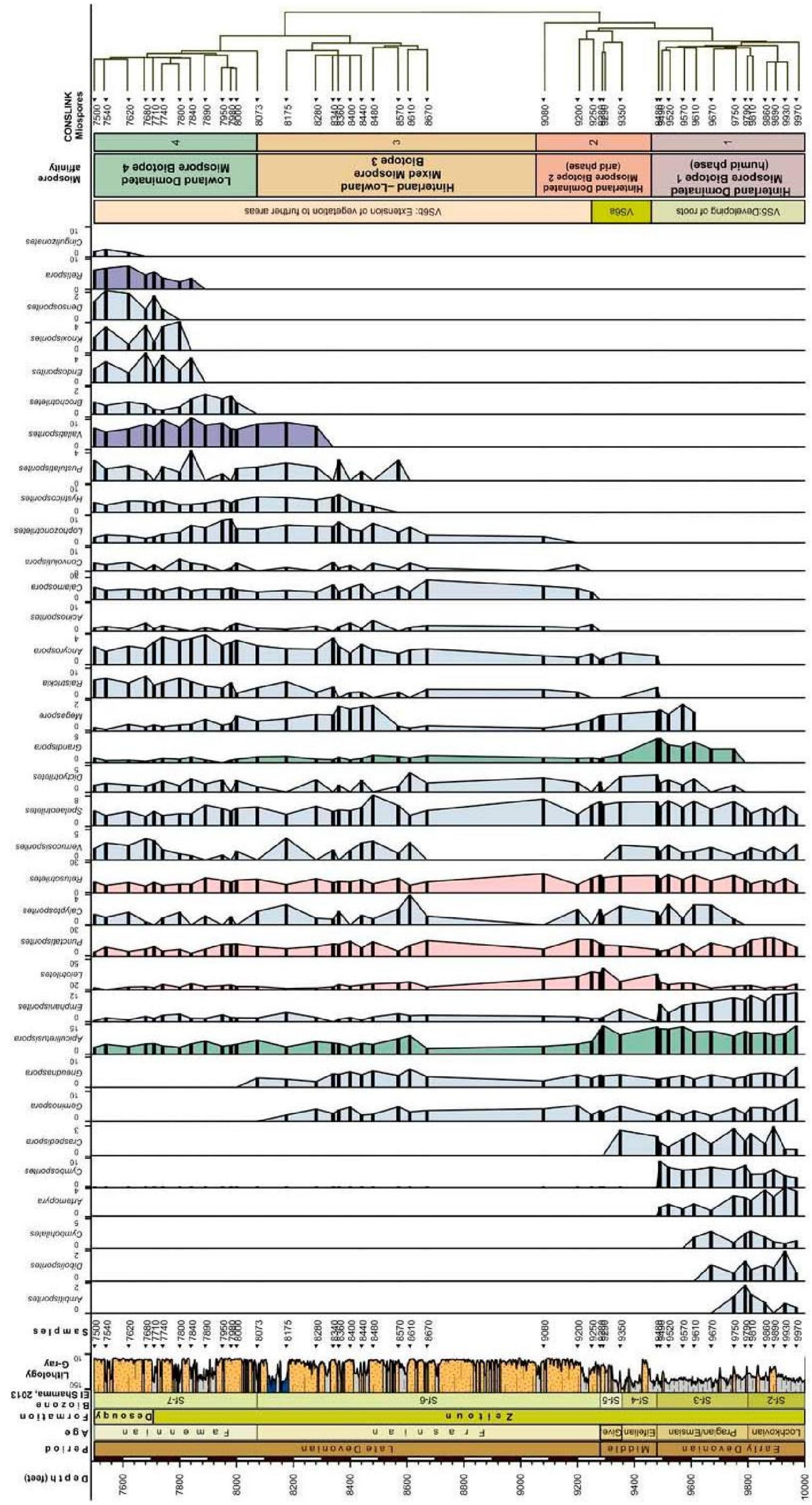


Fig. 3: Relative abundances log of the miospores and their biotopes as discriminated by CONSLINK. The vegetation stages are after Davies and Gibling (2010).

3.3 Palynofacies analysis and base sea level change

Palynofacies analysis depended herein on the combination of three types of multivariate statistical analyses to measure the stratigraphical variation of the depositional settings (Fig. 4). The statistical techniques include cluster analysis by Ward's method, principal component analysis (PCA) and constrained single linkage analysis (CONSLINK). The palynofacies classes used in the present study is selected to suit the organic composition of the Devonian Period that is rich in the zooclasts and different marine prasinophyte and acritarchs. The identification of particulate organic matters are mostly done with transmitted light, however the classification of the organic particles is supported largely with the observation of the reflected fluorescence lights that discriminate the cuticles of liptinite composition and miospores from other low on none fluorescent terrigenous material. In addition, the size of the transparent phytoclasts is an important parameter that used to assess the production and transportation of the terrestrial floral particles into the basin that depended on climate changes. Although Tyson (2000) postulated that the phytoclasts are rather reflect the sedimentological sorting rather than changes in the type and flux of phytoclasts. The cluster analysis resulted in identification of three biotopes in the Q–mode (samples groups, Makled *et al*., 2018; Makled *et al*., 2020). These biotopes agree with the CONSLINK cluster and PCA in addition to the CONSLINK biotopes of the miospores. While the miospores biotopes reflected the paleoclimatological and vegetation evolutionary changes, the introducing of the marine classes with the other terrigenous material in palynofacies analysis indicate the changes that can be attributed to the base sea level changes.

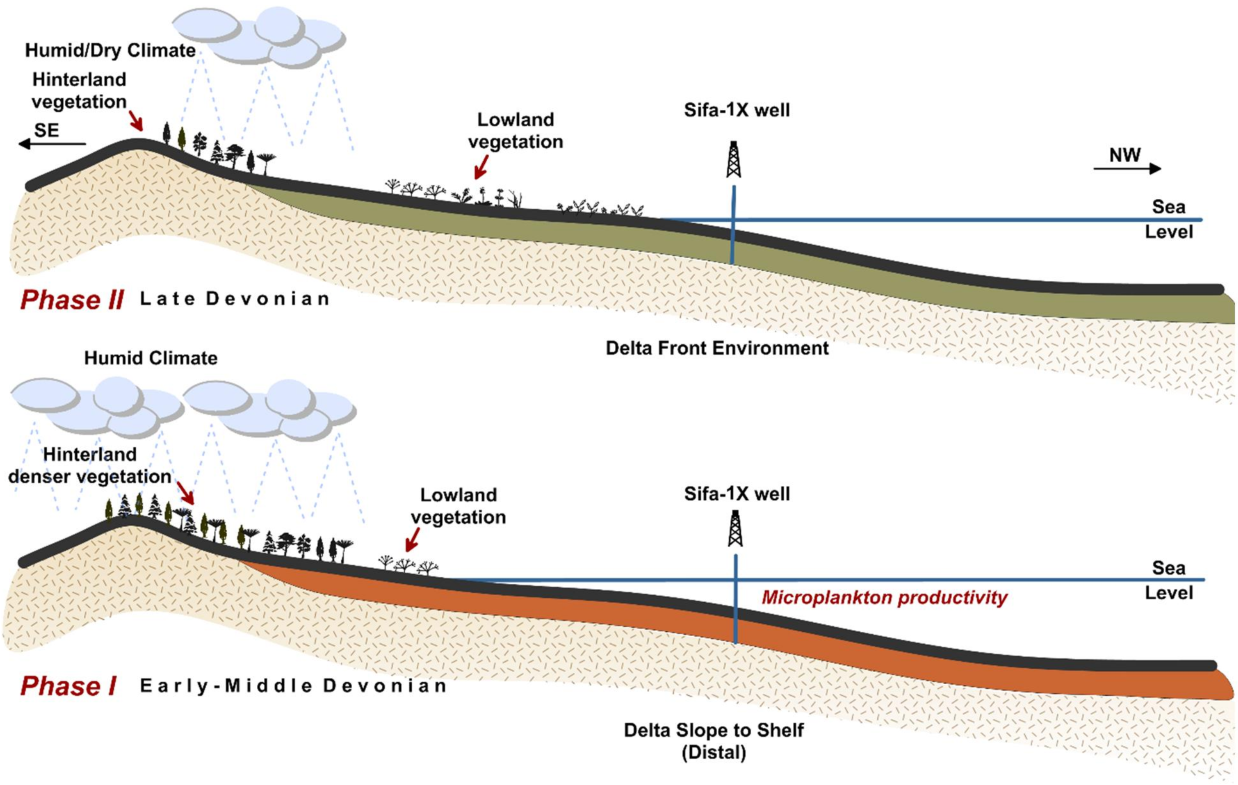
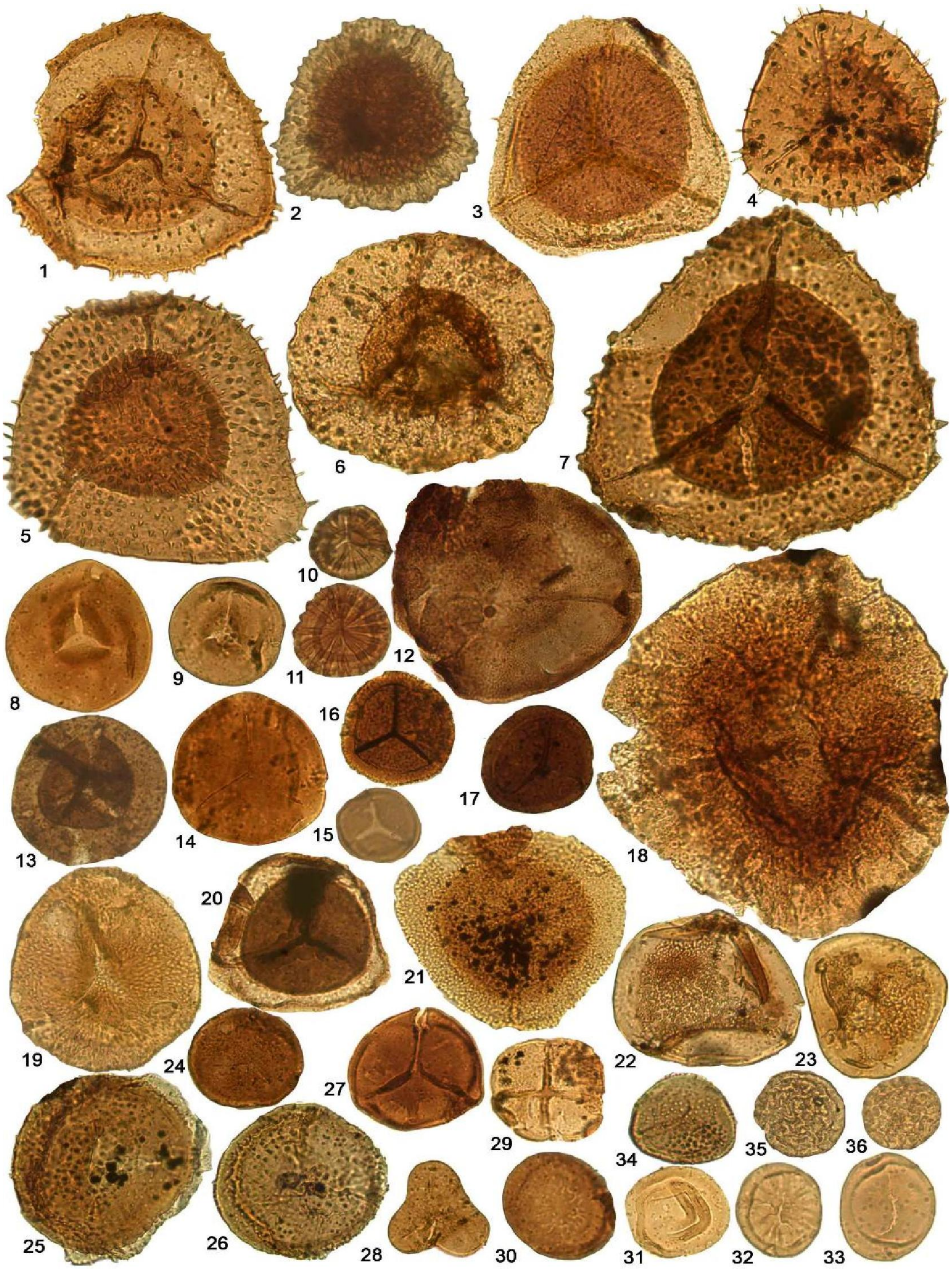


Fig. 4: Environmental models of Phase (I) and (II) showing the base level changes, size of the floral habitats, and paleoclimatological conditions.

(a). Delta slope to shelf palynofacies biotope A: This biotope contains 12 samples and occupies one continuous interval that extends from the depth of 9970 to 9480 ft. in the lower part of the Zeitun Formation and the Early Devonian (Lochkovian-Emsian). This biotope is well distinguished in the present study with high abundance of the fluorescent cuticles (17.7–24.9 %) that have larger mean grain sizes (41.0–49.0 µm) and strong yellow to orange fluorescence. The cuticles are different in composition and structure as well as the degree and color of the fluorescence. Most abundant type is the smooth waxy lustrous fragments that show faint botanical structure. These cuticle fragments have yellow to orange fluorescence in palynological samples. They have sharper and straighter edges than the other cuticles that give a splinter look than a rounded. The waxy cuticles are relatively larger in size and abundance than the cuticles with clear reticulum. The second abundant cuticles have distinguished botanical structures like pentagonal, hexagonal and rounded hexagonal cell patterns with stomata ribbed reticulum. The cellular sheets of higher land plants can be recognized with more regular rectangular cell patterns but without obvious stomata. These floras are thallophytes that have characters intermediate between the algae and embryophytes and they flourished in the Early and Middle Devonian (Edwards, 1982; Edwards and Wellman, 1996; Filipiak *et al*., 2012; Kondas, 2018). The identified nematophytes are *Nematothallus* and *Cosmochlaina* with reticulum showing no preferred alignment. The least abundant cuticles are network of tubular like structure. A similar assemblages to this identified in the present study is found in a nearby western coeval Early Devonian in Ghadames Basin, Libya, by Al Ameri (1984). He attributed the cuticles found herein to lycopod leafs. The *Cosmochlaina* and *Nematothallus* were observed also in Early Devonian sediment in Faghur Basin in Egypt by Makled *et al*. (2018). The other components of terrigenous affinity in this biotope are the brown wood fragments (2.6–11.2 %) and opaque phytoclasts (6.2–10.2 %). The miospores assemblages belong completely to Hinterland Dominated Miospore Biotope 1 (humid phase). The marine zoomorph palynomorphs (chitinozoans and scolecodonts) and marine zooclasts (mostly arthropods exoskeletons) have the highest relative abundances in this biotope. The chitinozoans are abundant and diverse in this biotope; they are represented by the short ovoid chamber *Conochitina*, long spinal appendices like *Ancyrochitina,* and smooth *Fungochitina*. The zooclasts comprise a significant component of the organic matters in the studied samples. Several types of the zooclasts are found in the studied samples with several structures and textures that belong to several eurypterid, annelid and insects (Miller, 1996; Filipiak and Zatoń, 2011; Filipiak *et al*., 2012). The eurypterid tooth–like cuticles are found frequently in the samples of this biotope. These cuticles are hollow curved tubes. Some of these eurypterid cuticles are found still attached to parts of the epidermal tissues. The acritarchs are of low abundances in this biotope in the palynological samples. They are diverse and comprise the netromorphs (*Navifusa*), short–spined acanthomorphs (*Visbysphaera* and *Micrhystridium*), long–spined acanthomorphs, long and branching processes polygonomorphs (*Evittia*, *Palacanthus, Stellinium* and *Veryhachium*), prismatomorphs (*Polyedryxium* and *Horologinella*), retrastomorphs (*Triangulina*) and sphaeromorphs. In general, the samples in this biotope are deposited in outer prodeltaic to shelf environment that received abundant terrigenous floral materials especially the hinterland floral parts without being accompanied with coarse grained sediments, which kept the sedimentation rates low.

(b) Delta front to delta platform palynofacies biotope B: This biotope includes 13 samples occupying a continuous interval in the Eifelian–Givetian (9480–8175 ft.) and the alternates with the biotope C in Frasnian in the upper part of Zeitun Formation. This biotope is mostly in the negative side of the component 1 and nearer to the biotope C which indicate their distinctive palynofacies composition. This biotope is attributed to CONSLINK cluster 2 and exchange with biotope C in the CONSLINK cluster 3 and Main statistical distinctive features of this biotope are the increase of the miospores and opaque phytoclasts with significant abundances of the acritarchs and prasinophytes with lower diversity. The cuticles are not diverse as in biotope A and mostly dominated with membranous cellular sheets. The waxy and nematophytes decreased in abundances. Both of the brown wood and opaque phytoclasts abundances increased in this biotope. The miospore assemblages varies between Hinterland Dominated Miospore Biotope 2 (arid phase) and Hinterland–Lowland Mixed Miospore Biotope 3. The pyrite infestation in the miospores is significant especially in the samples of CONSLINK 2. The marine components occur in significant abundance in the samples of this biotope where they are more distal representing the delta platform portion of the biotope. The marine zoomorphs abundances largely dropped with rare chitinozoans with absence of the scolecodonts. The zooclasts abundance is nearly the same as in the biotope A and dominated with membranous sheets and eurypterid tooth–like cuticles. The acritarchs are abundant like the in the biotope A, however, they are mostly of low diversity and dominated with sphaeromorphs and short–spined acanthomorphs. These acritarchs are indicative for shallow–near shore environment (Staplin, 1961; Richardson and Rasul, 1990; Tyson, 1995; Loydell *et al*., 2013).

Plate I:



1, 7 ***Grandispora libyensis***, depth 9570 ft.; 2 ***Grandispora macrotuberculata***, depth 9570 ft.; 3 ***Grandispora permulta***, depth 9520 ft.; 4 ***Grandispora douglastownense***, depth 9350 ft.; 5 ***Grandispora megaformis***, depth 9290 ft.; 6 ***Grandispora*** sp.; 8, 9 ***Retusotriletes rotundus***, depth 9080 ft.; 10, 11 ***Emphanisporites annulatus***, depth 9860 ft.; 12 ***Rhabdosporites langii***, depth 9280 ft.; 13 ***Spelaeotriletes granulatus***, depth 8480 ft.; 14 ***Ambitisporites dilutus***, depth 9970 ft.; 15 ***Punctatisporites planus***, depth 9570 ft.; 16, 17 ***Geminospora lemurata***, depth 8440 ft.; 18 ***Kraeuselisporites rugosus***, depth 7710 ft.; 19 ***Apiculiretusispora plicata***, depth 9480 ft.; 20 ***Endosporites micromanifestus***, depth 7710 ft.; 21 ***Calyptosporites stolidotus***, depth 7710 ft.; 22, 23 ***Cymbohilates*** sp. 1; 24 ***Cymbohilates*** sp. 2; 25, 26 ***Cymbohilates*** sp. 3; 27 ***Retusotriletes*** sp. 1; 28 ***Leiotriletes tumidus***, depth 9290 ft.; 29 ***Tetraletes variabilis***, depth 9930 ft.; 30 ***Cymbohilates comptulus***, depth 9670 ft.; 31***Gneudnaspora divellomedia***, depth 9610 ft.; 32, 33 ***Artemopyra recticosta***, depth 9790 ft.; 34 ***Cymbosporites*** sp.1, depth 9570 ft.; 35, 36 ***Chelinospora cantabrica***, depth 9860 ft.

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Plate II:

1 ***Dictyotriletes subgranifer***, depth 8610 ft.; 2 ***Brochotriletes*** sp. 1; 3 ***Brochotriletes*** sp. 2; 4, 5 ***Retispora lepidophyta***, depth 7620 ft.; 6, 7 ***Verrucosisporites premnus***, depth 9480 ft.; 8 ***Spelaeotriletes arenaceus***, depth 7540 ft.; 9 ***Hymenozonotriletes discors***, depth 9480 ft.; 10 ***Vallatisporites*** sp 1.; 11 ***Vallatisporites*** sp.2; 12 ***Verruciretusispora dubia***, depth 8610 ft.; 13 ***Raistrickia*** sp. 1.; 14 ***Acinosporites*** sp. 1.; 15 ***Lophozonotriletes*** sp.1.; 16, 17 ***Verruciretusispora*** spp.; 18 ***Schopfites*** sp. 1.; 19 ***Pustulatisporites*** sp. 1; 20, 21 ***Verrucosisporites nitidus***, depth 7500 ft.; 22 ***Verruciretusispora*** sp. 1; 23–25 ***Verrucosisporites congestus***, depth 7500 ft.; 26 ***Stenozonotriletes*** sp. 1; 27 ***Cristatisporites orcadensis***, depth 7540 ft.; 28 ***Heterotriletes*** sp.1; 29 ***Camarozonotriletes*** sp. 1; 30–32 ***Verrucosisporites premnus***, depth 9480 ft.; 33–35 ***Knoxisporites literatus***, depth 7710 ft.; 36 ***Convolutispora*** sp. 1; 37 ***Ancyrospora*** sp. 1; 38 ***Ancyrospora*** sp. 2; 39 ***Ancyrospora*** sp. 3

Plate III:

1–8 Cluster of miospores, dyads, tetrads and fragmented sporangium, 1 depth 9750 ft., 3 depth 9570 ft., 4 depth 9860 ft., 6 depth 9750 ft., 7, 8 depth 9480 ft.; 9–12 chitinozoans, 9 ***Fungochitina***, depth 9930 ft., 10, 11 ***Ancyrochitina***, depth 9860 ft., 12 ***Conochitina***, depth 9860 ft.; 13, 14 Scolecodonts jaw apparatuses, depth 9670 ft.; 15–17 Eurypterid spine–like cuticles; 18 Zooclasts of shorter conical shape horns, depth 9350 ft.; 19–23Smooth cuticles of eurypterid arthropod, 19 depth 9750 ft., 20, 21 depth 9810 ft., 22 depth 9610 ft., 23 depth 9350 ft.; 24–26 Spongy cuticles of eurypterid arthropod, 24 depth 9750 ft., 25 depth 9610 ft., 26 depth 9810 ft.; 27 Large fragments of the tissue that is attributed to the eurypterid spine–like cuticles; 28, 29 Eurypterid cuticle with smooth surface in the transmitted light, depth 9750 ft.; 30–34 Chitinous epidermal tissues with tapered spines of different lengths, 30, 31depth 9670 ft., 32 depth 9860 ft., 33 depth 9890 ft., 34 depth 9970 ft.

The *Botryococcus* are abundant, while the marine prasinophyte phycomata getting more abundant in the CONSLINK 2. The fungal bodies slightly increased in abundances. The AOM (resin and AOM) is observed in scarce quantities lower than these recorded in palynofacies type A. The depositional environment is in general enriched by terrigenous materials and with lesser marine types that decreasing upward from the samples of CONSLINK 2 to the CONSLINK 3. The detected trend of environmental changes is from delta platform to delta front.

(c) Delta front palynofacies biotope C: This biotope comprises 16 samples and extends of one continuous interval from the 8073 to 7500 ft. in the Famennian in the upper part of the Zeitun Formation and whole part of Desouqy Formation. This biotope represents the most proximal environmental settings in the present study. The cuticle abundances in this biotope are largely dropped, while the opaque phytoclasts and brown wood and miospores abundances increased significantly. The opaque phytoclasts increased relative abundances can be attributed to several reasons. The increasing of the vegetation litter on the forest ground with natural evolution of the terrestrial plant frequently increased episodic wildfire in the late Frasnian and Famennian, these phenomena increased the abundances of the opaque phytoclasts in the fluvial or near–shore marine sediments (Tyson, 1995). In addition, the widespread episodes of glaciations, which were widespread in the Frasnian and Famennian, could lead to concentrate the opaque phytoclasts. The glaciations could decrease the *in situ* production of the woody plants and prolonged exposure to the oxidation and reworking of older phytoclasts (Tyson 1995). The glaciations episodes have longer time span and can be recorded in the present study and they are associated with the early sea level rise (lowstand system tracts). The relatively eustatic sea level regression in Frasnian and Famennian is marked with coarser grained sediment. The coarse grained sediments generally incorporate larger amounts of opaque phytoclasts that characterize the high energetic of the fluvial and delta front environments (Tyson, 1995). The miospores belong to Hinterland–Lowland Mixed Miospore Biotope 3 and Lowland Dominated Miospore 4. The association of opaque phytoclasts and lowland miospore indicate the general lower sea level in comparison to the sea level in Early and Middle Devonian in Sifa–1 well that accompanied the elevated sedimentation rates. This is supported by low abundances of the marine subcategories in this palynofacies type. The marine zoomorphs and zooclasts were not observed in the samples of this palynofacies type. The relative abundance of acritarchs decreased significantly and only represented by shallow near–shore environment sphaeromorphs and short–spined acanthomorphs. Numerous cuticles show marks of cracked darker layer in fluorescence light mode that indicates to possible outer oxidation. The relative abundance of ***Botryococcus*** and marine prasinophyte phycomata are decreased and they are generally small and thin. Neither the AOM nor bituminite were observed in the palynological samples. The identified environmental setting of this palynofacies type is near shore proximal delta front environments.

3.4 Redox conditions, paleo productivity and sedimentation rate: roles in distribution and preservation quality of liptinite

Liptinite was the dominant organic matter in the studied sediments whether it is marine or terrigenous in most of the samples. The previously discussed results indicated that palynofacies biotope A, B and C are arranged from positive to negative values on component 1 and this was used to signify proximal distal trend (Figs. 4 & 5). The liptinite categories are also arranged on the same trend from the marine to terrestrial liptinite then brown wood (vitrinite) and opaque phytoclasts (inertinite) from positive to negative sides. The occurrences of the *Botryococcus* (type I, Tyson, 1995) in abundant values will increase even the quality in positive side. Consequently, the quality of organic matters is the highest in palynofacies biotope A and decrease in biotopes B and C. There are two important parameters that are linked to the study of the liptinite distribution that are thermal maturity and the total organic carbon (TOC wt %). Both of these parameters are independent on the liptinite quality. The thermal maturation that took place during the diagenesis and catagenesis affect the properties of the liptinite especially the fluorescence. The thermal maturity is assessed in the present study by comparing *Retusotriletes* grains RGB color channels measured in the digital images to spore colors of the thermal alteration index (TAI, Pearson, 1984).

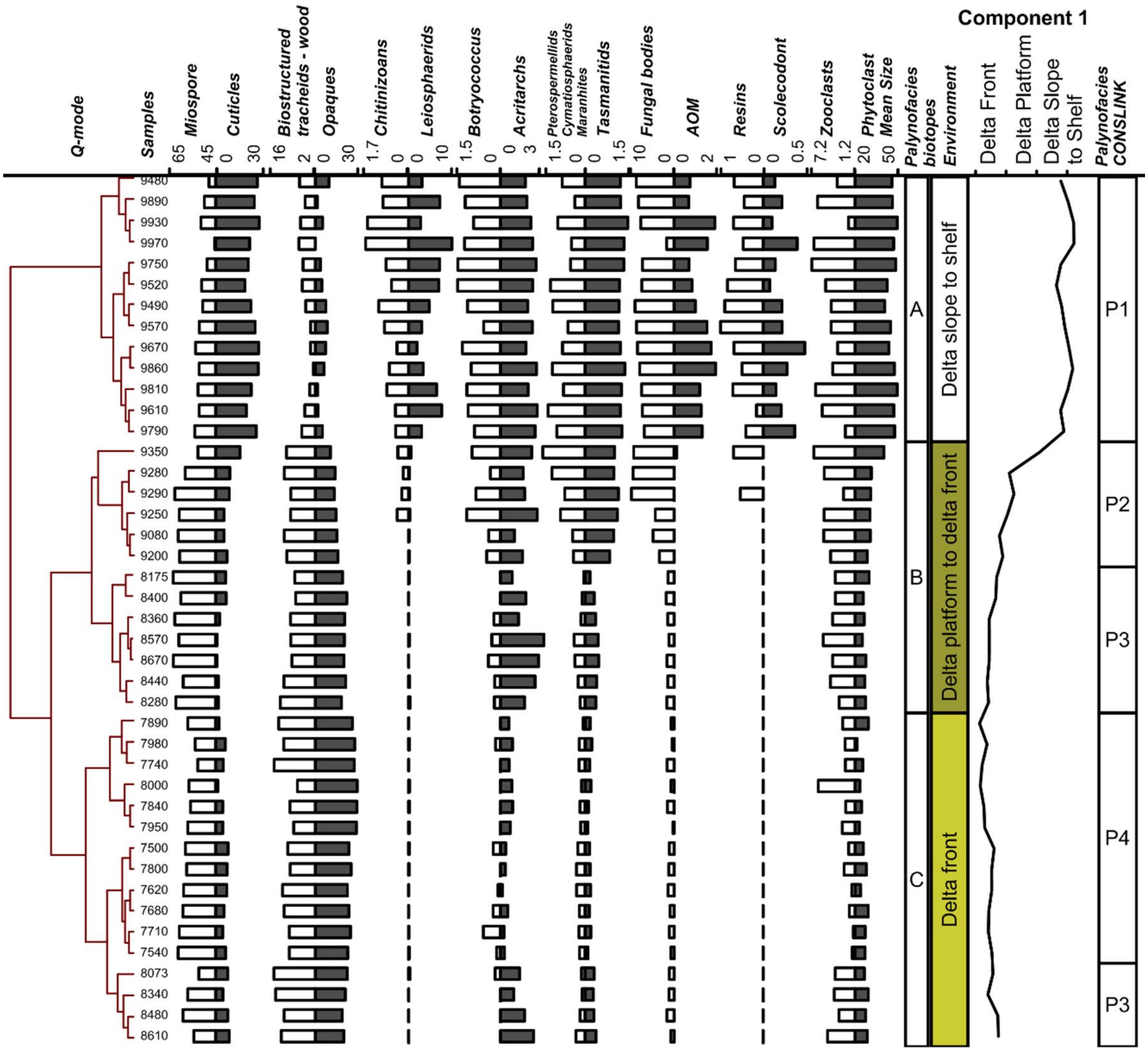

Fig. 4: Q mode cluster analysis of the relative abundances of the palynofacies categories, component 1 values and their biotopes interpretations.

The fluorescence color of the liptinite is another important feature to determine the thermal maturity levels and in the present study the liptinite including miospore (yellow–red), acritarchs (yellow–orange), Tasmanites (yellow), prasinophytes (yellow–green) and zooclasts (yellow–orange) remark the immature to early mature stages. The thermal maturity affect on the quantities of the organic matter, however, the maturity levels in studied samples are not high to cause a significant drop in their values. The measured values of the TOC are poor to good in the palynofacies biotopes. The calculated TOC values are used to present the relative differences between the biotopes. The TOC values can be used to understand some important aspects of the basinal settings that can affect on the organic matter quality and liptinite. The TOC values resulted from the interaction of three main parameters that are paleoproductivity, sedimentation rates (SRs), and redox conditions in marine settings (Katz, 2005; Tyson, 2005). The liptinite in the present study is also produced and transported effectively to the basin during most of the Devonian in the studied section in addition to marine micro–phytoplanktons high productivity as indicated by abundances of acritarchs and marine algae of palynofacies biotopes A and B in Early and Middle Devonian. The marine paleoproductivity was relatively dropped only in the late Frasnian and Famennian. In addition to the paleoproductivity, the calculated SR that was particularly low during the deposition of the biotope A and B reduce the organic matter dilution by the sediments, which would also lead to increase of the TOC (Tyson, 2005; Katz, 2005). However and despites the higher paleoproductivity and lower SR, the TOC are larger in the Biotope C. This indicate that the redox condition in the biotope A was not optimum to preserve high TOC and larger SR of biotope C with even higher oxidation levels helped to isolate the organic matter from active oxidation process (Katz, 2005; Tyson, 2005). There is a number of palynofacies and geochemical parameters that can be integrated to clear the oxygenation levels in the Devonian. Normally, the oxygen level in the basin is principally a function of mixing of the water masses, influx of terrigenous material, marine productivity and sedimentation rate (Tyson and Pearson, 1991; Tyson, 1995). These environmental conditions determine the available oxygen at the sediment water interface and how fast the organic matter are isolated from oxygenated layer by burial and then preserved (Katz, 2005; Tyson, 2005). The oxygen level affect on both the quantity and quality of the organic matters (Peters and Cassa, 1994). The essential palynofacies parameters that indicate the oxygen level is the preservation and abundance of the AOM (Tyson, 1995; Parrish, 1995). The AOM abundances recorded in the studied palynofacies slide are noticeably low as previously discussed. These low abundances indicate high dilution with terrestrial materials or high oxygen levels. The pyrite framboids are largely abundant in the condensed section in the samples of palynofacies biotope A in the Lower Devonian in Sifa–1 well. They are observed in the palynofacies slides in the pyritized fossils as well as a net of connected honeycomb shape nodules or individual scattered lumps in the sediments. The pyrite nodules are responsible of the dark color of the sediments in this part of the studied section. The pyrite formation is restricted to anoxic environment, beneath the oxic sediment layer or even within anoxic microenvironment like core of fecal pellets (Tyson, 1995). The larger amounts of pyrite are usually associated with the abundant algae, AOM and low SR in anoxic environments (Batten, 1996). Consequently, the relative higher pyrite abundances in palynofacies biotope A and partially in palynofacies B indicate the persistence of anoxic environment at least below an oxic layer if it was not the dominant. However, the palynofacies C had more oxygen enrichment and lower degree of pyritization may be because of higher SR and lower availability of marine metabolizable organic matter for sulphate reduction. The smaller size (>18 µm) and narrow size change indicate that framboids are formed in water–column, whereas the larger size and more variable sizes are formed in oxic–dysoxic environments (Wilkin *et al*., 1996). The sulfur and iron in the pyrite and bulk inorganic geochemical composition of the rock in addition to the TOC can be used to determine the oxygenation levels based on the sulphate reduction of the anaerobic bacteria. Accordingly, the pyrite formation is neither limited by the Fe nor organic matter, however, by the prolonged oxic condition that reduced the sulphate reduction. The conditions did not change significantly through the different palynofacies biotopes and obviously they have same redox conditions. Nevertheless, some variations are noticed in the trace element enrichments between palynofacies biotopes. The redox–sensitive trace elements (V, Ni, Cr, Zn and Cu) supported the previous results especially when they compared to the TOC and aluminum. The comparison between the TOC (wt %) with redox trace element is useful to determine the effect of oxygen depletion on the quantity of preserved organic matter.

3.5 Quality and organic geochemical characterization of the organic matter

The quality of organic matter is better assessed by the integration of microscopic and organic geochemical analyses. The previous results from microscopical investigations indicated abundant kerogen types I and II in palynofacies biotope A whereas the quality declined significantly in biotopes B and C. The organic geochemical analyses in the present study included elemental analysis (CHNSO) and pyrolysis gas chromatography (PyGC). The elemental analysis (CHNOS) is done on the isolated kerogen of 18 samples. However, the analysis gives valuable information about the kerogen type with consideration of the thermal maturity levels determined in the samples. The S/C versus the O/C present highly variable values of elemental sulfur (pyrite) but higher enrichments similar to kerogen type II and I fits. Devonian low abundances of the AOM are described in the North African Great Desert as "kerogene liptinique" by Combaz (1980). In general, the quality of palynofacies with low abundances of AOM is low. The pyrolysis gas chromatography (PyGC) is more reliable in assessment of kerogen type because it quantifies C, H and O assemblages and give the aliphatic C–bound hydrogen content in the kerogen that generate hydrocarbon during thermal maturation. Four samples were analyzed, three samples from palynofacies type A and one from biotope A. The PyGC analysis reveals dilution of the liptinite kerogen type II with kerogen type III (vitrinite or brown wood) and kerogen type IV (inertinite or opaque phytoclasts). The ratios indicate marine anoxic environmental settings and thermally mature kerogen for all biotopes and generally have a trend of the change with depth. The mixing of kerogen type II with kerogen type III can be assessed by calculation of assemblages of aliphatic compounds. The plot indicated that most of the samples are plotted in or near to oil–prone kerogen type I in all biotopes. Horsfield (1989) indicated that pyrolysate of the any kerogen is signifies the petroleum generated during the thermal maturation through a ternary plot. The samples distribution between these plots indicates the existence of kerogen type II that especially in the biotope A in the condensed section in the Early and Middle Devonian has potential to generate liquid hydrocarbons with consideration that the entire section is in the oil window as pointed by TAI.

4. Conclusions

The organic matter in the Sifa–1 well was examined by different methods, with a focus on the liptinite group macerals. The study concentrated on the stratigraphic range of the Zeitun Formation and lower part of Desouqy Formation, which extends chronologically from Lochkovian to Famennian. The sedimentation process witnessed drastic transformations that resulted from sea level and paleoclimatological changes between Early–Middle Devonian and Late Devonian. These changes controlled the sedimentation rates and quantity and quality of terrigenous and marine organic matter in the basin. The changes could be tracked by statistical analysis of the miospores genera and palynofacies categories. This analysis resulted in the definition of a number of paleoclimatological and depositional biotopes. These biotopes were integrated in a model that incorporated two phases, an Early–Middle Devonian transgressive phase and a Late Devonian regressive phase. Strata of the Early–Middle Devonian transgressive phase contain more abundant liptinite group macerals of both terrigenous and marine origin, which increased their potential to generate liquid hydrocarbons. The trace elements and pyrite content indicate only mild oxygen depletion, which was not suitable for abundant AOM (bituminite) preservation. This led to a significant reduction of organic matter quality, which was confirmed by organic petrographic, elemental, and pyrolysis gas chromatography analyses. These analyses indicate gas–prone kerogen type III and oil–prone kerogen type II mixed at different proportions. Organic matter in the Early–Middle Devonian transgressive phase was in the oil window in terms of thermal maturity, as indicated by the thermal alteration index of spores, thus had the potential to generate both liquid and gaseous hydrocarbons.

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References

Abd El–Gawad, E. A., M. F. Ghanem, M.M. Lotfy, D.A. Mousa, M.G. Temraz, A.M. Shehata, 2019. Burial and thermal history simulation of the subsurface Paleozoic source rocks in Faghur basin, north Western Desert, Egypt: Implication for hydrocarbon generation and expulsion history. Egyptian Journal of Petroleum, 28: 261–271.

Al–Ameri, T.K., 1984. Microstructures of possible early land plants from Tripolitania, North Africa. Review of Palaeobotany and Palynology, 40, 375–386.

Batten, D.J., 1996. Palynofacies and palaeo environmental interpretation. In: Jansonius, J. & McGregor, D. C. (Eds.): Palynology: principles and applications. American Association of Stratigraphic Palynologists, 3: 1011–1064.

Becker, R.T., F.M. Gradstein and O. Hammer, 2012. The Devonian Period. In: Gradstein, F. M.; Ogg, J. G.; Schmitz, M. D.; Ogg, G. (eds.): Geological Time Scale 2012. Elsevier BV 2, 562–604.

Boote, D. R. D., D.D. Clark–Lowes and M.W. Traut, 1998. Palaeozoic petroleum systems of North Africa. In: Macgregor, D. S.; Moody, R. T. J.; Clark–Lowes, D. D. (eds): Petroleum Geology of North Africa. Geological Society, London, Special Publication No. 132, 7–68.

Combaz, A., 1980. Les kerogenes vus au microscope, in Kerogen: Insoluble organic matter from sedimentary rocks (ed. Durand, B.), Editions Technip, Paris, pp. 55–111.

Davies, N.S., M.R. Gibling, 2010. Cambrian to Devonian evolution of alluvial systems: The sedimentological impact of the earliest land plants. Earth Science Reviews, 98, 171–200.

Edwards, D., 1982. Fragmentary non–vascular plant microfossils from the Late Silurian of Wales. Botanical Journal of the Lineaus Society 84, 223–256.

Edwards, D.and C. H.Wellman, 1996. Older plant macerals (excluding spores). In: Jansonius, J.; McGregor, D. C. (eds.), Palynology: Principles and Applications, vol. 1, Principles: American Association of Stratigraphic Palynologists Foundation, Publishers Press, Salt Lake City, p. 383–387.

El–Shamma, A.A., T.F. Moustafa and A.M. Hosny, 2011. Silurian–Devonian palynozonation of Sifa–1 borehole, Western Desert, Egypt. Egypt. Jour. Paleontol., 11, 207–227.

Filipiak, P., and M. Zatoń, 2011. Plant and animal cuticle remains from the Lower Devonian of southern Poland and their paleoenvironmental significance. Lethaia, 44: 397–409.

Filipiak, P., M. Zatoń, H. Szaniawski, R. Wrona and G.Racki, 2012. Palynology and microfacies of Lower Devonian mixed carbonate–siliciclastic deposits in Podolia, Ukraine. Acta Palaeontologica Polonica, 57 (4), 863–877.

Ghori, K.A.R., 1991. Petroleum geochemical aspects of Cyrenaica, NE Libya. Third Symposium on the Geology of Libya, vol. 7 (eds. M. J. Salem; M. T. Busrewil and A. M. Ben Ashour), Elsevier, Amsterdam, p. 2743–2756.

Hallett, D., and D. Clark–Lowes, 2012. Petroleum Geology of Libya. 391 pp.

Horsfield, B. (1989): Practical criteria for classifying kerogens: some observations from pyrolysis–gas chromatography. Geochimica et Cosmochimica Acta, 53, 891–901.

Katz, B.J., 2005. Controlling factors on source rock development – a review of productivity, preservation, and sedimentation rate. In: The Deposition of Organic–Carbon–Rich Sediments: Models, Mechanisms, and Consequences, Harris, N. (Ed). SEPM Special Publication No. 82, 7–16.

Keeley, M. L., 1994. Phanerozoic evolution of the basins of Northern Egypt and adjacent areas. Geologische Rundschau 83, 728–742.

Kondas, M., 2018. Nematophytes. Geology Today, 34 (2), 73–78.

Loydell, D. K.; Butcher, A.; Frýda, J. (2013): The middle Rhuddanian (Lower Silurian) 'hot' shale of North Africa and Arabia: An atypical hydrocarbon source rock. Palaeogeography, Palaeoclimatology, Palaeoecology, 386, 233–256.

Makled, W.A., A.E.A. Abd El–Moneim, T.F. Mostafa, M.Z. El–Sawy, D.A. Mousa and M.O. Ragab, 2020. Petroleum play of the Lower Cretaceous Alam El Bueib Formation in the El Noor–1X well in the north Western Desert (Egypt): A sequence stratigraphic framework. Marine and Petroleum Geology, 116, 104287.

Makled, W.A., T.F. Mostafa, D.A. Mousa and A.A. Abdou, 2018. Source rock evaluation and sequence stratigraphic model based on the palynofacies and geochemical analysis of the subsurface Devonian rocks in the Western Desert, Egypt. J. Mar. Pet. Geol. 89: 560–584.

Miller, M.A., 1996. Invertebrate cuticular fragments; in: Jansonius, J., McGregor, D. C. (ed.), Palynology: principles and applications. American Association of Stratigraphic Palynologists Foundation: 1, 381–382.

Parrish, J.T., 1995. Paleogeography of C_{org}-Rich Rocks and the Preservation versus Production Controversy. In: Huc, A. Y. (ed.): Paleogeography, Paleoclimate and Source Rocks. AAPG, Studies in Geology, 40, 1–20.

Pearson, D.L., 1984. Pollen/spore Color "standard," Version 2. Phillips Petroleum Co., Geology Branch, Bartlesville, Oklahoma.

Peters, K. E. and M. R. Cassa, 1994. Applied source rock geochemistry. In: Magoon, L. B.; Dow, W. G. (eds.): The petroleum system from source to trap. Am. Assoc. Pet. Geol. Bull 60, 93–120.

Richardson, J. B. and D.C. McGregor, 1986. Silurian and Devonian spore zones of the Old Red Sandstone Continent and adjacent regions. Geol. Surv. Canada, Bull. 364, p. 1–79.

Richardson, J. B. and S.M. Rasul, 1990. Palynofacies in a Late Silurian regressive sequence in the Welsh Borderland and Wales; Journal of the Geological Society, London, 147, 675–686.

Staplin, F.L., 1961. Reef–controlled distribution of Devonian microplankton in Alberta. Palaeontology, 4, 392–424.

Stein, W.E., F. Mannolini, L.V. Hernick, E. Landing and C.M. Berry, 2007. Giant cladoxylopsid trees resolve the enigma of the Earth's earliest fossil stumps at Gilboa. Nature 446, 904–907.

Tissot, B. P., B. Durand, J. Espitalie and A. Combaz, 1974. Influence of nature and diagenesis of organic matter in formation of petroleum. Am. Assoc. Petrol. Geol. Bull. 58: 499–506.

Tyson, R.V., 1993. Palynofacies analysis. In: Jenkins, D. J. (Ed.), Applied Micropalaeontology. Kluwer, Dordrecht, p. 153–191.

Tyson, R.V., 1995. Sedimentary Organic Matter: Organic Facies and Palynofacies. Chapman and Hall, London. 615 pp.

Tyson, R.V., 2000. Palynofacies prediction of distance from sediment source: a case study from the Upper Cretaceous of the Pyrenees. Geology, 28 (6), 569–571.

Tyson, R.V., 2005. The "productivity versus preservation" controversy: cause, flaws, and resolution. In; The Deposition of Organic–Carbon–Rich Sediments: Models, Mechanisms, and Consequences, Harris, N. (Ed). SEPM Special Publication No. 82, 17–33.

Tyson, R.V. and T.H. Pearson, 1991. Modem and ancient continental shelf anoxia: and overview, in Modern and Ancient Continental Shelf Anoxia (eds. R. V. Tyson and T. H. Pearson). Geological Society of London Special Publication, 58, 1–24.

Wilkin, R.T., H.L. Barnes and S.L. Brantley, 1996. The size distribution of framboidal pyrite in modern sediments: An indicator of redox conditions. Geochimica et Cosmochimica Acta, 60 (20), 3897–3912.