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FULL LENGTH ARTICLE

Mechanism of Late Campanian–Early Maastrichtian oil shale deposition and its sequence stratigraphy implications inferred from the palynological and geochemical analysis

Walid Ahmed Makled *, **Tarek Foad Mostafa, Abu Bakr Fathy Maky**

Exploration Department, Egyptian Petroleum Researches Institute, 1 Ahmed El Zomor St., El Zohor Region, Nasr City, Cairo 11727, Egypt

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Abstract Understanding the organic rich sediment deposition mechanism is vital for the purposes of their exploration. This should reconsider the sequence stratigraphic framework and its associated paleoenvironmental setting. The palynological and geochemical aspects of the organic rich beds from the Duwi Formation conducted on six phosphate mines in the Eastern Desert of Egypt are reported in the present study and they were used to investigate the paleoenvironmental settings that existed during its deposition. The palynomorph assemblages were dominated by moderately diverse and abundant dinoflagellates and in El-Nakheil, Wasif, Umm Hueitat and Mohamed Rabah mines and generally scarce palynomorph assemblages were generally detected at El-Beida and Younis mines. The dinoflagellates are mainly peridinioids, namely; *Alterbidinium acutulum*, *Cerodinium obliquipes*, *Palaeocystodinium australinum* and *Phelodinium tricuspis*, in addition to some gonyaulacoid such as *Kleithriasphaeridium readei*, *Hystrichosphaeridium* sp. A, *Hystrichosphaeridium* sp. B and *Spiniferites supparus*. These dinoflagellate assemblages are indicating Late Campanian–Early Maastrichtian age. The palynofacies analysis revealed enrichments with amorphous organic matter (AOM) at El-Nakheil and El-Beida mines, while the phytoclasts enrichments were found to be at the Younis mine. The enriched AOM samples are of Type I and II oil prone kerogen while the enriched phytoclasts are of Type III gas prone kerogen. In line with, the resulted kerogen types agreed with rock eval pyrolysis analysis. The integration of rock eval pyrolysis and other geochemical parameters with the palynofacies analysis indicated that the deposition of low organic matter sediments (TOC ~ 0.04–1.77 wt%) took place in a low stand system-tract. On the other hand, the sediments of high organic matter content (TOC ~ 9.66–22.23 wt%) were deposited in a trans-

* Corresponding author. Tel.: +20 1159881360.
E-mail address: walidmakled@yahoo.com (W.A. Makled).

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gressive system tract under low sedimentation rate. Eventually, the intermediate organic matter content sediments (TOC ~ 8.39–22 wt%) were deposited in a high stand system tract during an active paleoproductivity and upwelling.

1. Introduction

Duwi Formation is destined to pile up many valuable fortunes for Egypt. Since the 1950s it was the main source of phosphate minerals' exploitation, which composed the bases for important industries such as agricultural fertilizers. In the more recent years, there is growing evidence about its capacity to store uranium [1,2]. Since 1980s, the organic matter rich sediments (carbonaceous oil shales) accompanied phosphorites have drawn the attention [3,4]. These oil shale beds have been reported to catch fire [5]. The average oil content of weathered black shale samples is 19 gallon/ton [6]. These oil shale beds in Duwi Formation have many relatives in the neighbor countries such as Jordan and occupied Palestine. The oil shale beds in these countries are exploited regularly and are used in many industrial applications such as electricity production and cement industry as direct combustion; they are also used to produce liquid fuels by retorting [7,8]. These oil shale beds are associated with one large environmental setting that is known as Parrish and Curtis [9] upwelling belt. This belt existed in the Late Campanian–Early Maastrichtian in the southeastern Levant Basin. The majority of oil shale workers in such countries adopt the same model mechanism for the deposition of the oil shale beds. Accordingly, organic matter rich sediments of the oil shale beds resulted exclusively from the high surface paleoproductivity accompanied by the upwelling high nutrient levels and oxygen poor bottom water during the Late Campanian–Early Maastrichtian in the southeastern Levant Basin [10–13]. The limitation, that is considered as Achilles' heel in this Primary-Productivity-Driven model, is the weak concurrence between the oceanic primary productivity intensities and organic-carbon levels in sediment surface layers in modern oceanic upwelling zones (e.g., the Equatorial Pacific, Antarctic Divergences and the northwest African margin coastal upwelling) [14,15]. The outcome of dysoxic to anoxic conditions on the organic matter preservation is only graspable at slow sedimentation rates [16]. There are three factors controlling the total organic carbon content in the sediments, namely; organic matter input (productivity), organic matter preservation (oxygen deficiency) and dilution by mineralic sediment components. These factors are fully discussed in Katz [15] and Tyson [16]. The last factor is directly related to the sequence stratigraphic framework and its associated paleoenvironmental settings. The lower mineral sedimentation rates are associated with the flooding surfaces during the transgression system tracts.

The reconsideration of paleoproductivity as the major factor for the formation of the oil shale beds in the Upper Campanian–Lower Maastrichtian sediments is the central focus of the present study. The present paper aims to revaluate and explore the space relationship on the one hand between oil shale beds in the Duwi Formation in the Al-Qusseir area and on the other hand between these oil shale beds and their equivalents in adjacent countries in the perspective of the palynological and organic geochemical studies. This research study is based on twenty samples collected from some Egyptian localities and the geological knowledge available in the literature from the surrounding countries. The study of dinoflagellate biozonation and statistical distribution facilitate aging of certain dinoflagellate diversities and synchronize their excessive flux events in the different areas. These events were in turn exclusively connected to some intense paleoproductivity fluctuations in Parrish and Curtis [9] upwelling belt and deposition of the oil shale. In the present study, a revision of these concepts has been considered with referring to the recent studies of deposition of organic matter rich sediments in the Duwi Formation in the sequence stratigraphy framework and its associated paleoenvironmental settings.

2. Geological settings of the Duwi Formation

The Precambrian granite and metamorphic rocks (gneiss, schist) compose the basement complex in Egypt. They form a rough terrain at the Eastern Desert of Egypt along the Red Sea coast and Sinai. The Upper Cretaceous to Lower Cenozoic sedimentary rocks cover the basement complex in some areas (Fig. 1A). The Duwi Formation is a part of the Upper Cretaceous–Lower Cenozoic sedimentary sequence and is widely distributed in the Eastern Desert, Nile Valley and Western Desert areas. The Duwi Formation unconformably overlies the fluvial shale sequence of the mid Campanian Qusseir Formation, and conformably underlies the deep marine shales and marls of the mid Maastrichtian Dakhla Formation. Thus, deposition of the Duwi Formation represents an initial stage of the Late Cretaceous marine transgression in Egypt [10,17]. The Gebel Duwi region extends in a northwest direction along the western coast of the Red Sea from south of Al-Qusseir to Safaga, between latitude 25°50′ and 26°67′N and longitude 33°45′ and 34°25′E (Fig. 1A), covering an area of about 500 km^2 [18].

The general lithological compositions of the Duwi Formation in studied localities are presented in Fig. 2. The Duwi Formation is usually subdivided into three members by Said [19] and Temraz [18]. In [19], Said extended the use of the term Duwi Formation to laminated gray clays and chert phosphatic bands at Safaga and subdivided the whole section in the Red Sea area into three members, which are Atshan or "A", middle Duwi or "B" member and lower Abu Shegela or "C" member. The Atshan or "A" member is separated from the middle Duwi or "B" member by an Oyster limestone bed 6–16 m in thickness; while the lower Abu Shegela, or "C" member, is separated from the middle member by a shale unit of variable thickness (6–10 m). In the present time, the Duwi Formation is subdivided into four members, which are the lower, the middle, the upper and the uppermost members by Baioumy and Tada [10] and Baioumy et al. [17]. The oil shale beds are concentrated in the Atshan or "A" and middle Duwi or "B" members.