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Marine palynology and environmental interpretation of the Lower Cretaceous (Barremian?–Aptian) rock units in the Koppeh-Dagh Basin, NE Iran

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The Sarcheshmeh and Sanganeh formations are the Lower Cretaceous deep marine sequences of the Koppeh-Dagh sedimentary basin, which revealed a diverse assemblage of dinoflagellates. The paper discusses palynostratigraphy, palynofacies and palaeoenvironment of these rock units in a borehole drilled in the eastern part of this basin. Ninety-five ditch-cutting samples were prepared and studied palynologically, which resulted in recognition of 76 species of dinoflagellate cysts belonging to 29 genera. The recorded assemblages are in accordance with the *Odontochitina operculata* Zone suggesting a Barremian?–Aptian age for the formations. Palynological data extracted led to identification of five palynofacies types based on the categories of Tyson (1995). These indicate a marginal, proximal and distal shelf environment of deposition. The obtained data from calculated palaeoecological factors revealed a gradual sea level rise during the deposition of these rock units, resulting in replacement of the oxic/dysoxic Sarcheshmeh Formation by the dysoxic/anoxic Sanganeh Formation.

Key words: Koppeh-Dagh, palynostratigraphy, palynofacies, palaeoecology, palaeoenvironment.

INTRODUCTION

The Cretaceous period is associated with spreading of low-oxygen conditions in oceanic basins due to massive submarine volcanic activity and oceanic crustal production. These oceanic anoxic events (OAEs) led to deposition of large amounts of organic matter in many parts of the world especially in the Tethys Basin (Arthur et al., 1990; Leckie et al., 2002; Baudin, 2005; Steuber et al., 2005; Ando et al., 2008; Föllmi, 2012). The Koppeh-Dagh sedimentary basin, as part of the northern Tethyan realm (Glennie, 2000), stretches in an area covering northeastern Iran, southern Turkmenistan and north Afghanistan (Fig. 1A). It is known for high hydrocarbon potential and huge gas reservoirs (Kavoosi et al., 2010). The Aptian-Albian deep-marine successions of this basin, introduced as the Sarcheshmeh and Sanganeh formations, are rich in marine palynomorphs (dinoflagellate cysts). These marine elements are a major member of the Cretaceous microflora in the Tethyan realm and evaluation of their stratigraphic and environmental distribution is broadly applied in major hydrocarbon exploration projects (Kimyai, 2000; Torricelli, 2000; Pavlishina and Feist-Burkhardt, 2004; Oosting et al., 2006; Backhouse, 2006; Quattrocchio et al., 2006; Pestchevitskaya, 2007). The current study investigates palynology, palynostratigraphy and depositional setting of the Sarcheshmeh and Sanganeh formations in a borehole located in the east of the Iranian part of the basin. For confidential reasons of National Iranian Oil Company (NIOC), the real name of the studied well is not cited. Therefore, the subsurface section is renamed here as borehole A.

GEOLOGICAL SETTING

The Koppeh-Dagh Basin is an inverted structure formed in the Early to Middle Jurassic (Garzanti and Gaetani, 2002; Allen et al., 2003). A relatively continuous sedimentation from the Jurassic through the Eocene in the eastern parts of the basin (Afshar-Harb, 1994) rendered the thickest Cretaceous deposits of Iran (Berberian and King, 1981; Raisossadat and Moussavi-Harami, 2000; Raisossadat, 2006). The Early Cretaceous sea level rise resulted in a transgressive sedimentary megasequence that consists of four formations. The succession begins with the Neocomian terrigenous Shurijeh Formation passing into shallow-shelf strata of the carbonate Tirgan Formation of

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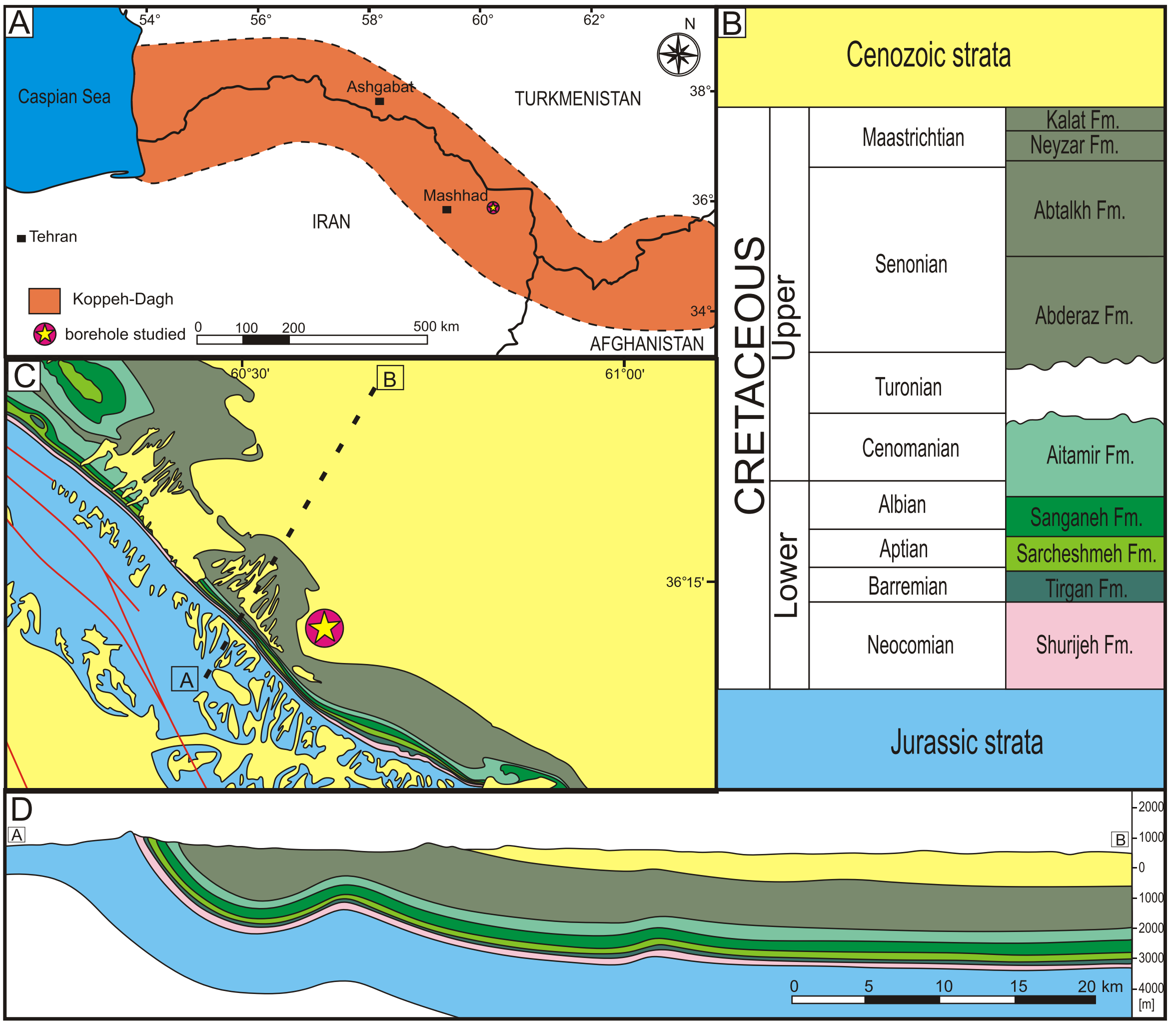

Fig. 1A – location map of the studied borehole; B – Cretaceous lithostratigraphic chart of the Koppeh-Dagh sedimentary basin; C – geological map of the study area (modified from Afshar-Harb, 1982); D – geological cross-section A–B shown in Figure 1C (modified from Afshar-Harb, 1982)

Barremian–Early Aptian age. These carbonates are in turn followed by relatively deep-marine strata of the Sarcheshmeh and Sanganeh formations (Fig. 1B; Robert et al., 2014). Figure 1D shows the structural relationships between the rock units across the AB profile (Fig. 1C) in the study area.

At the type section, the Sarcheshmeh Formation consists of marls and shales and the Sanganeh Formation is represented mainly by dark grey to black shales (Afshar-Harb, 1994). In borehole A, the thickness of the Sarcheshmeh Formation is 177 m, and the unit consists mainly of marls, shales and shaly limestones. The Sanganeh Formation is a 348 m thick succession of claystones and shales interbedded by limestones (Fig. 2).

MATERIAL AND METHODS

Ninety-five ditch-cutting samples from both the Sarcheshmeh and Sanganeh formations were collected and analysed for palynology. Of these, 48 samples were from the Sarcheshmeh Formation and 47 samples from the Sanganeh Formation (Appendix 1*).

Palynological slides were prepared in a conventional maceration procedure (Traverse, 2007). Cold hydrochloric (20%) and hydrofluoric (50%) acids were used to dissolve carbonates and silicates. No oxidants or alkalis were exerted. The residue was neutralized and centrifuged in aqueous solution of $ZnCl_2$ (specific gravity 1.9 g/cm^3), then sieved at 15 μm via a nylon mesh, and mounted on microscope slides using liquid Canada balsam. Prepared palynological slides were studied by a transmitted light microscope and the index species were photographed and presented in Figure 3. In this study, we also count and calculate percentages of the three main groups of palynological elements including amorphous organic matter (AOM), terrestrial elements (phytoclasts) and marine palynomorphs in all samples. The data gained are plotted on Tyson's ternary diagram (Tyson, 1995) for palaeoenvironmental interpretations

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1394

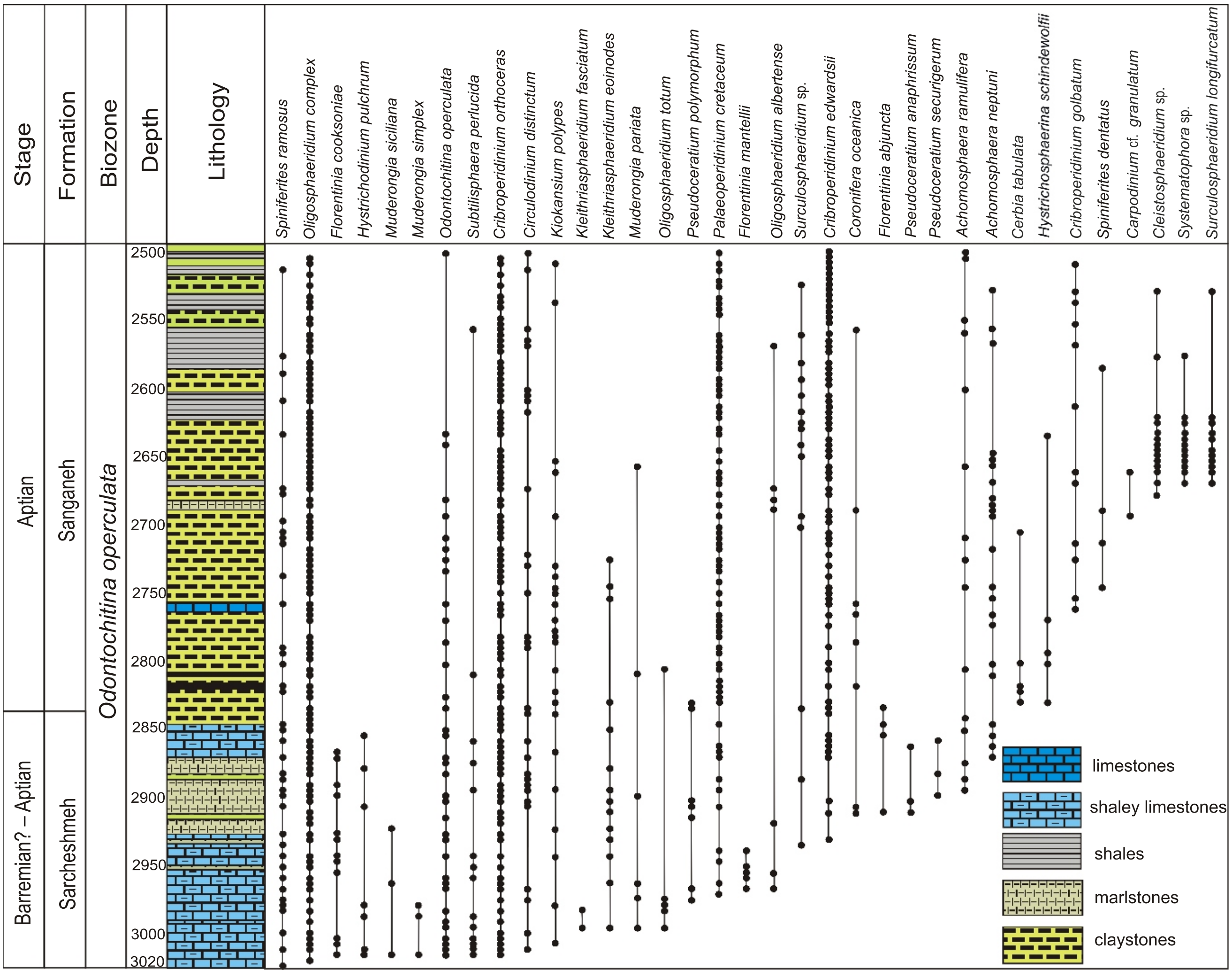

Fig. 2. Recorded marine palynomorphs and their distribution throughout the studied interval

(Fig. 4). The spore colour index (SCI) is also used here as another method in order to estimate the degree of organic maturity. It ranges from 1 to 10 reflecting a colour gradation from yellow to black (Marshall, 1990; Utting and Hamblin, 1991).

RESULTS AND DISCUSSION

PALYNOLOGY AND PALYNOSTRATIGRAPHY

Cretaceous dinoflagellate cysts have been studied by many researchers and widely used for biostratigraphy and age dating in the Tethyan Realm (Davey and Verdier, 1974; Hoedemaeker and Leereveld, 1995; Leereveld, 1997; Ibrahim et al., 2002). The Neocomian dinocyst assemblages revealed low-diversity communities (Stover et al., 1996) usually marked by the presence of *Cribroperidinium, Circulodinium, Muderongia, Pseudoceratium, Phoberocysta* and *Oligosphaeridium* genera (Davey, 1979; Rawson and Riely, 1982; Woollam and Riding, 1983; Helby et al., 1987; Stover et al., 1996). During the Barremian and Aptian, dinoflagellates increased in number and diversified (Stover et al., 1996). The first appearance of *Odontochitina operculata* and *Palaeoperidinium cretaceum* are recorded in the Barremian stage (Harding, 1990; Costa and Davey, 1992). The Aptian dinocyst assemblages are characterized by the co-occurrence of *Oligosphaeridium, Spiniferites, Kiokansium, Pseudoceratium, Hystrichodinium, Odontochitina* and *Florentinia* genera (Davey and Verdier, 1974; Costa and Davey, 1992; Torricelli, 2000; Helby et al., 2004).

In this study, palynological investigations revealed that the Sarcheshmeh and Sanganeh formations are dominated by dinoflagellate cysts. Thirty-two species of dinoflagellate cysts belonging to 19 genera were recorded in the Sarcheshmeh Formation. The Sanganeh Formation was richer and more diverse, yielding 53 species belonging to 28 genera. Spore and pollen grains and acritarchs were also present in both formations. Except for the basal intervals of the Sarcheshmeh and the upper parts of the Sanganeh formations in which dinoflagellate cysts preservation is poor, they are generally preserved moderate to good in the rest of the two rock units studied. The assemblages detected in the Sarcheshmeh and Sanganeh formations are dominant and characterized by the presence of *Achomosphaera neptuni, Callaiosphaeridium asymmetricum, Cerbia tabulata, Circulodinium distinctum, Coronifera oceanica, Kleithriasphaeridium eoinodes, Cribroperidinium edwardsii, Cr. orthoceras, Florentinia abjuncta, Fl. cooksoniae, Hystrichodinium pulchrum, Hy. ramoides, Hystrichosphaerina schindewolfii, Kiokansium polypes, Muderongia pariata, Mu. simplex, Odontochitina operculata, Oligosphaeridium complex, Ol.*

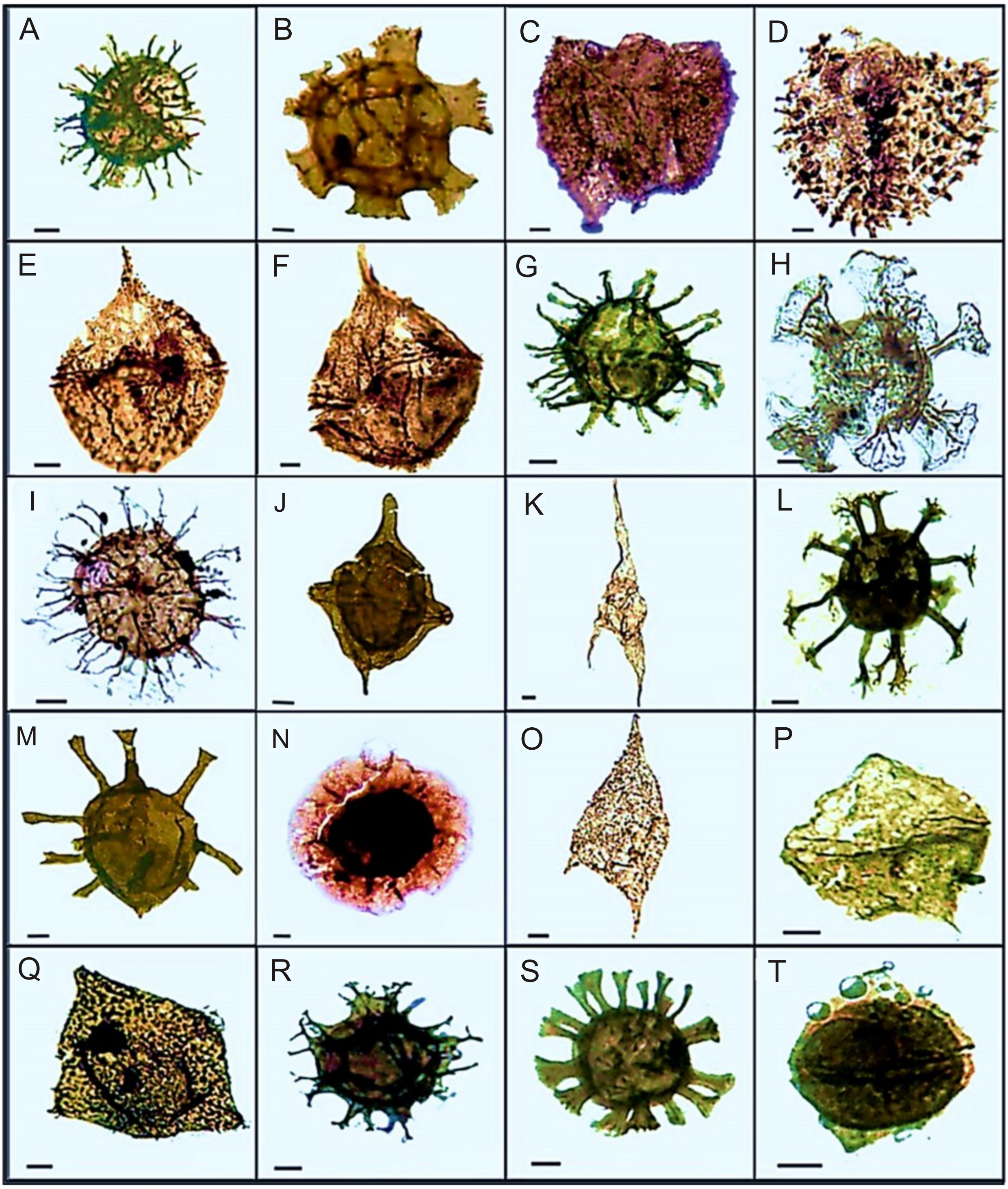

Fig. 3. Some of the recorded palynomorphs from the studied borehole (scale bars are 10 μm), A, B, G, J, L, M, P–T – Sarcheshmeh Fm.; C–F, H, I, K, N, O – Sanganeh Fm.

A – *Achomosphaera ramulifera* (Deflandre, 1937) Evit, 1963; **B** – *Callaiosphaeridium asymmetricum* (Deflandre and Courteville, 1939) Davey and Williams, 1966; **C** – *Cerbia tabulata (*Davey and Verdier, 1974) Below, 1981; **D** – *Circulodinium distinctum* (Deflandre and Cookson, 1955) Jansonius, 1986; **E** – *Cribroperidinium edwardsii* (Cookson and Eisenack, 1958) Davey, 1969; **F** – *Cr. orthoceras* (Eisenack, 1958) Davey, 1969 emend. Sarjeant, 1985; **G** – *Hystrichodinum ramoides* Alberti, 1961; **H** – *Hystrichosphaerina schindewolfii* Alberti, 1961; **I** – *Kiokansium polypes* (Cookson and Eisenack, 1962) Below, 1982 emend. Duxbury, 1983; **J** – *Muderongia simplex* Alberti, 1961; **K** – *Odontochitina operculata* (Wetzel, 1933) Deflandre and Cookson, 1955; **L** – *Oligosphaeridium complex* (White, 1842) Davey and Williams, 1966; **M** – *Ol. totum* Brideaux, 1971 emend. Dörhöfer and Davies, 1980; **N** – *Petrospermella* sp.; **O** – *Pseudoceratium pelliferum* Gocht, 1957; **P** – *Palaeoperidinium cretaceum* (Pocock, 1962) Lentin and Williams, 1976; **Q** – *Pseudoceratium polymorphum* (Eisenack, 1958) Bint, 1986 emend. Dörhöfer and Davies, 1980; **R** – *Spiniferites ramosus* (Ehrenberg, 1838) Mantell, 1854; **S** – *Kleithriasphaeridium eoniodes* (Esienack, 1958) Davey, 1974 emend. Sarjeant, 1985; **T** – *Subtilisphaera perlucida* (Alberti, 1959) Jain and Millepied, 1973

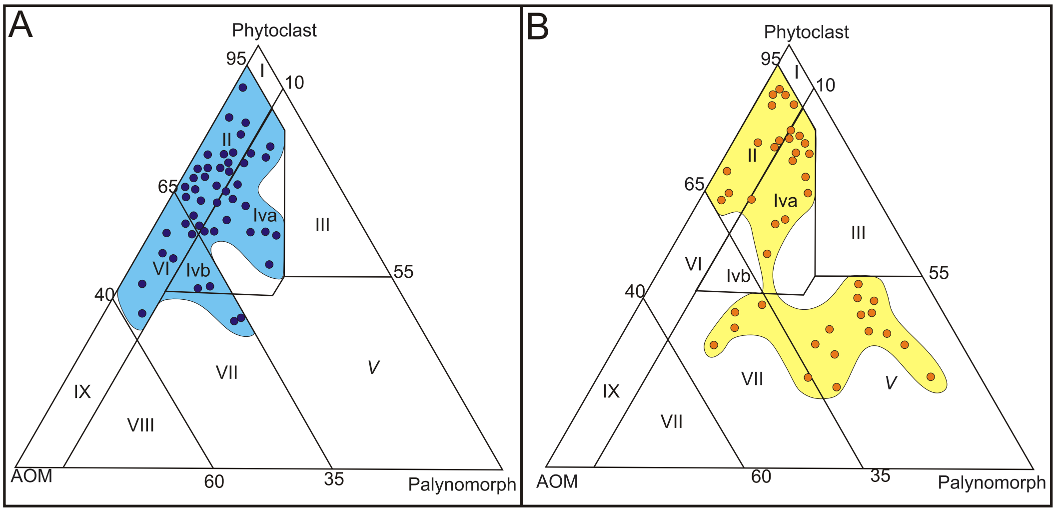

Fig. 4. The diagrams of Tyson (1995) for (A) Sarcheshmeh Formation and (B) Sanganeh Formation

totum, Palaeoperidinium cretaceum, Pseudoceratium polymorphum, Ps. securigerum, Spiniferites ramosus and *Subtilisphaera perlucida* (Figs. 2 and 3).

The last occurrences of species such as *Achomosphaera neptuni*, *Cerbia tabulata* and *Hystrichosphaerina schindewolfii* proved the Aptian age in the Tethyan realm (Davey and Verdier, 1974; Leereveld, 1995; Stover et al., 1996). Moreover, high frequency and abundance of *Odontochitina operculata, Oligosphaeridium complex* and *Circulodinium distinctum* were used for subdividing the Aptian stage (Kimyai, 2000), and the presence of *Coronifera oceanica* and *Surculosphaeridium longifurcatum* indicates Aptian age in Western Europe (Torricelli, 2000; Heimhofer et al., 2005). Helby et al. (1987) introduced a comprehensive palynozonation for the Australian Basin. Our dinocysts recorded from the Sarcheshmeh and Sanganeh formations are in reasonable accordance with the *Odontochitina operculata* Oppel Zone. This palynozone and part of the *Muderongia superzone* (Helby et al., 1987) are defined between the first occurrences of *Odontochitina operculata* and the first occurrence of *Psedoceratium turneri* (Helby et al., 1987). There is no consensus about the lower boundary of this zone, as in Australia it is dated Aptian (Morgan, 1980; Helby and McMinn, 1992; Helby et al., 1987, 2004; Ooisting et al., 2006) or Barremian-Aptian (Backhouse, 1988). In Europe, this zone has been regarded as the marker of the Barremian (Davey, 1979; Heilmann-Clausen, 1987; Harding, 1990; Costa and Davey, 1992).

According to the palynomorphs recorded here, the assemblages could be assigned to the Barremian?–Aptian, and the *Odontochitina operculata* palynozone is constrained.

PALYNOFACIES

Palynofacies has an important application in palynological studies that are widely used for palaeoenvironmental reconstruction, basin analysis, petroleum exploration, and evaluation of source rocks potential. Various concepts, such as: estimating distance to shoreline, water depth, sequence stratigraphy, reconstruction of palaeoenvironment and its effect on palaeoecological factors, can be understood from palynofacies studies (Tyson, 1995; Bombardier and Gorin, 2000; Oboh-Ikuenobe and de Villiers, 2003). One of the most useful applications is the use of palynofacies analysis as a proxy to evaluate source rock horizons that are of immense practical significance in hydrocarbon systems (Batten, 1996; Batten and Stead, 2005). Total organic carbon (TOC) values are in direct relation with the amount of AOMs in palynofacies studies (Tyson, 1995; Zobaa, 2011). The AOM-rich zones are characteristic of highly oil-prone kerogen type I, while kerogen types II and III are controlled by both phytoclasts and AOM and indicate oil- to gas-prone horizons (Tyson, 1993, 1995; Ibrahim et al., 1997).

During the past decades, different types of palynofacies characterizations for palaeoenvironmental interpretation have been published (e.g., Tyson, 1993, 1995; Batten, 1996; Batten and Stead, 2005). Tyson (1995) described a ternary kerogen plot based on three major groups of organic matter remains and defined nine different palynofacies zones, each showing a specific palaeoenvironmental condition. In the current study, percentages of the three main kerogen types were calculated (Appendix 1) for detailed palynofacies analysis. Results show abundance of phytoclasts in most parts of the Sarcheshmeh Formation and in the basal section of the Sanganeh Foramation. Meanwhile, upwards in the Sanganeh Formation, the amount of phytoclasts decreased and the frequency of AOM and palynomorphs increased, which is generally interpreted as reflecting a sea level rise (transgression) (Eshet et al., 1988a, b; Habib and Miller, 1989; Gorin and Steffen, 1991; Gregory and Hart, 1992; Carvalho et al., 2006). Using the Tyson ternary diagram, five types of palynofacies have been identified based upon the distance from the source region. The palynofacies are of types II, IV, V, VI and VII. They represent marginal, proximal and distal shelves and are used to study depositional setting (Figs. 4 and 5).

Palynofacies II. This palynofacies encompasses enormous amounts of phytoclasts varying from 65 to 95%. AOM and marine palynomorphs were <30 and 10%, respectively. These phytoclast-rich facies is deposited in a marginal dysoxic-anoxic basin and its kerogen is of III type, which is gas-prone. This palynofacies is dominant within the Sarcheshmeh Fm., while it is limited only to the lower parts of the Sanganeh Fm. (Fig. 6).

Palynofacies IV. Terrestrial elements vary between 42–75%, AOM from 5 to 41.1%, while marine palynomorphs vary from 10 to 32%. These characteristics are indicative of palynofacies IV of Tyson (1995), revealing a transitional, shelf-to-basin environment, and, it is mainly gas-prone due to its high terrestrial kerogen content (Tyson, 1995). Palynofacies type IV in the Sarcheshmeh Formation reflected a sea level fluctuation

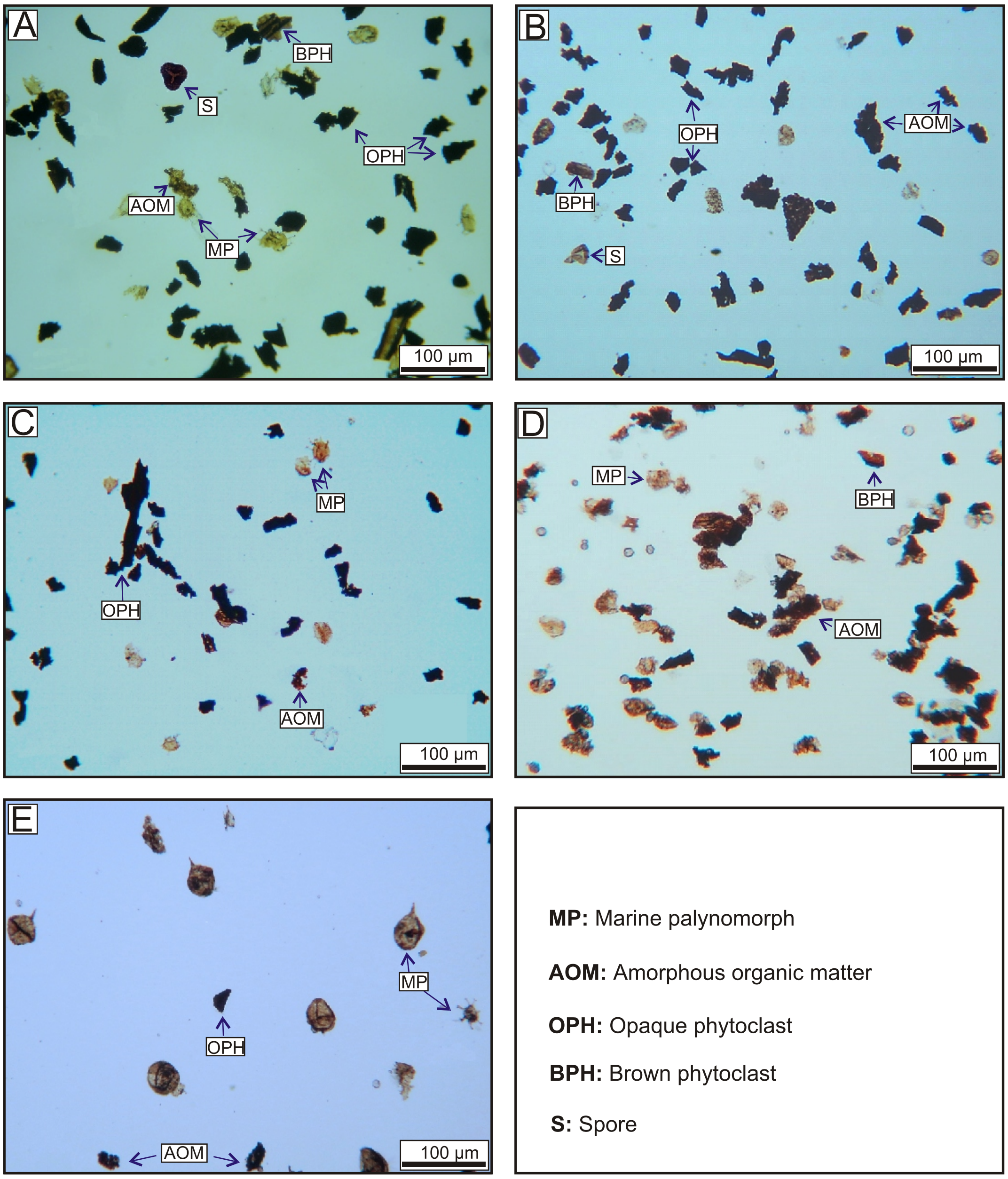

Fig. 5. Examples of recognized palynofacies within the Sarcheshmeh and Sanganeh formations

A – palynofacies II (2932 m); **B** – palynofacies VI (2862 m); **C** – palynofacies IV (2752 m); **D** – palynofacies VII (2616 m); **E** – palynofacies V (2552 m)

from shallower to deeper conditions in the basin. Similar to palynofacies type II, this facies,was recorded mainly in the lower parts within the Sanganeh Formation.

Palynofacies V. In this palynofacies, dinoflagellate cysts significantly increased and reached their highest percentage (45–65%) in the studied sequences. Other organic matter clasts, such as phytoclasts, were between 25 and 46% and AOMs vary from 10 to 30%. This palynofacies is referred to kerogen type II and is deposited on an oxic distal shelf (Tyson, 1995). The frequency and good preservation state of dinocysts could be attributed to high sedimentation rate. Presence of palynofacies V in the studied sequence is interpreted as corresponding to the maximum flooding (transgression) in a shelf and coincided with development of a proper condition for deposition of organic-rich shales. This facies is confined to the upper parts of the Sanganeh Formation and is not known from the Sarcheshmeh Formation.

Palynofacies VI. Tyson (1995) proposed a proximal suboxic-anoxic shelf sedimentary environment for this palynofacies. Amorphous organic matter and terrestrial phytoclasts were the major constitutive components of the palynological kerogens, and marine palynomorphs constituted <10%. According to Tyson (1995), kerogen of palynofacies VI is of oil-prone type (kerogen type II) due to its high AOM content. In contrast to palynofacies V, this palynofacies is not found in the Sanganeh Formation and scattered at low frequency only in the Sarcheshmeh Formation.

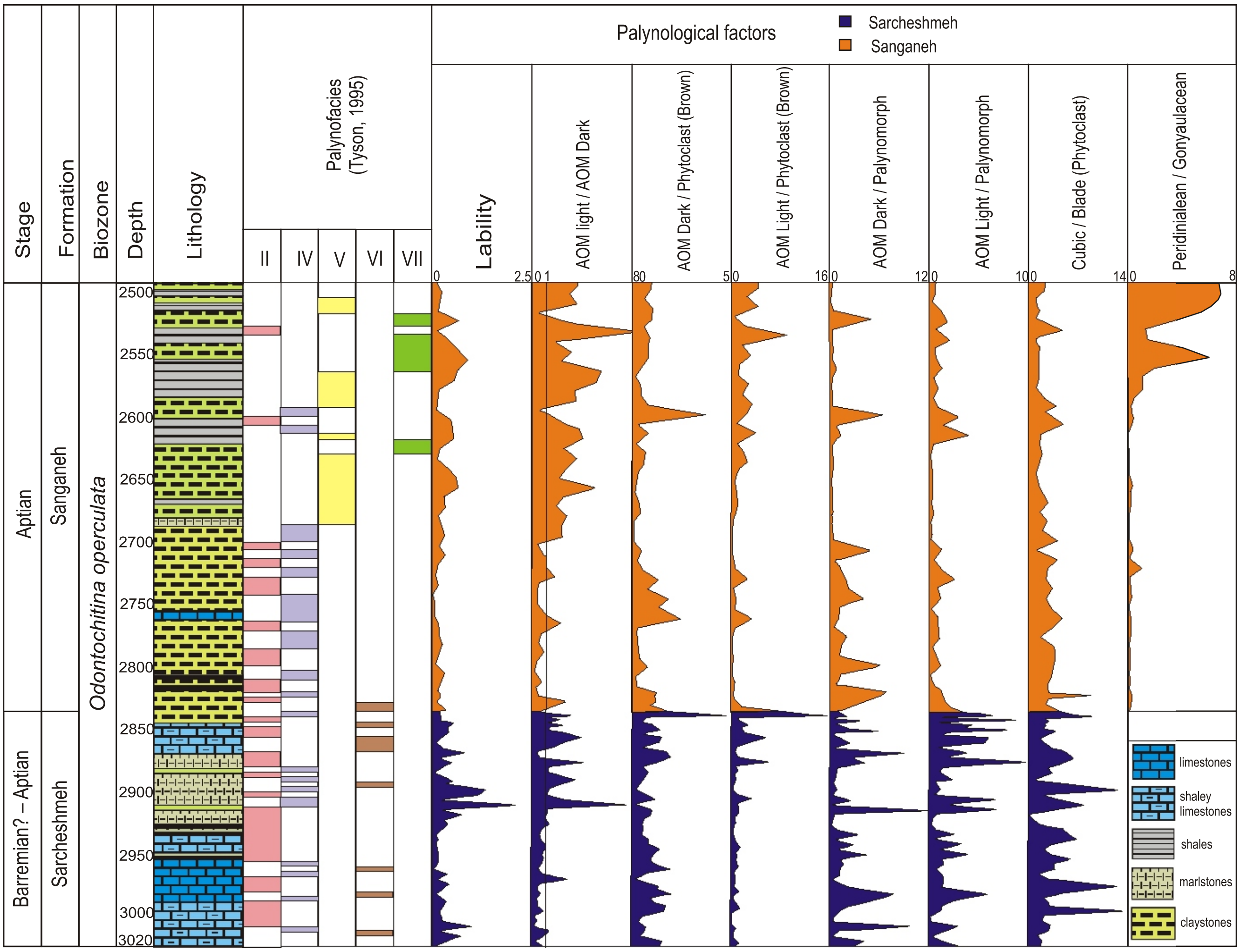

Fig. 6. Variations in proxies used for palaeoenvironmental interpretations in the studied rock units

Palynofacies VII. The kerogen composition of this palynofacies, in similar with palynofacies VI, is characterized with the dominance of AOMs and phytoclasts; however, the frequency of marine palynomorphs increased (up to 10%). Palynofacies VII refers to oil-prone kerogen of type II deposited in a distal dysoxic–anoxic shelf (Tyson, 1995). This facies is not common and has only been detected from small intervals in both formations.

DEPOSITIONAL SETTING AND ENVIRONMENTAL RECONSTRUCTION

In order to reconstruct the palaeoenvironment and its prevalent conditions, palynofacies data combined with prominent palaeoecological results, obtained from some calculated palaeoecological factors, have been used (Fig. 6). The palaeoecological factors used are the ratios of brown to opaque phytoclasts (Lability), light AOM to dark AOM, AOM to brown phytoclasts, AOM to marine palynomorphs, and, finally, cubic to bladed phytoclasts. These palaeoecological parameters are diversely used to determine sea level changes, sedimentation rates, palaeoproductivity and differentiation of oxidant, dysoxic and anoxic environments (Tyson, 1993; Van-Waveren and Visscher, 1994; Bombardier and Gorin, 2000). Generally, phytoclasts depend on land plants. Their abundance shows an environment close to the shorelines; however, high values of bladed phytoclasts along with dominance of marine palynomorphs (in comparison with terrestrial materials) mark offshore environments (Boulter and Riddick, 1986; Bombardier and Gorin, 2000; Schioler et al., 2002). The amount of oxygen in the depositional environments is usually estimated using the AOMs content of rock units. Based on this, high values of AOMs, especially light AOMs (the light AOM to dark AOM ratio >1), reflect dominance of an anoxic condition (Bombardier and Gorin, 2000). In contrast to this, black colour clasts (dark AOMs and opaque phytoclasts) show a relatively oxic environment (Van-Waveren and Visscher, 1994). The sedimentation rate could also be evaluated by use of palynomorphs preservation. In these cases, the maximum perseverance of dinoflagellate cysts occurs in an anoxic condition with high sedimentation rate (Van-Waveren and Visscher, 1994; Bombardier and Gorin, 2000).

According to the obtained data (presented in Fig. 6), a marginal basin extended during deposition of the Sarcheshmeh Formation. It was more stable during deposition of its lower part, reflecting some sea level fluctuations in the upper part of the formation. A gradual sea level rise can be interpreted. Due to this, a dysoxic/anoxic dominance with low sedimentation rates can be detected in the upper part in contrast to the oxic/dysoxic condition in the lower section of the formation. The sea level rise, A

Spores and pollen colour	SCI
Pale yellow	1
Pale yellow - lemon yellow	2
Lemon yellow	3
Golden yellow	4
Yellow orange	5
Orange	6
Orange brown	7
Dark brown	8
Dark brown - black	9
Black	10

B

Spores and pollen colour	TAI	Petroleum generation
Pale yellow to yellow	1	Immature kerogen
Yellow to orange brown	2	Oil window
Dark brown	3	Gas window
Brownish black to black colour	4	Wet gas limit Dry gas preservation
Vitreous black- fossils brittle	5	Dry gas preservation limit

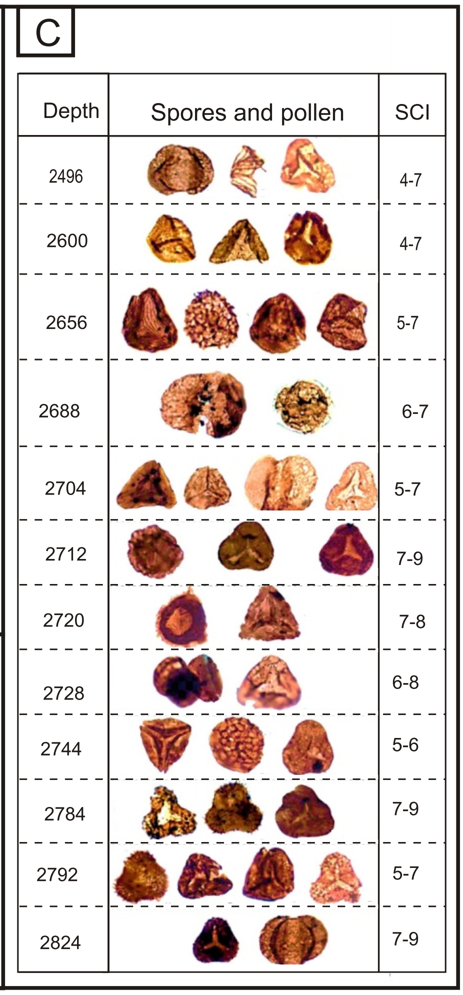

Fig. 7A – spore colour index (SCI) and colour changes within spores and pollen (modified from Marshall, 1990); B – correlation between colour changes in spores and pollen, thermal alteration index (TAI) and petroleum generation zones (Utting and Hamblin, 1991); C – some of the recorded spore and pollen grains in the Sanganeh Formation

the start of which is recorded in the upper part of the Sarcheshmeh Formation, extended up into the lower part of the Sanganeh Formation revealing a transitional zone between shelf and basin. In the upper part of the Sanganeh Formation, palynofacies types V and VII are dominant, indicate a neritic marine environment, and result from a gradual sea level rise. These palynofacies form the kerogen type II/III, which is an oil and gas-producing component, and enrich hydrocarbon generation possibilities of this sector. The gradual sea level rise can also be understood from a gradual increase in the number of chorate dinocyst forms (Brinkhuis and Zachariasse, 1988; Carvalho, 2004). The bloom of *Cribroperidinium* genus in the upper part of the Sanganeh Formation (Fig. 5E) also confirms the neritic environment (Leereveld, 1995). The palaeoecological factors show extension of an anoxic/dysoxic condition with higher sedimentation rates (due to high preservation of marine palynomorphs) in the upper parts of the Sanganeh Formation in compare with other parts of the studied column. Moreover, in the Sanganeh Formation the Peridinioids to Gonyalacoids (P/G) dinocysts ratio (Harland, 1973) was also hired to gain more precise palaeoenvironmental interpretations. The recorded peridinioid forms in the Sanganeh Formation include *Cribroperidinium, Eucladinium, Palaeoperdinium* and *Subtilisphaera* genera. Prominent increasing of P/G ratio in the upper parts of the Sanganeh Formation emphasized extension of the anoxic conditions and high palaeoproductivity due to the presence of upwelling currents (Reid, 1977; May, 1980; Costa and Davey, 1992) that may led to expansion of the oceanic anoxic events (OAEs) that resulted deposition of source rocks. As a result, extension of anoxic condition, high sedimentation and high palaeoproductivity and increase in AOMs values, give us valuable keys to conclude a fair potential production zone in the upper parts of the Sanganeh Formation. Based on the microscopic observations, the spore colour index (SCI) practiced on the samples collected from the Sanganeh Fm. (Fig. 7). The SCI values varies from golden yellow to dark brown (SCI 4-8, depth ranges 2496–2824 m) for the majority of the grains. The SCI 4-8 is in accord with the thermal alteration index (TAI) 2-3 of Utting and Hamblin (1991) (Fig. 7A, B) that indicate a thermally mature to hydrocarbon generation zones (oil and gas windows).

CONCLUSIONS

The palynological studies were performed on the Lower Cretaceous shaley succession of the Sarcheshmeh and Sanganeh formations in the Koppeh-Dagh Basin of northeastern

Iran. They have led to the recognition of 32 species of dinocysts from the Sarcheshmeh Formation. The recorded assemblages from the Sanganeh Formation revealed a richer marine assemblage with 53 dinocyst species. These palynomorph assemblages suggest a Barremian?–Aptian and Aptian age for the Sarcheshmeh and Sanganeh formations, respectively. Based on these palynoflora assemblages, the studied succession is also assigned to the *Odontochitina operculata* Oppel Zone. Moroever, percentages of the three main types of kerogen from palynological slides were calculated for detailed palynofacies studies, and five different facies types (palynofacies types II, IV, V, VI and VII of Tyson, 1995) are characterized ranging from marginal to distal shelves. Palynofacies data combined with palaeoecological evidence show a gradual relative sea level rise upward in the section, and dominance of an anoxic environment especially in the upper part of the Sanganeh Fm. The abundance of palynofacies types V and VII, presence of anoxic condition, accumulation of hydrocarbon-prone kerogen (type II/III) and SCI values (that suggested thermally matured components) in the upper part of the Sanganeh Fm. indicate potential for petroleum (mainly gas) production.

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