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Palynology and petroleum potential of the Kazhdumi Formation (Cretaceous: Albian–Cenomanian) in the South Pars field, northern Persian Gulf

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ABSTRACT

The Kazhdumi Formation of the Bangestan Group is a well-known source rock that has produced abundant oil in most petroleum fields in the Zagros Basin, which stretches from northwest to southwest Iran over hundreds of kilometres. The formation reaches a thickness of 230 m at the type section in northwest Zagros but thins out to 40–50 m in wells studied from the South Pars giant petroleum field, where it comprises mainly grey shales with occasional intercalations of marls and sandstones. South Pars, best known as the Iranian part of the world's largest non-associated gas field, contains small quantities of oil above and below the Kazhdumi Formation.

Palynology has been used to assess the age and palaeoenvironment of the Kazhdumi Formation and to evaluate its petroleum potential. A total of 68 ditch cutting samples recovered from five wells, of which four are oil-prone, have been analyzed. An age between late Albian and Cenomanian is established for the formation based on dinoflagellate cyst biostratigraphy, and four palynofacies types have been recognized using the relative proportions of terrestrial elements, marine palynomorphs and amorphous organic matter (AOM). The ratio of terrestrial to marine elements is high in most samples, indicating a nearshore sedimentary environment.

Twenty-two samples from the four oil-prone wells were also selected for geochemical analysis using Rock-Eval pyrolysis. Results show that the Kazhdumi Formation at South Pars, in contrast to the Zagros Basin, is gas-prone (predominantly type III kerogen), thermally immature, and poor in terms of hydrocarbon generation. It could not have produced the oil in those oil-prone wells studied.

1. Introduction

Current petroleum reserves in the Cretaceous and Tertiary petroleum system of southwestern Iran were generated from six known source rocks: the Garu (Neocomian), Gadvan (Barremian), Kazhdumi (Albian–Cenomanian), Ahmadi (lower Cenomanian), Gurpi (Santonian–Paleocene) and Pabdeh (Paleocene–Eocene) formations (Motiei, 2003). These formations together account for 99% of Iran's inland reserves (Tehran Energy Consultants, 2001). The hydrocarbons are trapped in two main reservoirs, the Oligocene–Miocene Asmari Formation and the Albian–Campanian Bangestan Group.

In the central and southern parts of the Dezful Embayment in southwestern Iran, the Kazhdumi Formation exceeds 200 m in thickness and is thermally mature. There, it is associated with a good reservoir (the Asmari Formation) which is capped by a thick Miocene gypsum unit known as the Gachsaran Formation. This reservoir is one of the best performing petroleum systems in Iran (Bordenave and Huc, 1995; Shakib, 1987).

Given that the Kazhdumi Formation has proved to be one of the main petroleum source rocks for most of Iran's inland oil fields (Bordenave and Burwood, 1990, 1995; Bordenave and Huc, 1995; Shakib, 1987), its evaluation in the Persian Gulf using palynology and geochemical analysis is clearly of interest.

South Pars (Fig. 1) is the Iranian part of the world's largest non-associated gas field (Aali et al., 2006). The Kazhdumi Formation lies above this gas accumulation and is not directly associated with it, but small quantities of oil have been discovered above and below the Kazhdumi Formation. The aims of this paper are to: (1) date the Kazhdumi Formation in the South Pars field using dinoflagellate cysts; (2) use palynofacies analysis and Rock-Eval pyrolysis to establish whether the Kazhdumi Formation has produced oil in South Pars, given its importance as a source rock elsewhere in Iran; and

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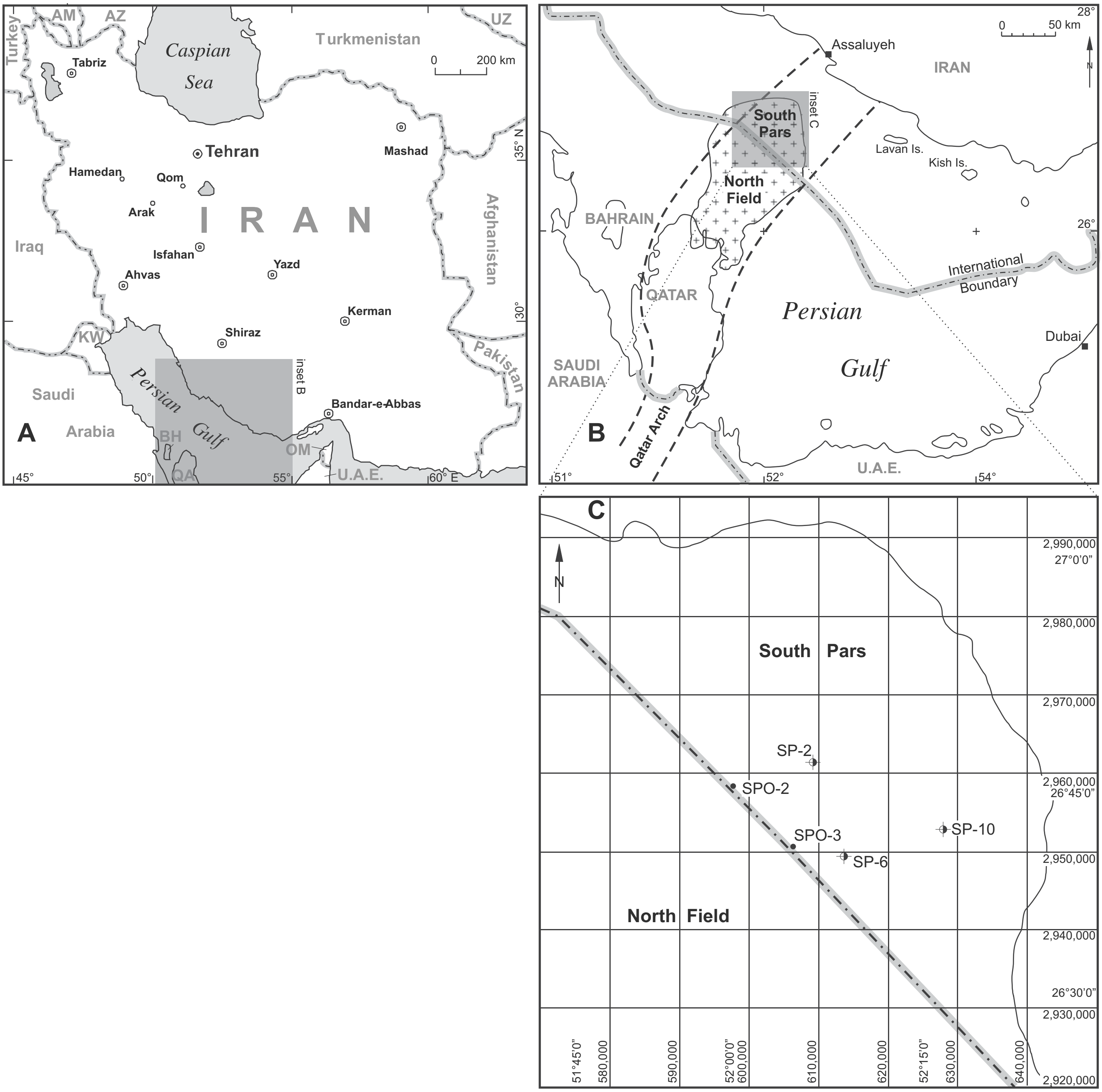


Fig. 1. Location of the South Pars field and the wells studied.

(3) use palynofacies analysis to elucidate the depositional history of the Kazhdumi Formation in this area.

2. Geographical location

The South Pars field is located in the Persian Gulf at the border between Iran and Qatar, and is 100 km from the port of Asaluyeh on the southern coast of Iran, 105 km northeast of Qatar, and 330 km northwest of Dubai (Fig. 1). The Qatari part of the field (North Field) was discovered in 1971 (Konert et al., 2001) whereas the Iranian sector was detected only in 1990 with the drilling of well SP-1. This giant field has an estimated 3700 km^2 extent and is located between 51°50′ and 52°40′E, and between 26°25′ and 27°5′N. The wells studied are SPO-2, SPO-3, SP-2, SP-6 and SP-10, and their positions are shown on Fig. 1B and C.

3. Geology

The South Pars–North Field petroleum field is the result of positive regional epeirogenic movements of the Qatar Arch (Fig. 1B). This uplifted arch has divided the Persian Gulf into two distinct sedimentary basins, one to the northwest and the other to the southeast, each with its own sedimentary regimes and styles of hydrocarbon reservoirs (Sharland et al., 2001; Aali et al., 2006). Although various structural and geological factors have affected the shape and position of this region, the north–south trend of the

Table 1
Summary of samples utilized in the present study of the Kazhdumi Formation

Well	SPO-2	SPO-3	SP-6	SP-10	SP-2
Sampling interval (m)	2	2	5	5	4
Number of samples	23	20	7	9	9
Thickness of formation (m)	50	44	45	43	40

Qatar Arch is accepted as being the most important factor in forming the South Pars–North Field structure. This geological structure has formed suitable packages of lithostratigraphic units containing source rocks, reservoirs of late Permian and early Triassic age, and cap rocks (Aali et al., 2006).

The Kazhdumi Formation lies above the main gas and condensate reservoirs at South Pars. This and its equivalents represent an influx of clastics during the Albian following emergence and erosion of shallow-water Aptian carbonates. At this time, alluvial plains covered most of Saudi Arabia, Kuwait and Iraq west of the Euphrates river, with deltas prograding to the east, beyond which were shallow-marine waters of the Fars Platform, or deeper anoxic waters of the Dezful Embayment (which corresponds approximately to the province of Khuzestan), and more distally the open waters of the southern Tethys beyond which now exists the Zagros Fault. The region was equatorial, and a humid climate prevailed (Bordenave, 2002). The Kazhdumi Formation is a distal equivalent of nearshore sandstones and shales of the Burgan Formation in Kuwait, and the Nahr Umr Formation in Iraq and Qatar (Alsharhan and Nairn, 1997; Ibrahim and Al-Hitmi, 2000; Alavi, 2004). In the Dezful Embayment the Kazhdumi Formation is a dark, organic-rich, ammonite-bearing argillaceous limestone and calcareous shale of open-marine facies. It is a principal source rock in this petroleum rich area.

In the South Pars field the Kazhdumi Formation is 40–50 m thick (Table 1) and comprises grey to greenish and brownish shales with occasional marl intercalations. A few sandstone layers occur in the lower parts of the formation in two of the wells studied in the western part of the field. These sandstones are quartzitic, medium- to coarse-grained, well-sorted and well-rounded to rounded, glauconitic, and contain some iron oxides and lignites (Tehran Energy Consultants, 2001).

Although the South Pars field is known for the huge gas reservoirs it contains, some wells have revealed oil in the Daryan and Sarvak formations below and above the Kazhdumi Formation (Fig. 2). Indeed, wells SP-2, SP-6, SPO-2 and SPO-3 in the present study are oil-prone. Whether the Kazhdumi Formation, a well-known source rock for oil in the Zagros Basin, has produced oil in the South Pars field is open to question.

The Kazhdumi Formation has not been dated biostratigraphically in the South Pars field, but elsewhere it, or its equivalents, is considered Albian or Albian–early Cenomanian in age

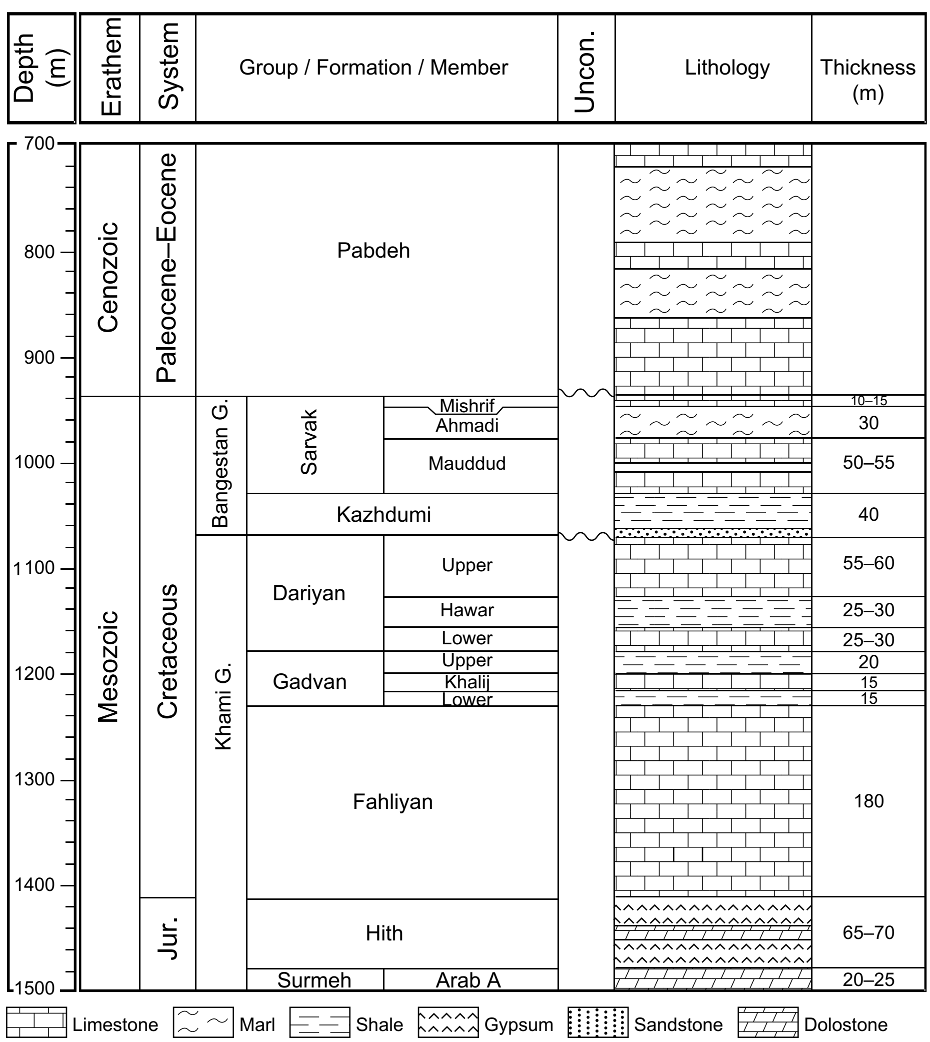
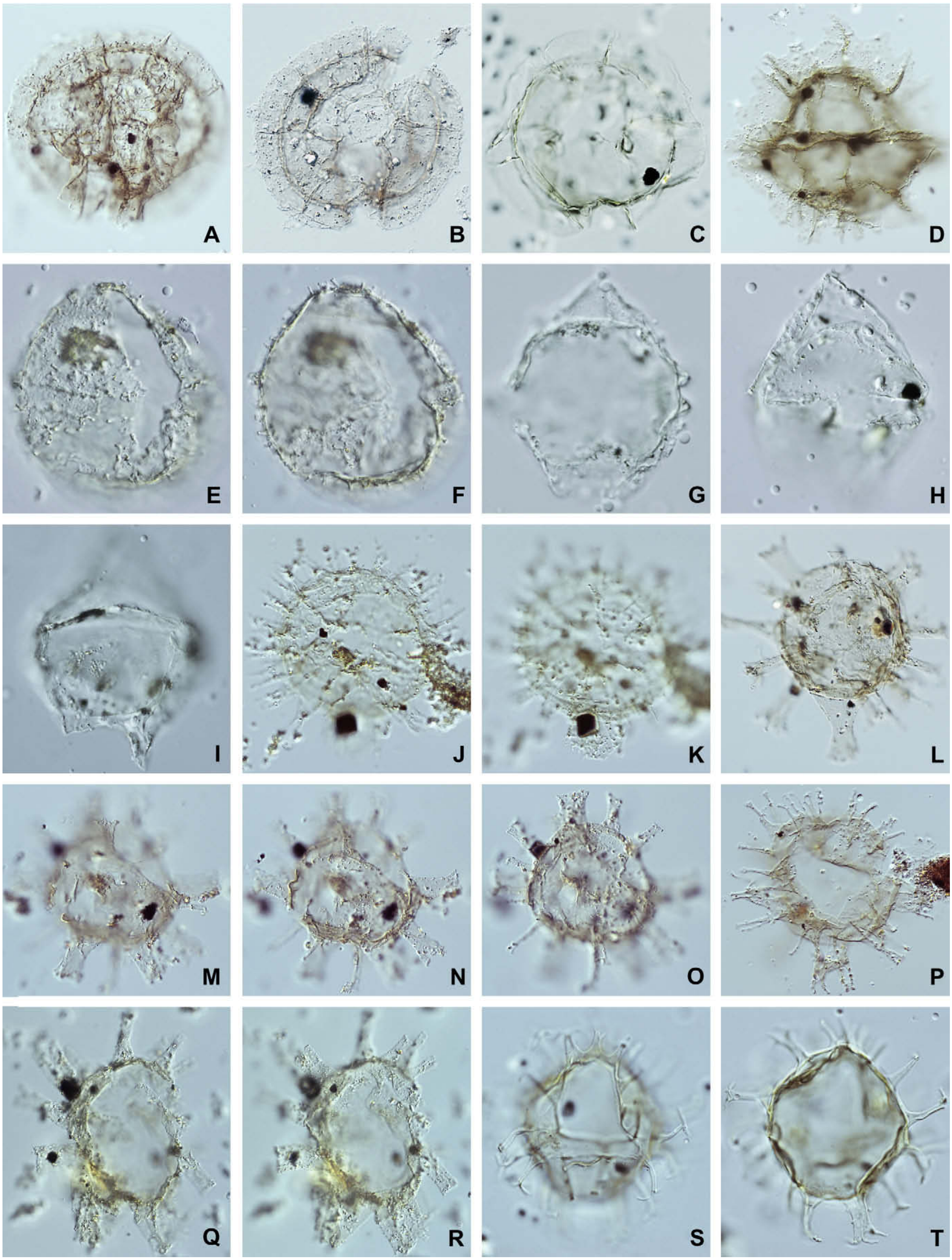


Fig. 2. Jurassic–Cretaceous stratigraphy of South Pars, Iran (Tehran Energy Consultants, 2001).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based on foraminifera and palynology (El Beialy and Al-Hitmi, 1994; Ibrahim and Al-Hitmi, 2000; Al-Ameri et al., 2001).

4. Methods

Sixty-eight ditch cuttings from five wells, SPO-2, SPO-3, SP-2, SP-6 and SP-10, were provided by the National Iranian Oil Company (NIOC) and prepared in the palynology laboratory of the Department of Geology of the University of Tehran. Standard preparation methods were used (Traverse, 2007). Cold hydrochloric (20%) and hydrofluoric (50%) acids were used to dissolve carbonates and silicates. No oxidants or alkalis were used. The residue was neutralized and centrifuged in $ZnCl_2$ (specific gravity 1.9), then sieved at 15 μm using a nylon mesh, and mounted on microscope slides using liquid Canada balsam. The microscope slides were examined with a Leica DM 2500 optical microscope equipped with a DFC 490 digital camera at the Department of Earth Sciences, Brock University, Canada. Biostratigraphically useful species are illustrated (Plates I and II). Palynofacies analyses were also performed on these microscope slides (Plate III). A total of 300 organic particles were classified and counted per sample, and their proportions calculated.

The petroleum potential and generation of the formation was estimated using Rock-Eval pyrolysis (Lafargue et al., 1998) at the research institute of the National Iranian Oil Company (NIOC). Twenty-two samples of mainly shale lithology from the four oil-prone wells SPO-2, SPO-3, SP-2 and SP-6 were pyrolyzed for this purpose. The acquisition parameters S1 (free hydrocarbon), S2 (pyrolyzed hydrocarbon resulting from the decomposition of kerogen), S3 (expulsion of CO_2), and T_{max} (the temperature at which the S2 peak occurs) were measured to determine the level of thermal maturation and source rock potential.

5. Palynology

5.1. Dinoflagellate cyst biostratigraphy and age

Of a total of 68 samples analyzed from the five wells (Fig. 3A–E), 48 samples yielded dinoflagellate cysts, resulting in a relatively sparse association of 22 taxa. These are as follows: *Achomosphaera ramulifera*, *Achomosphaera sagena*, *Carnarvonodinium* sp., *Coronifera oceanica*, *Cribroperidinium exilicristatum*, *Cribroperidinium orthoceras*, *Dinopterygium tuberculatum*, *Dinopterygium* sp. *Florentinia abjuncta*, *Florentinia cooksoniae*, *Florentinia deanei*, *Florentinia mantellii*, *Odontochitina operculata*, *Oligosphaeridium complex*, *Oligosphaeridium poculum*, *Pervosphaeridium truncatum*, *Spiniferites ramosus*, *Subtilisphaera hyalina*, *Subtilisphaera perlucida*, *Trichodinium castanea*, *Trichodinium ciliatum* and *Xiphophoridium alatum*.

Of these taxa, *A. sagena* has a range base in the upper Albian (101 Ma) of northern mid-latitudes, *D. tuberculatum* has a range base in the middle Albian (107.8 Ma) of southern mid-latitudes, *F. deanei* has a range base in the upper Albian (101 Ma) of northern mid-latitudes, *P. truncatum* has a range base in the middle Albian (106.4 Ma) of northern mid-latitudes, *X. alatum* has a range base in the middle Albian (106.8 Ma) of northern mid-latitudes and upper Albian (104 Ma) in equatorial latitudes, and *O. poculum* has a range top in the lower Turonian (92.2 Ma) of northern mid-latitudes (Brinkhuis et al., 2006, who used the time scale of Gradstein et al., 2005). Moreover, *F. cooksoniae* has a range top in the upper Cenomanian, and *F. mantellii* has a range top in the mid-Turonian (Stover et al., 1996).

Based on the range bases of *A. sagena*, *F. deanei* and *X. alatum*, and the range top of *F. cooksoniae*, an age somewhere between late Albian and late Cenomanian is indicated for the association. These index species are not consistently present in all five wells, but the assemblages are generally similar throughout, and the Kazhdumi Formation has a distinctive lithology that allows subsurface correlation to be made confidently between our wells (Fig. 2). We therefore propose a late Albian–Cenomanian age for our sampled intervals in all five wells. We did not attempt to subdivide the Kazhdumi Formation into biozones because of its relatively thin (40–50 m) development in this area, and owing to the stratigraphic limitations of ditch cutting samples.

The Nahr Umr Formation in neighbouring Qatar has been considered equivalent to the Kazhdumi Formation (Alsharhan and Nairn, 1997), although it reaches a thickness of 137 m in western Qatar (Ibrahim and Al-Hitmi, 2000). The Nahr Umr Formation has been dated as early Albian based on foraminifera (Hewaidy and Al-Hitmi, 1994), and middle and late Albian based on palynology (El Beialy and Al-Hitmi, 1994; Ibrahim and Al-Hitmi, 2000). The dinoflagellate cyst assemblages recorded by El Beialy and Al-Hitmi (1994) and Ibrahim and Al-Hitmi (2000) comprise relatively long ranging taxa, with few of the stratigraphically diagnostic taxa present in our study being recorded. The presence of *D. tuberculatum* (range base middle Albian 107.8 Ma in southern mid-latitudes; Brinkhuis et al., 2006) and *Xenascus ceratioides* (range base early Albian; Stover et al., 1996), both reported by Ibrahim and Al-Hitmi (2000), is nonetheless consistent with an Albian age for the Nahr Umr Formation. Dinoflagellate cysts have also been reported from the Nahr Umr Formation and superjacent Mauddud Formation in the East Baghdad oilfield of Iraq by Al-Ameri et al. (2001). The assemblages are somewhat similar to ours, and it is noteworthy that *X. alatum* is restricted to their TA zone (Nahr Umr Formation and lower Mauddud Formation) which they date as latest Albian to early Cenomanian. The underlying PC zone (Nahr Umr Formation; middle and late Albian) of Al-Ameri et al. (2001) corresponds to the total ranges of *T. castanea* and *Luxadinium propatulum*, of which only *T. castanea* is present in our material. In northeast Libya, a dinoflagellate cyst biostratigraphy was established for the Lower to lowermost Upper Cretaceous by Uwins and Batten (1988). Their associations IIIA (middle to late Albian) and IVA and IVB (Vraconian to early Cenomanian) have some elements in common with our assemblages, including *X. alatum* (not reported in their older associations), *T. castanea*, *S. perlucida* and *F. mantellii*.

5.2. Palynofacies

Palynofacies studies were undertaken to assess the palaeoenvironmental conditions under which the Kazhdumi Formation

Plate I. Dinoflagellate cysts from the Kazhdumi Formation, South Pars petroleum field. Various magnifications. An England Finder reference follows the sample and slide number for each specimen. All photomicrographs are interference contrast images. (A) *Dinopterygium tuberculatum*, sample SP-6-75-80, slide 6, F52/1, lower focus, maximum width, 66 μm. (B) *Dinopterygium tuberculatum*, sample SP-6-75-80, slide 5, K19/0, upper focus, maximum diameter, 68 μm. (C) *Dinopterygium* sp., sample SP-2-1126, slide 1, N16/4, middle focus, maximum width, 60 μm. (D) *Xiphophoridium alatum*, sample SPO-3-1032, slide 2, E4/4, upper focus, central body length, 53 μm. (E, F) *Trichodinium castanea*, sample SP-10-195-200, slide 1, N27/2; (E) upper focus; (F) middle focus; length, 51 μm. (G) *Subtilisphaera perlucida*, sample SP-6-75-80, slide 6, H38/0, middle focus, length, 43 μm. (H, I) *Subtilisphaera hyalina*, sample SP-6-75-80, slide 1, H36/3; (H) upper focus; (I) lower focus; width, 43 μm. (J, K) *Coronifera oceanica*, sample SPO-3-1020, slide 3, H53/3; (J) middle focus; (K) lower focus, central body length, 41 μm. (L) *Florentinia deanei*, sample SPO-3-1030, slide 1, C48/0, upper focus, central body length, 42 μm. (M, N, O) *Florentinia deanei*, sample SPO-2-1014, slide 4, M36/3; (M) upper focus; (N) middle focus; (O) lower focus; central body maximum diameter, 45 μm. (P) *Florentinia mantelii*, sample SPO-2-1018, slide 5, P30/4, middle focus, central body maximum diameter, 43 μm. (Q, R) *Florentinia cooksoniae*, sample SPO-3-1020, slide 1, V58/0; (Q) upper focus; (R) middle focus; central body maximum diameter, 52 μm. (S, T) *Spiniferites ramosus*, sample SP-2-1130, slide 1, R50/2; (S) upper focus; (T) middle focus, endoblast length, 39 μm.

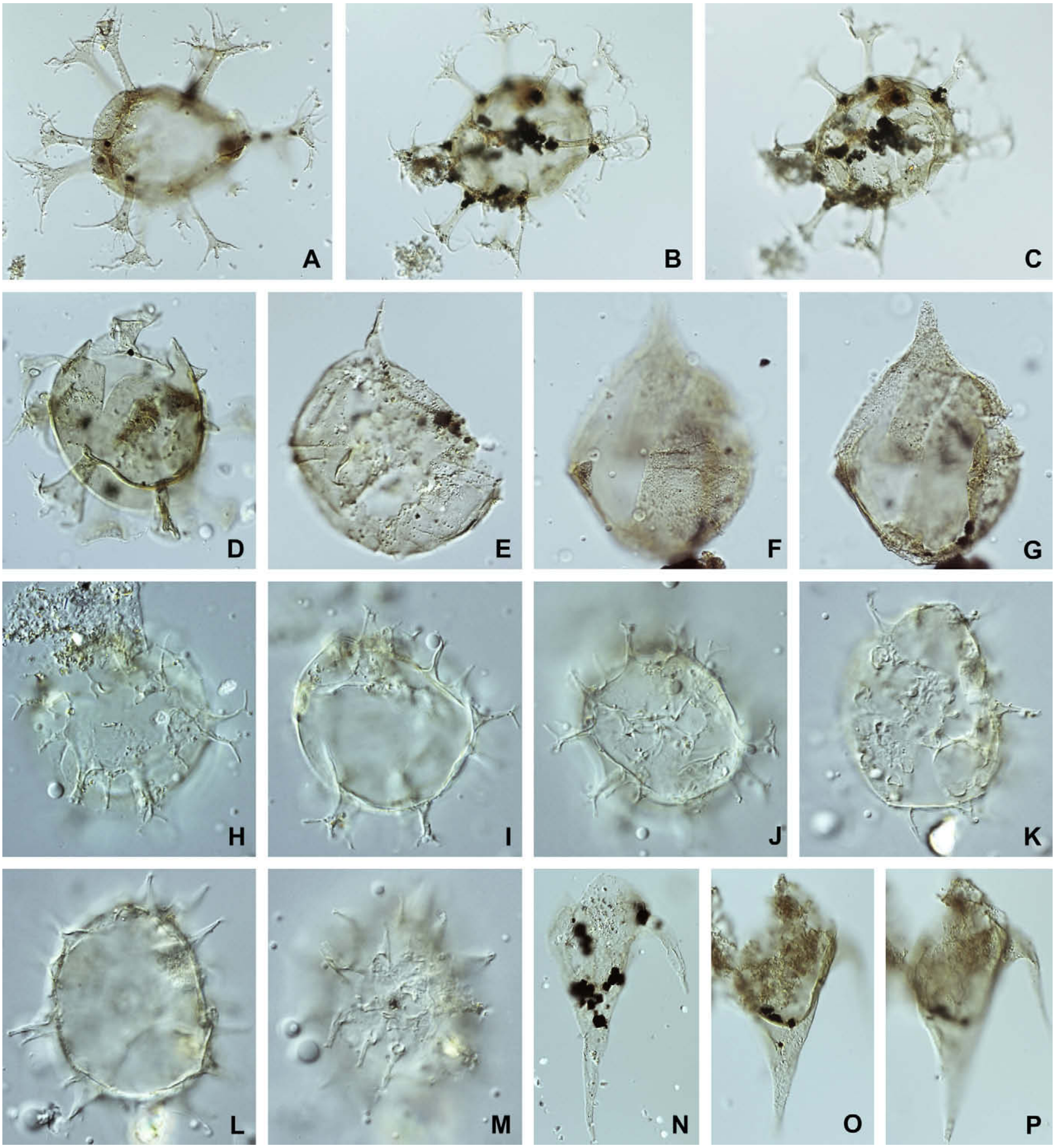

Plate II. Dinoflagellate cysts from the Kazhdumi Formation, South Pars petroleum field. Various magnifications. An England Finder reference follows the sample and slide number for each specimen. All photomicrographs are interference contrast images. (A) *Oligosphaeridium complex*, sample SPO-3-1032, slide 4, H45/0, upper focus; central body maximum diameter, 59 µm. (B, C) *Oligosphaeridium complex*, sample SPO-3-1030, slide 1, H48/3; (B) upper focus; (C) lower focus; central body maximum diameter, 55 µm. (D) *Oligosphaeridium poculum*, sample SP-6-75-80, slide 2, B47/3, upper focus; central body width, 58 µm. (E) *Cribroperidium orthoceras*, sample SPO-2-1010, slide 2, A18/2, lower focus; length including apical horn, 77 µm. (F, G) *Cribroperidinium exilicristatum*, sample SP-10-205-210, slide 3, T32/4; (F) upper focus; (G) middle focus; length including apical horn, 88 µm. (H, I, J) *Achomosphaera sagena*, sample SP-6-75-80, slide 2, D22/2; (H) upper focus; (I) middle focus; (J) lower focus; length and width of central body, 37 and 35 µm. (K, L, M) *Pervosphaeridium truncatum*, sample SP-10-70-75, slide 2, N23/0; (K) upper focus; (L) middle focus; (M) lower focus; length of central body, 42 µm. (N) *Odontochitina operculata*, sample SPO-3-1038, slide 4, G43/2, lower focus; length, 102 µm. (O, P) *Odontochitina operculata*, sample SPO-2-1014, slide 2, N28/4; (O) upper focus; (P) middle focus; length, 101 µm.

was deposited, and to evaluate whether in our study area this formation is oil- or gas-prone (Tyson, 1987, 1989, 1993, 1995; Batten, 1996; Batten and Stead, 2005).

For each sample, relative proportions were determined for the three main groups of palynological elements: marine palynomorphs (dinoflagellate cysts, rare acritarchs, foraminiferal linings), terrestrial elements (phytoclasts, spores, pollen), and amorphous organic matter (AOM). These were plotted for each well both using Tyson's ternary diagram for palaeoenvironmental interpretations (Fig. 4) and stratigraphically (Fig. 5). Based on the

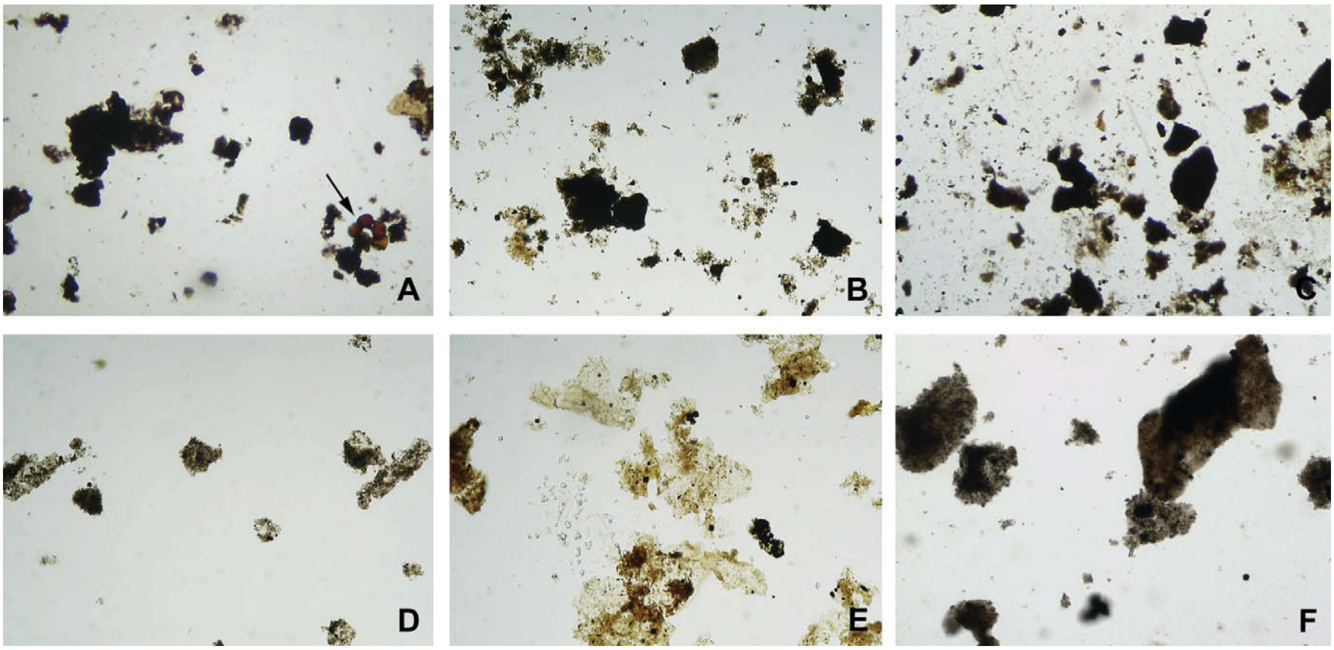

Plate III. Palynofacies from the Kazhdumi Formation, South Pars petroleum field. Various magnifications. All photomicrographs are in bright field illumination. (A) Palynofacies type 1 (PF-1), showing dominance of degraded terrestrial elements, with subsidiary AOM, and a sparse marine element here represented by a foraminiferal lining (arrow). Sample no. 210-215, slide 5; width of photomicrograph, 470 μm. (B) Palynofacies type 2 (PF-2), showing dominance of degraded terrestrial elements, with subsidiary AOM, and no marine palynomorphs. Sample no. 2-1038, slide 2; width of photomicrograph, 600 μm. (C) Palynofacies type 2 (PF-2), as for (B). Sample no. 3-1042, slide 1; width of photomicrograph, 470 μm. (D) Palynofacies type 3 (PF-3), showing dominance of AOM with subsidiary degraded terrestrial elements. Sample no. 3-1014, slide 4; width of photomicrograph, 470 μm. (E) Palynofacies type 4 (PF-4), showing dominance of AOM with minor terrestrial elements, sample no. 3-1002, slide 1; width of photomicrograph, 600 μm. (F) Palynofacies type 4 (PF-4), showing dominance of AOM. Sample no. 2-1032, slide 2; width of photomicrograph, 225 μm.

relative abundances of these three groups, four types of palynofacies were differentiated. These are:

Palynofacies type 1 (PF-1) is dominated by terrestrial elements (48–88%) with subsidiary AOM (10–46%) and marine palynomorphs (1–25%).

Palynofacies type 2 (PF-2) is dominated by terrestrial elements (65–88%), with subsidiary AOM (12–35%) and no marine palynomorphs.

Palynofacies type 3 (PF-3) is dominated by AOM (73–98%), with minor amounts of terrestrial elements (0–25%) and usually minor amounts of marine palynomorphs (0–5%).

Palynofacies type 4 (PF-4) is dominated by AOM (95–99%), with minor terrestrial elements (1–5%) and no marine palynomorphs (Fig. 5).

6. Interpretation of depositional environment

Tyson plots (Fig. 4) clearly show a dominance of terrestrial elements for three of the five wells, with terrestrial elements and AOM being co-dominant in wells SPO-2 and SPO-3. Marine palynomorphs are rare but persistent in all five wells. This reflects a relatively nearshore marine influence for all the wells.

The distribution of palynofacies types reinforces this interpretation, with PF-1 (characterized by dominant terrestrial elements) being stratigraphically the most pervasive palynofacies type. PF-3 and PF-4 are dominated by AOM. Because AOM is essentially structureless at the resolution of optical microscopy, it is not possible to determine whether its origin is marine or terrestrial. However, given the general abundance of terrestrial elements, the presence of nearly structureless degraded woody particles, and the persistently low abundances of marine palynomorphs, the AOM in our samples is likely to be derived mostly from the breakdown of woody terrestrial material.

Palynofacies types PF-1 and (usually) PF-3 contain marine palynomorphs, whereas PF-2 and PF-4 do not. This distribution is also reflected in the distribution of marine dinoflagellate cysts through each of the five wells, except that samples 1034 (PF-2) and 1032 (PF-4) in well SPO-2 contain rare dinoflagellate cysts that were not detected during the palynofacies count (Fig. 3). Combining the palynofacies and dinoflagellate cyst distributions throughout the five wells shows that only two intervals in two wells (samples 1046–1038 in SPO-2, and samples 1006–1002 in SPO-3) have no marine influence. This absence might imply terrestrial conditions, but could equally reflect a strong dilution of marine elements by terrestrial organic input, given that these intervals cannot be correlated across wells.

The palynofacies across the five wells studied do not follow a clear stratigraphic succession. This may partly result from a localized degradation of terrestrial elements into AOM, which could explain the similar stratigraphic positions of PF-3 in well SPO-2 and PF-3 and PF-4 in well SPO-3, but also suggests that depositional conditions were localized. It is nonetheless evident that marine conditions prevailed through most or all of the interval covered in our study, and that the abundance of terrestrial elements suggests close proximity to a fluvio-deltaic source.

7. Geochemical analyses

To evaluate the hydrocarbon generation potential of the Kazhdumi Formation in the South Pars field, 22 samples from the oil-prone wells SP-2, SP-6, SPO-2 and SPO-3 were subjected to Rock-Eval pyrolysis. Four parameters were acquired: S1, free hydrocarbons; S2, pyrolyzed hydrocarbons resulting from the decomposition of kerogen; S3, quantity of CO_2; and T_{max}, the temperature at which most of the hydrocarbons were produced. These parameters were used to calculate the following:

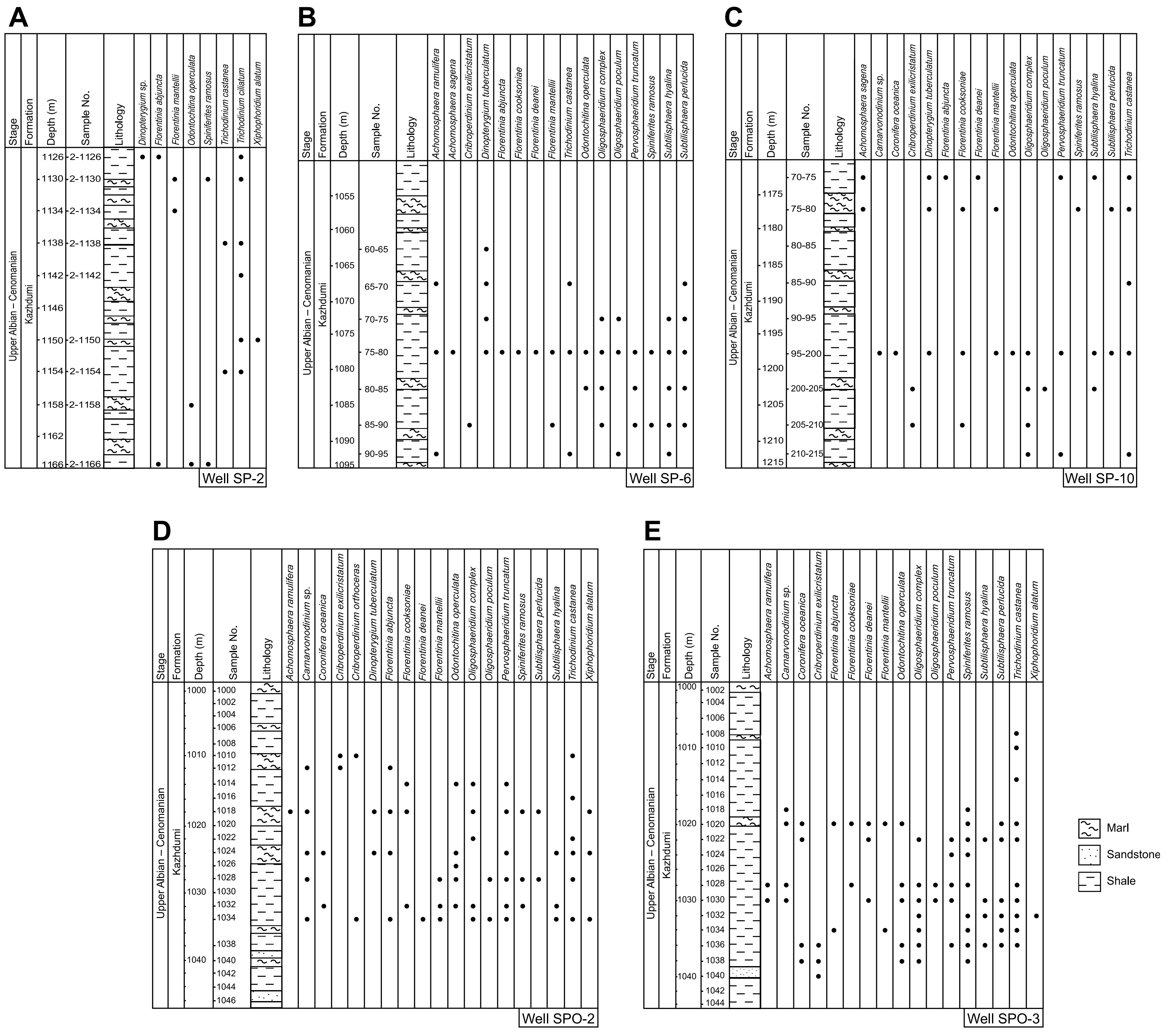

Fig. 3. Lithology and stratigraphic distribution of dinoflagellate cyst species recorded in each of the five studied wells of the South Pars field. (A) Well SP-2; (B) well SP-6; (C) well SP-10; (D) well SPO-2; and (E) well SPO-3.

TOC, total amount of organic carbon
OI, oxygen index (OI = S3 × 100/TOC)
HI, hydrogen index (HI = S2 × 100/TOC)
PI, production index (PI = S2/S1 + S2)

The three main factors for evaluating the potential of a rock to produce petroleum are:

1. Potential quantity of produced hydrocarbon which is based on S1, S2 and TOC.
2. Type of produced hydrocarbon which is based on the HI and S2/S3 ratio.
3. Level of thermal maturity for petroleum generation which is based on PI and T_{max} (Peters and Cassa, 1994).

The parameters measured are presented in Table 2. For simplification, the ranges and averages of factors TOC, S1, S2 and T_{max} for the studied samples are presented in Table 3. The standard guidelines for interpreting these values are given in Table 4.

Comparing the values of S1, S2, T_{max} and TOC based on Rock-Eval pyrolysis of the samples studied (Table 2) with standard guidelines (Peters and Cassa, 1994; Table 4), it becomes evident that the Kazhdumi Formation in the South Pars petroleum field is poor in terms of production potential, and therefore could not have produced hydrocarbons in commercial quantities. T_{max} values for the Kazhdumi Formation range between 370 and 426 °C (Table 3), and consequently show the deposits to be thermally immature. Values for TOC range from 0.12 to 1.2 wt% (average 0.486) and are generally poor to fair with respect to organic concentration. The unusually high values of S1 in a few samples such as 1042 (well SPO-2) and 1004, 1012, 1018, and 1042 (well SPO-3) are probably a result of contamination of these samples with some oil migrated from underlying formations (M.R. Kamali, personal communication, 2006).

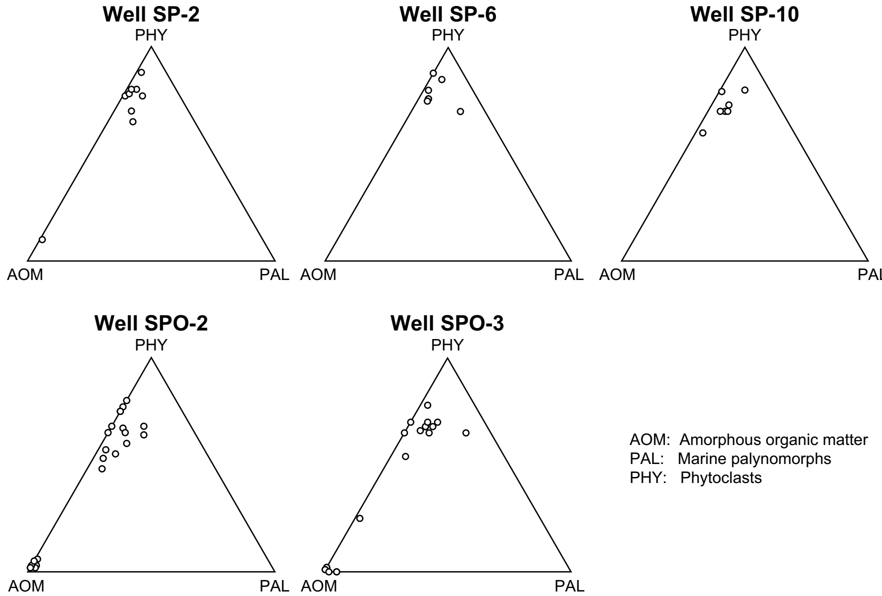

Fig. 4. Tyson-type ternary diagrams showing distribution of principal palynological groups for the wells studied.

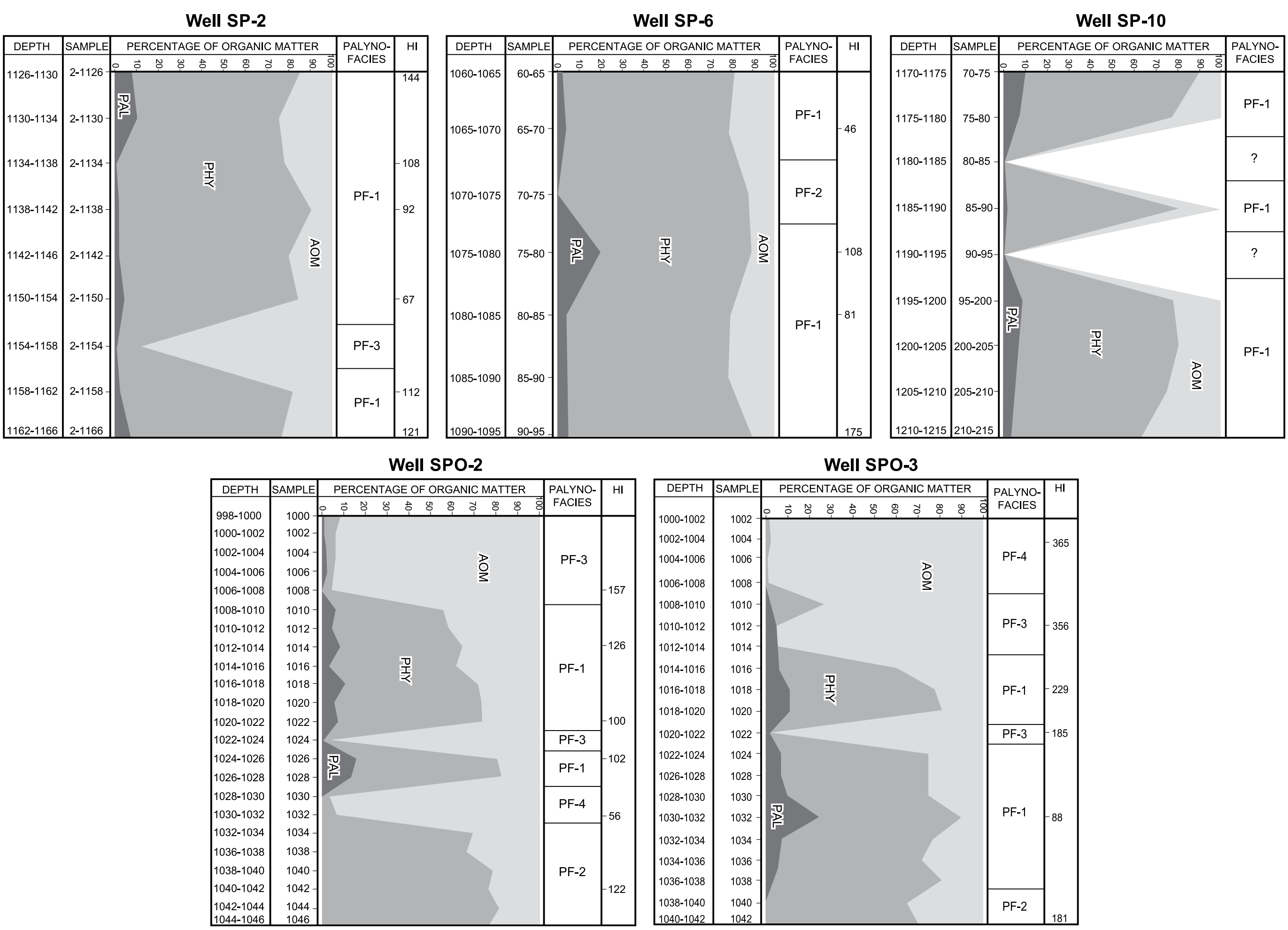

Fig. 5. Stratigraphic distribution of principal palynological groups and associated palynofacies types (PF-1–4) together with hydrogen index (HI) values for each of the wells studied.

Table 2
Measured parameters based on Rock-Eval pyrolysis for the studied samples of the Kazhdumi Formation

Well, sample no.	S1	S2	S3	T_{max}	HI	OI	TPI	TOC
SPO-2, 1008	0.99	0.6	1.98	421	157	388	0.55	0.51
SPO-2, 1014	0.84	0.6	3.17	376	126	674	0.58	0.47
SPO-2, 1022	0.61	0.31	2.02	378	100	652	0.66	0.31
SPO-2, 1026	1.05	0.52	2.46	370	102	482	0.67	0.51
SPO-2, 1032	0.79	0.26	2.18	370	56	484	0.78	0.45
SPO-2, 1042	2.58	1.39	1.57	405	122	138	0.66	1.14
SP-2, 1126	0.27	0.26	0.46	426	144	256	0.51	0.18
SP-2, 1134	0.24	0.28	1.65	419	108	635	0.46	0.26
SP-2, 1138	0.6	0.55	4.08	386	92	680	0.52	0.6
SP-2, 1150	0.62	0.31	2.9	382	67	630	0.67	0.48
SP-2, 1158	0.38	0.37	2.69	381	112	815	0.51	0.33
SP-2, 1166	0.63	0.69	3.5	387	121	614	0.48	0.57
SPO-3, 1004	2.43	1.97	0.45	421	365	63	0.56	0.54
SPO-3, 1012	2.88	2.85	0.82	420	356	102	0.6	0.8
SPO-3, 1018	1.15	1.12	0.77	415	229	157	0.51	0.49
SPO-3, 1022	0.83	0.63	1.09	370	185	321	0.57	0.34
SPO-3, 1032	0.68	0.3	1.05	380	88	309	0.69	0.34
SPO-3, 1042	3.26	2.17	1.05	418	181	88	0.6	1.2
SP-6, 65-70	0.14	0.06	1.17	421	46	900	0.7	0.13
SP-6, 75-80	0.13	0.13	0.57	425	108	475	0.5	0.12
SP-6, 80-85	0.23	0.17	0.93	387	81	443	0.57	0.21
SP-6, 90-95	1.07	1.24	0.71	422	175	100	0.48	0.71

7.1. Kerogen types

Kerogen is often defined as the organic content of sedimentary rocks that is insoluble in common organic solvents (but see Batten, 1996, p. 1022 for discussion). Kerogen is the main source of petroleum and controls the type of petroleum produced. Sedimentary rocks usually contain the following kerogen types: type I (algal kerogen), type II (liptinitic kerogen), type III (humic or coaly kerogen), and type IV (inertinitic kerogen). Of central interest to our study is the discrimination of type II kerogen, which is typically marine in origin and derived predominantly from zooplankton and phytoplankton, and type III kerogen, which is terrestrial and derived from the lignin of higher plants.

Kerogen types are distinguishable under the light microscope and by geochemical analyses that obtain the HI and OI. The OI reflects the liberated CO_2 (S3) and the HI reflects hydrocarbons freed from thermal decomposition of the kerogen (S2) during pyrolysis. The chemical characteristics of each kerogen type are given in Table 3 (from Peters and Cassa, 1994).

Only three samples from the Kazhdumi Formation have HI values greater than 200. These are the uppermost samples in well SPO-3 and have HI values of 229, 356 and 365 (Fig. 5). The remaining samples have HI values in the range 46–185, almost exclusively indicating type III kerogen and hence a primarily terrestrial origin. These type III kerogen samples are associated with all four palynofacies types (PF-1–4). The low HI values are in accord with the dominance of terrestrial phytoclasts in PF-1 and -2. In well SPO-2, low HI values associated with palynofacies types PF-3 and PF-4 imply that the dominant component, AOM, is mostly terrestrially derived. The uppermost samples in well SPO-3 have HI values that fall within the lower part of the type II range, which might imply increased marine influence. However, this interpretation is not supported by palynology because dinoflagellate cysts are rare in the upper part of the Kazhdumi Formation in well SPO-3. As mentioned above, these samples are suspected of oil contamination from lower in the well, and this probably accounts for their unusually high HI values. Plotting values of HI against OI on a van Krevelen-type diagram (Fig. 6) further illustrates the predominance of type III kerogen in each of the four wells analyzed. Kerogen type III is gas-prone, and we therefore consider the Kazhdumi Formation in our wells to have little potential for producing oil.

Table 3
Range and averages of the measured parameters based on Rock-Eval pyrolysis for the studied samples of the Kazhdumi Formation

Parameter	S1	S2	TOC	T_{max}
Range	0.13–3.26	0.06–2.85	0.12–1.2	370–426
Average	1.02	0.76	0.486	399.09

Table 4
Guidelines for pyrolysis parameters of quality, quantity and thermal maturity (from Peters and Cassa, 1994)

Quantity	TOC (wt%)	S1 (mg HC/g rock)	S2 (mg HC/g rock)
Poor	0–0.5	0–0.5	0–2.5
Fair	0.5–1	0.5–1	2.5–5
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	**R_o (%)**	**T_{max} (°C)**	**TAI**
Immature	0.2–0.6	<435	1.5–2.6
Mature			
Early	0.6–0.65	435–445	2.6–2.7
Peak	0.65–0.9	445–450	2.7–2.9
Late	0.9–1.35	450–470	2.9–3.3
Postmature	>1.35	>470	>3.3

8. Conclusions

In the giant South Pars petroleum field, the Kazhdumi Formation attains a thickness of only 40–50 m and is represented by shales with some intercalations of marls and occasional sandstones. Sixty-eight ditch cutting samples from five wells were analyzed for palynology, and 22 from four of these wells for geochemical analyses. A moderately low diversity dinoflagellate cyst association of 22 taxa has been recorded, and based on the presence of *A. sagena*, *F. cooksoniae*, *F. deanei* and *X. alatum*, an age somewhere between late Albian and late Cenomanian is indicated for the Kazhdumi Formation. This represents the first age assessment of the Kazhdumi Formation in the South Pars field and is consistent with age assessments elsewhere for this formation and its lateral equivalents.

Palynofacies analyses, supported by geochemical evidence, indicate that the primary source of organic material in the Kazhdumi Formation at the South Pars field is of terrestrial origin, with a minor but pervasive marine element. Deposition evidently occurred in a nearshore marine palaeoenvironment influenced strongly by fluvio-deltaic conditions. Deltaic and nearshore palaeoenvironments also characterize the Burgan Formation in Kuwait and the Nahr Umr Formation in Iraq and Qatar (Alsharhan and Nairn, 1997; Ibrahim and Al-Hitmi, 2000; Al-Ameri et al., 2001; Alavi, 2004), which are lateral equivalents of the Kazhdumi Formation. Regionally, the South Pars locality can perhaps be seen as an eastward extension of these deltas. In the more inland areas of Iran, these deltas had passed into more open-marine environments, leading to the deposition of what became important oil source rocks for which the Kazhdumi Formation is best known.

The Kazhdumi Formation in the South Pars field is shown to be gas-prone, based on palynofacies analysis that identifies terrestrial phytoclasts (woody elements and leaf tissues) as a principal

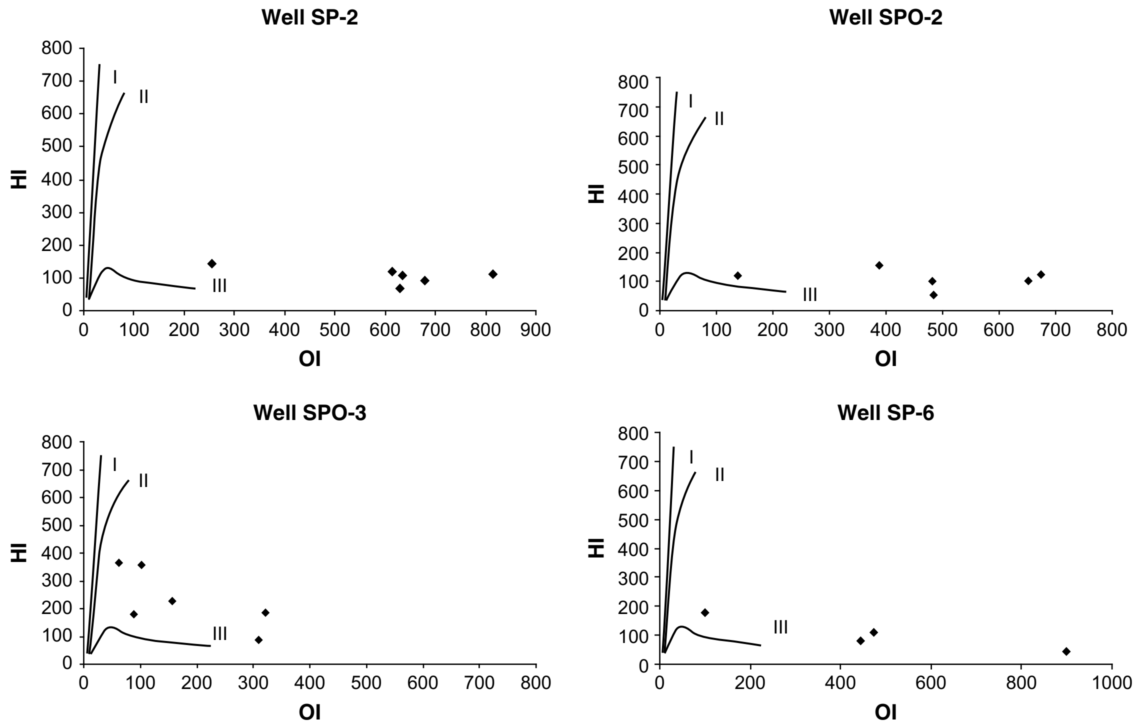

Fig. 6. Van Krevelen-type diagram (van Krevelen, 1993) of hydrogen/oxygen indices (HI/OI) plotted for each of the four wells analyzed. The plots show a predominance of type III kerogen.

component, and Rock-Eval pyrolysis that shows the predominance of type III kerogen. However, the deposits have a relatively low organic content and are thermally immature. The Kazhdumi Formation has not generated commercial quantities of hydrocarbons in the South Pars field, in spite of being a well-known petroleum source rock in most inland oil fields in Iran. This study shows the value of integrating both palynology and geochemistry for reconstructing palaeoenvironments and evaluating petroleum potential.

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Appendix. Full authorial citation for the species recorded

Achomosphaera ramulifera (Deflandre, 1937) Evit, 1963
Achomosphaera sagena Davey and Williams, 1966
Coronifera oceanica Cookson and Eisenack, 1985 emend. May, 1980
Cribroperdinium exilicristatum (Davey, 1969) Stover and Evitt, 1978
Cribroperidium orthoceras (Eisenack, 1958) Davey, 1969 emend. Sarjeant, 1985
Dinopterygium tuberculatum (Eisenack and Cookson, 1960) Stover and Evitt, 1978
Florentinia abjuncta Duxbury, 1983
Florentinia cooksoniae (Singh, 1971) Duxbury, 1980
Florentinia deanei (Davey and Williams, 1966) Davey and Verdier, 1973
Florentinia mantellii (Davey and Williams, 1966) Davey and Verdier, 1973
Odontochitina operculata (Wetzel, 1933) Deflandre and Cookson, 1955
Oligosphaeridium complex (White, 1842) Davey and Williams, 1966
Oligosphaeridium poculum Jain, 1977
Pervosphaeridium truncatum (Davey, 1969) Below, 1982 emend. Harker and Sarjeant in Harker et al., 1990
Spiniferites ramosus (Ehrenberg, 1838) Mantell, 1854
Subtilisphaera hyalina Singh, 1983
Subtilisphaera perlucida (Alberti, 1959) Jain and Millepied, 1973
Trichodinium castanea (Deflandre, 1935) Clarke and Verdier, 1967
Trichodinium ciliatum (Gocht, 1959) Eisenack and Klement, 1964
Xiphophoridium alatum (Cookson and Eisenack, 1962) Sarjent in Davey et al., 1966

References

Aali, J., Rahimpour-Bonab, H., Kamali, M.R., 2006. Geochemistry and origin of the world's largest gas field from Persian Gulf, Iran. Journal of Petroleum Science & Engineering 50, 161–175.
Al-Ameri, T.K., Al-Najar, T.K., Batten, D.J., 2001. Palynostratigraphy and palynofacies indications of depositional environments and source potential for hydrocarbons: the mid Cretaceous Nahr Umr and lower Mauddud formations, Iraq. Cretaceous Research 22, 735–742.
Alavi, M., 2004. Regional stratigraphy of the Zagros fold-thrust belt of Iran and its proforeland evolution. American Journal of Science 304, 1–20.
Alsharhan, A.S., Nairn, A.E.M., 1997. Sedimentary Basins and Petroleum Geology of the Middle East. Elsevier Science B.V., Amsterdam, The Netherlands, 843 pp.
Batten, D.J., 1996. Palynofacies and palaeoenvironmental interpretation. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principals and Applications, vol. 3. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 1011–1064.

Batten, D.J., Stead, D.T., 2005. Palynofacies analysis and its stratigraphic application. In: Koutsoukos, E.A.M. (Ed.), Applied Stratigraphy. Springer, Dordrecht, pp. 203–226.
Bordenave, M.L., Burwood, R., 1990. Source rock distribution and maturation in the Zagros orogenic belt: provenance of the Asmari and Bangestan reservoir oil accumulations. Organic Geochemistry 16, 369–387.
Bordenave, M.L., Burwood, R., 1995. The Albian Kazhdumi Formation of the Dezful Embayment, Iran: one of the most efficient petroleum generating systems. In: Katz, B.J. (Ed.), Petroleum Source Rocks. Springer Verlag, Heidelberg, pp. 183–207.
Bordenave, M.L., Huc, A.Y., 1995. The Cretaceous source rocks in the Zagros Foothills of Iran: an example of a large size intracratonic basin. Revue de L'institut Français du Petrole 50, 727–753.
Bordenave, M.L., 2002. The middle Cretaceous to early Miocene petroleum system in the Zagros domain of Iran and its prospect evaluation. In: AAPG Annual Meeting, Houston, Texas, pp. 1–9.
Brinkhuis, H., Head, M.J., Pearce, M.A., Pross, J., Riding, J.B., with contributions from Fensome, R., Williams, G.L., Weegink, J.W., Verreussel, R., 2006. Advanced course in Jurassic–Cretaceous–Cenozoic organic-walled dinoflagellate cysts: morphology, paleoecology and stratigraphy. Urbino, Italy. Course Manual, p. 116 plus CD.
El Beialy, S.Y., Al-Hitmi, H.H., 1994. Micropalaeontology and palynology of the lower and middle Cretaceous Thamama and Wasia Groups, DK-C well, Dukhan Oil Field, western Qatar. Bulletin de la Société Géologique de France 47, 67–95.
Gradstein, F.M., Ogg, J.G., Smith, A.G. (Eds.), 2005. A Geologic Time Scale. Cambridge University Press, U.K., 589 pp. [Imprinted 2004].
Hewaidy, A., Al-Hitmi, H., 1994. Cretaceous–early Eocene biostratigraphy of the Dukhan Oil Field, west Qatar, Arabian Gulf. In: Earth Science Series, vol. 8. MERC Ain Shams University, pp. 1–24.
Ibrahim, M.I.A., Al-Hitmi, H.H.A., 2000. Albian–Cenomanian palynology, paleoecology and organic thermal maturity of well DK-B in the Dukhan Oil Field of western Qatar. GeoArabia 5, 483–508.
Konert, G., Afif, A.M., AL-Hajari, S.A., Droste, H., 2001. Paleozoic stratigraphy and hydrocarbon habitat of the Arabian Plate. GeoArabia 6, 407–442.
Lafargue, E., Marquis, F., Pillot, D., 1998. Rock-Eval 6 applications in hydrocarbon exploration, production, and soil contamination studies. Oil & Gas Science and Technology 53, 421–437.
Motiei, H., 2003. Stratigraphy of Zagros. A Publication of the Geological Survey of Iran, 536 pp. (in Persian).
Peters, K.E., Cassa, M.R., 1994. Applied source rock geochemistry. In: Magoon, L.B., Dow, W.G. (Eds.), The Petroleum System – from Source to Trap. AAPG Memoir, vol. 60, pp. 93–120.
Shakib, S.S., 1987. Age biozonation and stratigraphy of Kazhdumi formation of SW, Iran. Rivista Italiana di Paleontologia e Stratigrafia 93, 201–224.
Sharland, P.R., Archer, R., Casey, D.M., Davies, R.B., Hall, S.H., Heward, A.P., Horbury, A.D., Simmons, M.D., 2001. Arabian Plate sequence stratigraphy. In: GeoArabia, Special Publication, vol. 2. Gulf PetroLink, Bahrain, 371 pp.
Stover, L.E., Brinkhuis, H., Damassa, S.P., de Verteuil, L., Helby, R.J., Monteil, E., Partridge, A.D., Powell, A.J., Riding, J.B., Smelror, M., Williams, G.L., 1996. Mesozoic–Tertiary dinoflagellates, acritarchs and prasinophytes. In: Jansonius, J., McGregor, D.C. (Eds.), Palynology: Principles and Applications, vol. 2. American Association of Stratigraphic Palynologists Foundation, Dallas, Texas, pp. 641–750.
Tehran Energy Consultants, 2001. South Pars Oil Reservoir Modeling Study, vol. 1. Tehran, Iran, unpublished.
Traverse, A., 2007. Paleopalynology. Topics in Geobiology, second ed. Springer, Dordrecht, The Netherlands, 813 pp.
Tyson, R.V., 1987. The genesis and palynofacies characteristics of marine petroleum source rocks. In: Brooks, J., Fleet, A.J. (Eds.), Marine Petroleum Source Rocks. Geological Society, London, Special Publication, vol. 26, pp. 47–67.
Tyson, R.V., 1989. Late Jurassic palynofacies trends, Piper and Kimmeridge Clay Formations, UK onshore and northern North Sea. In: Batten, D.J., Keen, M.C. (Eds.), Northwest European Micropalaeontology and Palynology. Ellis Horwood Publishers, Chichester, pp. 135–172.
Tyson, R.V., 1993. Palynofacies analysis. In: Jenkins, D.J. (Ed.), Applied Micropalaeontology. Kluwer Academic Publishers, Dordrecht, pp. 153–191.
Tyson, R.V., 1995. Sedimentary Organic Matter. Organic Facies and Palynofacies. Chapman and Hall, London, 615 pp.
Uwins, P.J.R., Batten, D.J., 1988. Early to mid-Cretaceous palynology of northeast Libya. In: Arnauti, A., Owens, B., Thusu, B. (Eds.), Subsurface Palynostratigraphy of Northeast Libya. Garyounis University Publications, Benghazi, Libya (SPLAJ), pp. 215–257.
van Krevelen, D.W., 1993. Coal: Typology – Physics – Chemistry – Constitution, third ed. Elsevier Science, Amsterdam, 979 pp.