

Eocene climatic events recorded in dinoflagellate cyst assemblages from the Kopeh-Dagh Basin, NE Iran; a statistical approach

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Abstract To evaluate the climate events of the Eocene, a section of the Khangiran Formation, dated Early–Middle Eocene based on Planktonic foraminifera (P6–P11 zones) was selected in the Kopeh-Dagh Basin of Northeastern Iran and sampled systematically for palynological studies. Statistical notions such as Detrended Correspondence Analyses and Canonical Correspondence Analyses were practiced on the data gathered. Results were plotted and drawn as statistical diagrams for abundance of climate proxy genera and environmental parameters. These suggests a shift from a warm, high-nutrient, low-oxygen environment of inner neritic setting to a relatively colder, less nutrient and high-oxygen outer neritic environment from the Early to the Middle Eocene.

Keywords EECO · MECO · Dinocyst assemblages · Kopeh-Dagh Basin · Iran

Introduction

The Paleogene period is known as the most significant dynamic period of climatic global changes. During this period, the atmospheric carbon dioxide concentration was much higher than today (Smith et al. 2010; Pearson and Palmer 2000; Zachos et al. 2010), making the early Paleogene

climatologically distinct from other intervals. Paleogene is characterized by globally warm climate, as it reached maximum warmth in Early Eocene when the sea surface temperature in the Antarctic Ocean, rise as high as 30 °C with the least temperature change at different latitudes (Bijl 2011). The Early Eocene Climate Optimum (EECO) followed by a second event, the Middle Eocene Climate Optimum (MECO), which unlike the EECO is not interpreted as exclusively a “climate optimum” but a significant triggering event for climate reversal into a cooling global climate at the beginning of the Oligocene which was accompanied by glaciations (Brinkhuis 1994; Sluijs and Brinkhuis 2009; Smith et al. 2010; Zachos et al. 2010; Bijl et al. 2011).

Eukaryotic production patterns of dinoflagellates as marine microorganisms which are extremely sensitive to even the slightest changes in the physico-chemical characteristics of waters (Pross and Brinkhuis 2005; Taylor 1987) is directly related to patterns of surface currents, upwelling, mixing rate, surface winds, and also global carbon cycle (Taylor 1987; Zachos et al. 2010). Furthermore, some cysts, particularly those regarded as heterotrophic taxa, could be considered as critical tools in reconstructing the patterns of eukaryotic production (Sluijs et al. 2005).

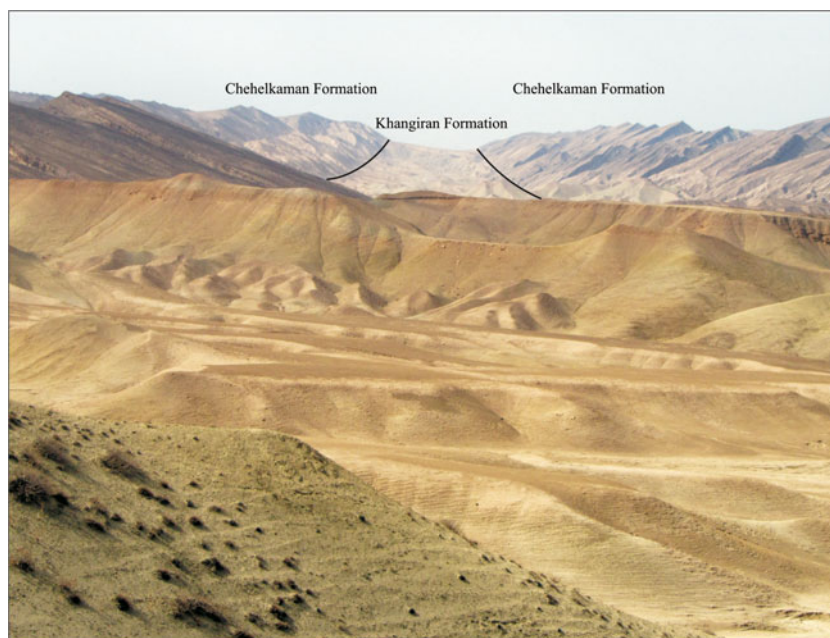
The Kopeh-Dagh basin of Northeastern Iran contains many rock units spanning generally from Triassic to Pliocene in age and forming sections of as thick as 8,000 m. The Khangiran Formation, on which the present study has been carried on, is one of the most important formations (Fms) in this basin as it is home to the youngest and yet most important marine deposits (Afshar-Harb 1969) composing a continuous sequence of intercalated olive-gray calcareous shales. It has been dated as of Early Eocene to Late Oligocene in age (Aghanabati 2006). Planktonic foraminiferal studies of the formation at the present locality (Figs. 1 and 2) revealed microfossil zones of P6–P11 with an age of Early–Middle Eocene for the formation (Salahi 2011).

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Fig. 1 A northward view of the Khangiran Fm sandwiched between Chehel Kaman Formation



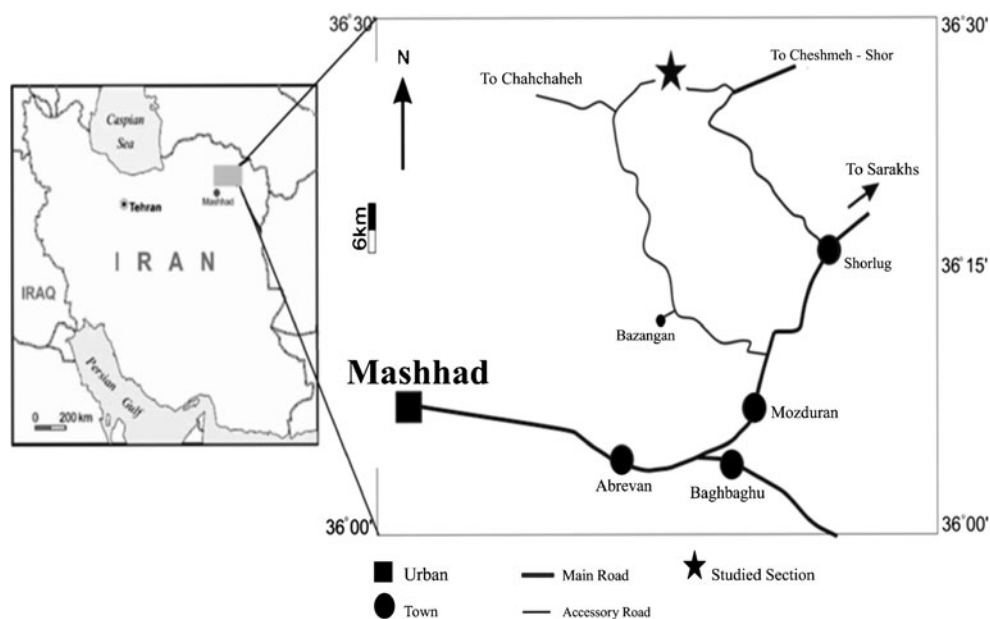
Geology

The Khangiran Formation in Chehel Kaman syncline section (latitude: $36^{\circ}33'16''$ E and longitude: $36^{\circ}36'5.6''$ N) is composed of alternated green-yellow marl with intercalated silty layers. The 136-m thick formation is underlain by the Chehel Kaman Formation while due to the sandwiching position of the formation within the syncline; the upper boundary is not visible (Fig. 1).

Material and methods

Forty-five samples with an interval of 3 m were taken from the formation under study and treated palynologically using standard techniques for preparation (Traverse 2007). The preparation briefly consists of HCl 10 % and HF 44 % digestion, neutralization, boiling with HCl 10 %, sieving through 20- μ m mesh nylon sieve, heavy liquid separation by $ZnCl_2$ solution, centrifuging, staining, and finally mounting on microscope

Fig. 2 Location map of the section studied



slides using liquid Canada Balsam. The slides were then studied under a Nikon light microscope (with $\times 10$ and $\times 40$ objective lenses). Palynomorphs in each sample were counted and categorized into groups including, unidentified dinocysts, palynodebries, spore and pollen, and fungi. Identifiable dinocysts were also counted, differentiated, and used for statistical approaches. The well-known dinocysts were photographed and presented in Plate 1.

Data manipulation and preparation for statistical analysis

At least 200 grains were counted and differentiated into groups for each sample. For some samples where total grains were less than 200, the number was then converted to 200 and standardized and percentage of each group was calculated. After inserting data in Microsoft Excel 2007, data were moved to STATISTICA V.10™ and dinocyst abundance and distribution diagrams along the stratigraphic column of the formation were erected. Statistical analyses were performed as multivariate notions on the basis of different studies (e.g., Versteegh and Zonneveld 1994; Bijl 2011; Sluijs and Brinkhuis 2009; Lepš and Šmilauer P 2003; Hill and Gaugh 1980).

Statistical concepts and methods

The data were presented and interpreted via using unconstrained ordination methods of Detrended Correspondence and Canonical Correspondence analyses (DCA and CCA). When statistical methods are used, a linear relationship between the abundance of species and environmental changes is often assumed. However, if large gradients are concerned, it is most likely that species show a non-linear response curve in relation to these gradients. They often show an abundance optimum along a gradient. Therefore, it might be preferred to use unconstrained ordination methods which is based on non-linear response curves (Lepš and Šmilauer P 2003; Versteegh and Zonneveld 1994). Unconstrained ordination methods are techniques in which there is often one or two (mutually exclusive) gradients representing optimal anticipating structures used to corresponding species linear responses in regression models and such optimal conditions considered for the entire primary data. These methods place the species optimum on a gradient and emphasize less abundant species (Versteegh and Zonneveld 1994; Sluijs and Brinkhuis 2009). Ordination methods arrange samples and species along gradients such that samples (or species) located close together are more similar in species composition (respectively; occur in the same samples) and samples (or species) located far apart have dissimilar species composition (or do not occur in the same samples). Both DCA and CCA are based on the assumption that the species composition of a sample is a result of the environmental (biotic and abiotic) conditions on

the sample site. Consequently, differences in species composition between the samples are the result of gradual (biotic and abiotic) changes in environmental conditions (Versteegh and Zonneveld 1994). As Versteegh and Zonneveld (1994) argue, the position of species optima is determined on the axes in standard deviation (SD). That is, on the ordination axes, four types of SD were identifiable on which a species appears, rises to mode, and disappear again. Thus, species plotted with more than four SD will not appear in similar samples. Furthermore, such samples are not expected to have any species in common. The second axis illustrates environmental variations (Hill and Gaugh 1980; Versteegh and Zonneveld 1994). DCA uses the variation in species composition between the samples to determine the underlying gradients influencing the data. The basic assumption of this method is that the most important environmental gradient causes the largest variation in the species composition. By means of a two-way weighted averaging algorithm the direction of this variation is calculated and represented as the first DCA axis (e.g., Hill and Gaugh 1980; Versteegh and Zonneveld 1994).

CCA can define different environmental variables according to the distribution of assemblage composition along the axes. The CCA identifies the position of species optima, based on the inferred environmental variables. As the CCA distribute the species abundance on optimum gradients along the axes; the species from the axes show less role in environment which means they are ecologically persistent or non-effective. Therefore, samples with frequencies less than 3 % were omitted in order to avoid the low frequency samples effect (TerBraak 1986).

Paleoenvironmental reconstruction could represent a more comprehensive portrayal of species that respond most to the environmental changes. The CCA categorizes all the calculated environmental variables as environmental proxy species. These variables include: frequency distribution of cold–warm water species (C/W), inner neritic to oceanic species (IN/O), outer neritic to oceanic species (ON/O), and abundance of inshore/offshore proxy morphotypes [(chorate/proximochorate + proximate + cavate, (C/PPC)) sensu Ghasemi-Nejad et al. 1999]. This type of ordination, which is shown along two axes with two eigenvalues, clearly demonstrates the statistical value of each species according to environmental indicators. Major environmental variables, encompassing temperature, sedimentary environment, salinity, and productivity are defined through these concepts.

Results

Figures 3 and 4 present our results of statistical analyses. An eigenvalue is provided for each analysis (Table 1). These eigenvalues represent variability in statistical data defined on each axis.

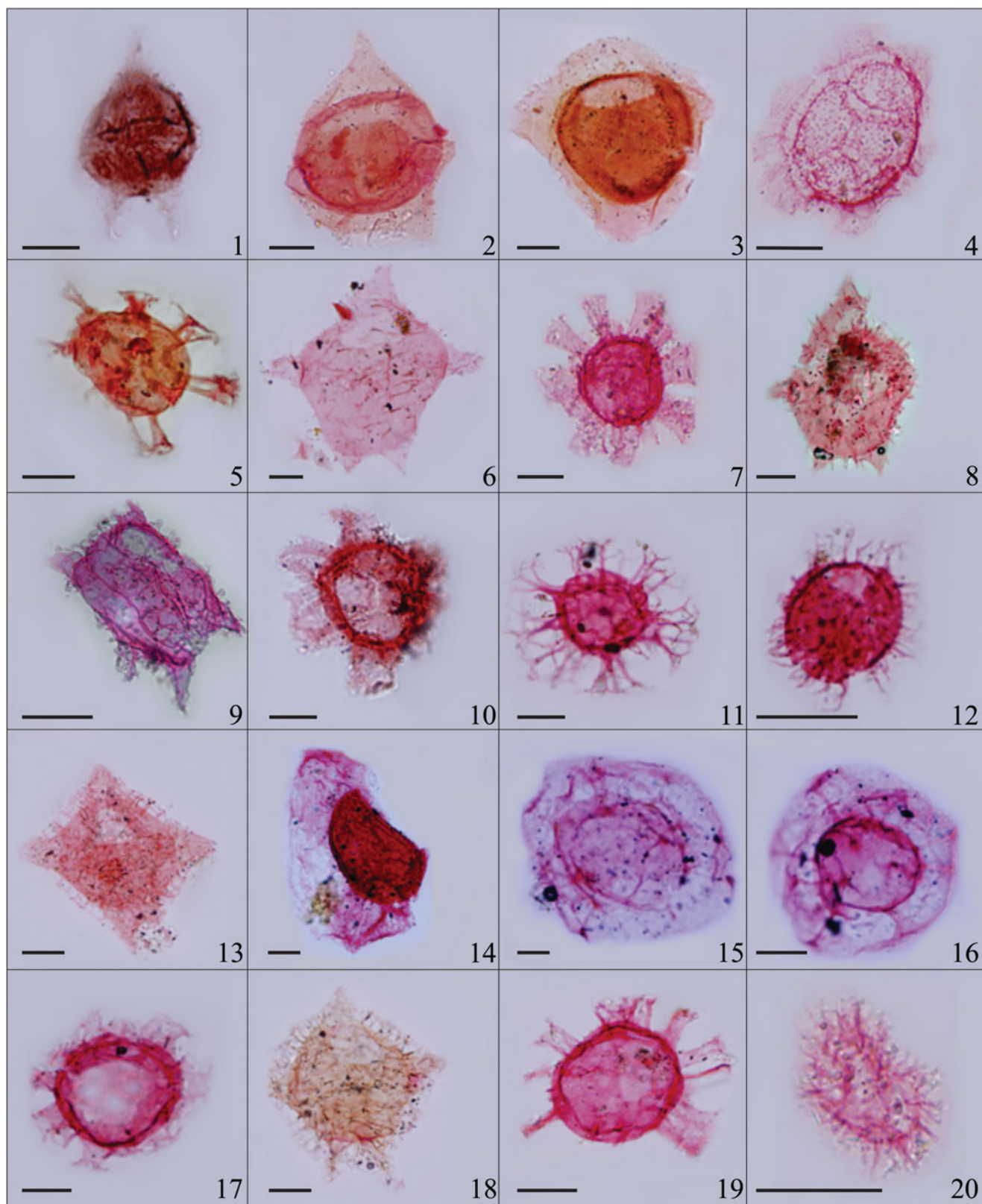


Plate 1 Selected dinocysts from the Khangiran Fm. Scale bar represents 50 μ . 1 *Cerodinium wardanese*, 2 *Deflandrea phosphoritica*, 3 *Dracodinium politum*, 4 *Dinopterygium cladoides*, 5 *Hystrichosphaeridium* sp., 6 *Wetzeliella* sp., 7 *Hystrichokolpoma* sp., 8 *Wetzeliella* sp., 9 *Wetzeliella articulata*, 10 *Hystrichokolpoma rigaudiae*, 11 *Spiniferites* sp., 12

Operculodinium sp., 13 *Charlesdownia crassiramosa*, 14 *Thalassiphora delicata*, 15 *Thalassiphora* sp., 16 *Hystrichostrogylon* sp., 17 *Hystrichokolpoma* sp., 18 *Charlesdownia coleothrypta*, 19 *Cordosphaeridium fibrospinosum*, 20 *Operculodinium* sp.

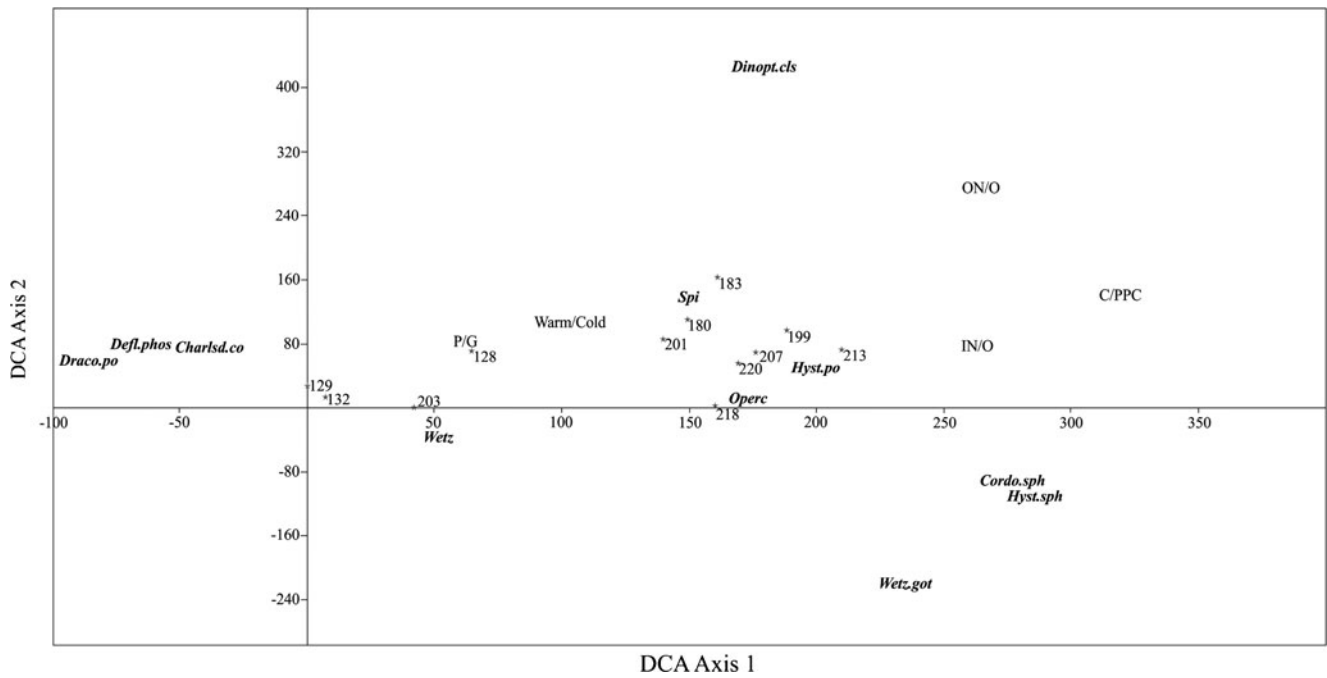


Fig. 3 Detrended Correspondence Analysis diagram. *Draco.po* *Dracodinium politum*; *Defl.phos* *Deflandrea phosphoritica*; *Charlsd.co* *Charlesdownia coleothrypta*; *Wetz* *Wetzelioleoides*; *Operc* *Operculodinium* sp.; *Spi* *Spiniferites* sp.; *Hyst.po* *Hystrichokolpoma* sp.; *Cordo.sp.* *Cordosphaeridium* sp.; and *Hyst.sph*: *Hystrichosphaeridium* sp.

Environmental factors: *P/G* productivity index (Versteegh and Zonneveld 1994), *Warm/Cold* dinos ratio, *ON/O* and *IN/O* habitats ratio, and *C/PPC* ratio of Chorate forms to other three groups (proximate, proximochorate, and cavate) Ghasemi-Nejad et al. 1999. For illustration, see the text

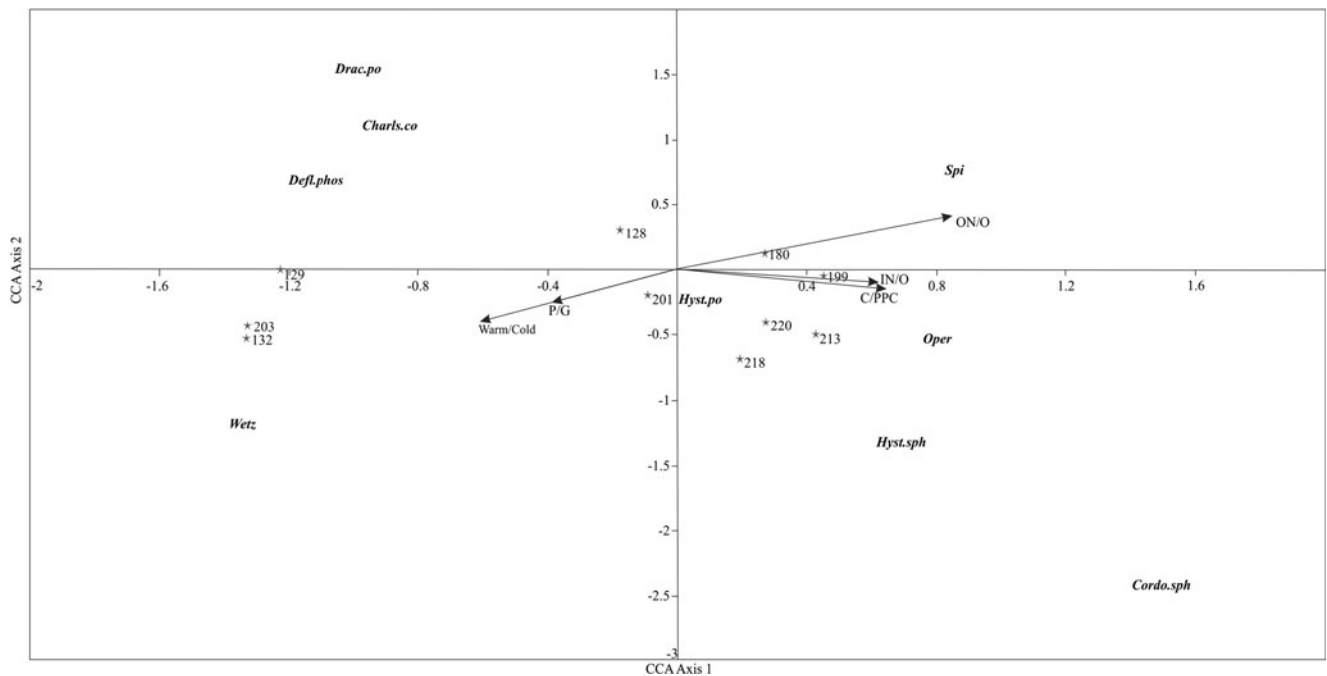


Fig. 4 Canonical Correspondence Analysis diagram. *Draco.po* *Dracodinium politum*; *Defl.phos* *Deflandrea phosphoritica*; *Charlsd.co* *Charlesdownia coleothrypta*; *Wetz* *Wetzelioleoides*; *Operc* *Operculodinium* sp.; *Spi* *Spiniferites* sp.; *Hyst.po* *Hystrichokolpoma* sp.; *Cordo.sph* *Cordosphaeridium* sp., and *Hyst.sph* *Hystrichosphaeridium* sp.

Environmental factors: *P/G* productivity index (Versteegh and Zonneveld 1994), *Warm/Cold* dinos ratio, *ON/O* and *IN/O* habitats ratio, and *C/PPC* ratio of Chorate forms to other three groups (proximate, proximochorate and cavate) Ghasemi-Nejad et al. 1999. For illustration, see the text

DCA

The DCA diagram (Fig. 3), clearly separates warm climate/high productive species from cold-water forms. The warm climate indicator species have allocated on the left side of the diagram, while cold climate indicator species on the middle of the diagram closer to the first axis. Cold climate indicator species, however, demonstrate a general cooling trend towards the middle Eocene. This could also be inferred from the samples distance from the P/G ratio, the productivity gradient. Furthermore, warm climate-dominated samples are plotted in closest position to the

productivity index (P/G). The placement of these samples in the vicinity of productivity gradient was clued as to the effect of temperature on productivity gradient during the Early Eocene. Such trend is not traceable for the middle Eocene indicator species. Species distribution along the DCA axes show that such species as *Operculodinium* sp., *Spiniferites* sp., *Hystrichokolpoma rigaudiae*, *Hystrichokolpoma spinosum*, and *Hystrichokolpoma* sp. are allocated within middle Eocene samples on the first axis of DCA. *Spiniferites* sp. and *Operculodinium* sp. are considered as cold-water species and their presence, along with *Hystrichokolpoma* spp., are considered

Table 1 Counts and calculated data for statistical analysis

Samples	T	P.M	Dinos	AOM	P	G	W/C	P/G	C/PPC	IN/O	ON/O
128	0	0	411	26	110	141	1	0.0079	1.157	0.9	0.9
132	0	11	69	72	29	0	1	0	0	0	0
135	0	0	10	0	0	0	1	0	0	0	0
138	0	0	2	0	0	0	0	0	0	0	0
141	0	0	0	0	0	0	0	0	0	0	0
144	0	0	0	0	0	0	0	0	0	0	0
146	0	0	0	0	0	0	0	0	0	0	0
148	0	0	0	0	0	0	0	0	0	0	0
150	0	0	1	0	0	0	0	0	0	0	0
153	0	0	1	0	0	0	0	0	0	0	0
155	0	43	3	32	0	0	0	0	0	0	0
159	0	0	6	0	0	0	0	0	0	0	0
163	0	0	0	0	0	0	0	0	0	0	0
169	0	66	3	28	0	0	0	0	0	0	0
172	1	1	0	0	0	0	0	0	0	0	0
175	3	3	1	0	0	0	0	0	0	0	0
178	4	4	0	0	0	0	0	0	0	0	0
180	0	184	84	104	8	38	0	0.03	4.25	0.058	0.8
183	41	171	8	175	0	0	0	0	0	0	1
187	9	14	48	79	0	8	0	0	0	0	0
190	1	58	4	69	0	0	0	0	0	0	0
193	0	0	0	0	0	0	0	0	0	0	0
196	0	12	4	322	0	0	0	0	0	0	0
199	5	5	32	0	0	11	0	0.09	5.5	1	1
201	9	104	5	136	0	0	1	0	0	0	0
203	14	33	18	47	4	2	1	0.5	0	0	0
207	5	62	89	119	3	54	0	0.01	8.85	1	1
213	3	29	30	84	2	13	0	0.083	6.5	0.6	0.6
215	77	74	3	114	1	0	0	0	0	0	0
218	1	153	100	43	22	56	0	0.018	2	0.79	0.7
220	0	31	46	30	7	23	1	0.052	3.5	0.875	0.9
223	0	59	0	376	0	0	1	0	0	0	0
226	1	1	3	0	0	1	1	0	0	0	0
229	7	7	6	0	0	0	1	0	0	0	0
236	0	20	1	114	0	0	0	0	0	0	0
247	0	192	0	247	0	0	0	0	0	0	0

to suggest neritic to mostly neritic environments (Guasti 2005; Bijl, et al. 2011; Bijl 2011).

CCA

Environmental indicator factors including P/G, W/C, and also environmental preferences data including IN/O, ON/O, and C/P + P + C indices are presented in Table 2. Data with values less than 3 % were deleted from calculations. Table 3 provides dinocysts counting data and eigenvalues for CCA drawn graphically as Fig. 4. As shown on Fig. 4, samples 128, 129, 132, 199, 201, and 203 have the closest position to axis 1 with an eigenvalue frequency distribution of 71.97 % (128, 129, 132, and 199 are belong to Early Eocene, while 201 and 203 to Middle Eocene.) On ordination methods, higher eigenvalues indicate optimum allocation of species rather than environmental variables (Hill and Gaugh 1980). The figure also demonstrates alignment of productivity and temperature in this study though they have not reportedly been aligned in previously existing literature (Dale 1976; Popselva, et al. 2004; Pross and Brinkhuis 2005; Sluijs et al. 2005). Essentially, the length of arrows in statistical ordinations indicates the tendency of environmental parameters and most adaptable dinocyst distribution. *Spiniferites* and *Operculodinium* spp. For example, show the most adaptable distribution to outer neritic environment. In addition, the proxy, C/PPC (offshore/inshore), and environmental indicators of IN/O and ON/O are all directed to the same direction at the positive end of axis 1 which demonstrates most adaptation of studied genera with neritic environment (allocated around axis 1, with 71.97 % of eigenvalue).

Palaeoecological preferences

Palaeotemperature

Large numbers of heterotrophic dinocysts such as *Deflandrea phosphoritica* and *Wetzelialla* sp. were recorded at the base of the formation. Though, as Dale (1976) and Shin et al. (2012) argues, the existence of heterotrophic dinocysts may not always be interpreted as warm temperature but, as shown on CCA diagram in this case study correspondence between productivity and temperature is visible. The diverse and abundant dinocysts in the base samples of the Khangiran Formation may also provide clues for other ecologically favorable factors such as

Table 2 Data for CCA eigenvalues and eigenvalues percentages. For illustrations see the text

Axis	Eigenvalue	Percent
1	0.21446	71.97
2	0.06554	21.99
3	0.0177	5.94
4	0.0002909	0.09762

nutrient which could have caused a rise in productivity. Abundance of warm-water species such as the following: *Charlesdownia coleothrypta*, *Cordosphaeridium fibrospinosum*, *Cordosphaeridium gracile*, *Deflandrea phosphoritica*, *Dracodinium politum*, *Dinopterygium cladoides*, *Hystrichokolpoma spinosum*, *Hystrichokolpoma rigaudiae*, *Wetzelialla articulate*, *Wetzelialla salmandica*, and *Wetzelialla* sp. in the lowermost 5 m of the formation and also the calculated ratios of W/C index; presented as Table 1,

Table 3 Counts for some proxy forms in samples studied

Sample Numbers	Spi	Defl	Oper	Wetz	Hyst.po	Cordo.sph
128	76	53	49	30	5	2
132	0	10	0	19	0	0
135	0	0	0	0	0	0
138	0	0	0	0	0	0
141	0	0	0	0	0	0
144	0	0	0	0	0	0
146	0	0	0	0	0	0
148	0	0	0	0	0	0
150	0	0	0	0	0	0
153	0	0	0	0	0	0
155	0	0	0	0	0	0
159	0	0	0	0	0	0
163	0	0	0	0	0	0
169	0	0	0	0	0	0
172	0	0	0	0	0	0
175	0	0	0	0	0	0
178	0	0	0	0	0	0
180	20	4	7	4	5	1
183	6	0	0	0	0	0
187	6	0	0	0	0	0
190	0	0	0	0	0	0
193	0	0	0	0	0	0
196	0	0	0	0	0	0
199	4	0	7	1	0	0
201	0	0	0	0	1	0
203	0	2	0	3	0	0
207	31	2	22	3	0	9
213	4	0	4	2	2	2
215	0	0	0	0	0	0
218	17	0	19	21	5	11
220	9	0	7	1	1	2
223	0	0	0	0	0	0
226	0	0	0	0	0	0
229	0	0	0	0	0	0
236	0	0	0	0	0	0
247	0	0	0	6	0	0

Spi *Spiniferites* sp., *Defl* *Deflandrea phosphoritica*, *Oper* *Operculodinium* sp., *Wetz* *Wetzelioideas*, *Hyst.po*: *Hystrichokolpoma* sp., and *Cordo.sph* *Cordosphaeridium* sp.

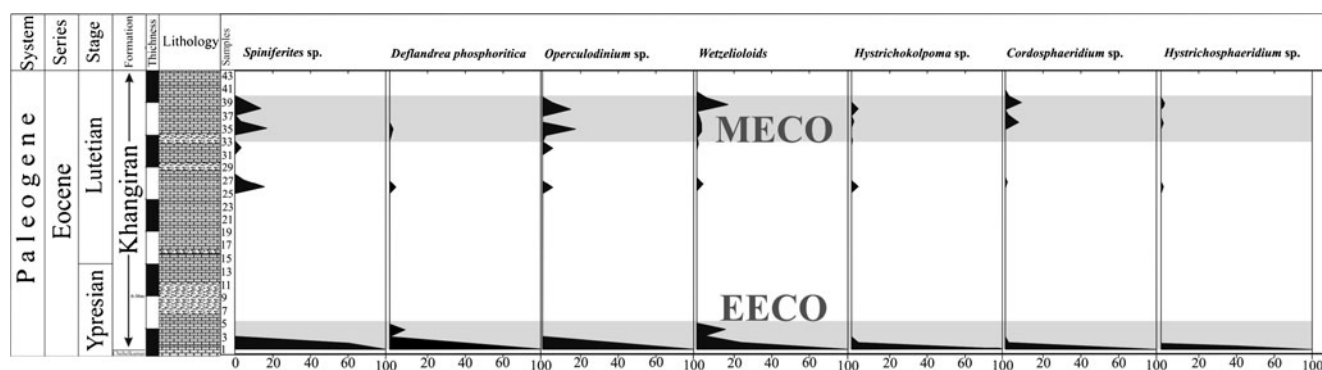


Fig. 5 Abundance and distribution of dominant dinocysts from bottom to the top of the formation, highlighted areas indicate akin to Climate Optimums

demonstrate semi-equatorial climate for the Khangiran Fm during the Early Eocene. Higher up in the section, however, absence of dinocysts and their poor preservation did not allow palaeoenvironmental interpretations. In contrast, in upper parts, 53 m from the base of the Fm in the Middle Eocene samples preservation become better and dinocysts are identifiable and countable. Here, the assemblages of the Middle Eocene indicate evidences of a cold climate via the presence and abundance of cold preference species such as *Spiniferites* sp. and *Operculodinium* sp. The warm climate confirmed at the basal samples of the Khangiran Fm via abundance of warm-water dinocysts and also consistent abundance of peridinioids/gonyaulacoids could be attributed and accentuated to Early Eocene temperature rising, caused by significant amounts of carbon dioxide, referred as the Greenhouse effect (Pearson and Palmer 2000; Sluijs et al. 2005; Zachos et al. 2010; Bijl 2011)

Oxygen and nutrients

Peridinioids were largely present in the lower part of the formation studied indicating high levels of productivity during the

depositional course of this part. Popselva et al. (2004) related such high marine productivity to upwelling coastal currents. The absence of dinocysts in the middle parts of the formation has confined productivity reconstruction. However, a significant decline in nutrients was detected in the middle parts of the formation between 40 to 53 m from the base of the section where the two autotrophic forms, *Operculodinium* sp. and *Spiniferites* spp. are present largely indicating a decline in productivity in offshore areas (Popselva et al. 2004). Oxygen decline proves to be one of the major factors controlling diversity and abundance of dinoflagellates species. Changes in diversity of dinocyst assemblages could reflect major oxygen changes in the environment (Pross 2001; Versteegh and Zonneveld 1994). Existence and relative abundance of *Spiniferites* sp. throughout the formation studied leads to assume that the Khangiran Formation has been generally well ventilated in both upper and lower sectors. The samples studied have also revealed low diversity and they only contain some sorts of poorly preserved forms suggesting high-oxygen levels during much of the formation's sedimentation course. Abundance of *Deflandrea phosphoritica*, as Brinkhuis (1994) argues was always observed

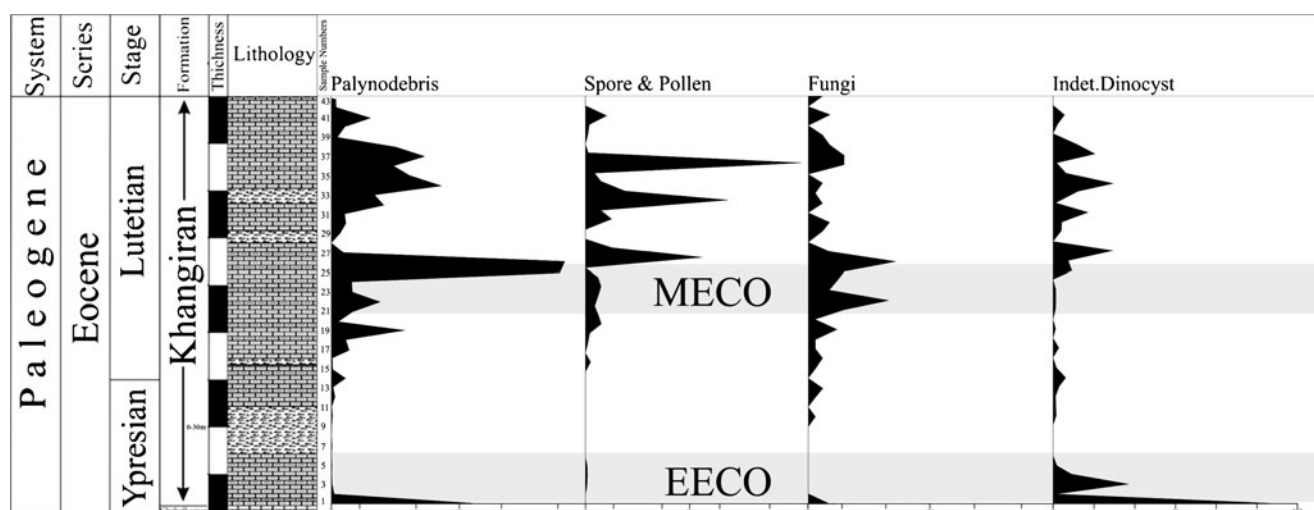


Fig. 6 Palynological elements abundance and distribution: palynodebris, spores and pollen, fungi, and indeterminate dinocysts. Highlighted areas indicate Climate Optimums

in nutrient-rich areas including estuaries or inner neritic environments. Palaeoenvironmental analysis from the Early Eocene to Middle Eocene suggest that productivity and nutrient level changed from a high-productivity inner neritic environment to either a restricted marine environment or a low-productivity, high-oxygen open sea.

Salinity and palaeoenvironment

Sluijs et al. (2005) noted morphological variations in dinoflagellates resulted in from changes in salinity. They further argued that increase in the frequency of *Heteraulacysta* and the allied species (such as *Dinopterygium cladoides*) is a defining feature for restricted environments with high values of salinity. *Dinopterygium cladoides* is only rarely recorded here and can not be used as a proxy. From the Early Eocene to Middle Eocene, diversity of species declines. The moderate increase in diversity of dinocyst species is interpreted to show an environment of near shore in Early Eocene while in the Middle Eocene, the environment was slightly further away from the shorelines. The calculated values for IN/O and ON/O during the Early Eocene were almost equal whereas, the ON/O outvalued IN/O in the Middle Eocene. These findings were confirmed by the alignment of their index arrows in the CCA diagram. The abundance of *Spiniferites* spp. indicates low-salinity levels (Mudie et al. 2001). Therefore, the Eocene basin of Khangiran formation had a low-salinity throughout most of the sedimentation period.

Statistical analyses of CCA diagram suggest that IN/O arrows are closer to the center of the diagram than those of ON/O; also, well correspondence between C/PPC values with those of IN/O, the increase of chorate cysts in the terminal parts of the formation, and the association of these arrows with exclusively neritic proxy genera and species such as *Operculodinium* sp. and *Spiniferites* sp. indicate that the Eocene basin of the Khangiran Fm turned from a neritic during the Early Eocene into a mainly outer neritic basin in the Middle Eocene with no significant changes in salinity level. The abundance and distribution of dominant dinocysts are shown in Figs. 4 and 5. Figure 6 presents the palynological elements of the Khangiran Formation throughout the section studied.

Concluding remarks

To investigate whether the Eocene well-known climatic events could be recorded here in the Kopeh-Dagh basin of northeastern Iran, the Khangiran Formation, with an Early to Late Eocene age, was studied palynologically. Using statistical ordination concepts and multivariate techniques, abundance and allocation of dinocyst were analyzed and the Canonical Correspondence Analysis and Detrended Correspondence Analysis were performed. Statistical values

and diagrams indicate major changes in environmental parameters during the Early Eocene towards Middle Eocene, which affected the composition of dinocyst assemblages. Based on these recorded changes, the formation has undergone a shift from a warm, high-nutrient, low-oxygen environment with inner neritic conditions in the Early Eocene to a relatively colder, outer neritic environment with less nutrients and high level of oxygen in the Middle Eocene while, salinity level followed an almost constant trend. The results suggest that the two well-known climatic events of the Eocene, EECO, and MECO, had major influences on the dinoflagellates cyst assemblages recorded within the Khangiran Fm. In this north-eastern basin of Iran, the former had a warming effect and the latter generated oxygen in the environment.

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