

Organic geochemistry and palynology of Lower Cretaceous Züünbayan oil shales, Mongolia

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Abstract : Biomarkers and spore-pollens were analyzed for twenty-six oil shales from the Züünbayan Group, Lower Cretaceous lacustrine sedimentary sequences in eastern Mongolia.

The distributions of n-alkane, steranes, hopanes, gammacerane and gammacer-2-ene indicate diversity in the contributions of an autotrophic prokaryote such as a cyanobacterium, nonmarine algae, terrestrial higher plants, heterotrophic bacteria and bacterivorous ciliates. The presence of thermally unstable compounds and low concentrations of diagenetically-generated compounds indicate that the samples are in an immature stage below the oil generation window.

Good correlations exist among organic carbon content, oil yield, bitumen content and n-heptadecane anomaly $\{2 \times n-C_{17} / (n-C_{16} + n-C_{18})$ n-alkane ratio}. This indicates that the organic carbon content and oil yield were related to the contribution of a blooming autotrophic prokaryote which sourced the dominant n-heptadecane.

High C/S ratio of the samples and the low concentration of organic sulfur compounds indicate that the Züünbayan oil shales were deposited in a freshwater environment. A palynological analysis shows a common assemblage of the Neocomian sediments belonging to the Boreal palynofloral Province. The detailed assemblage suggests that the area where the Züünbayan oil shales were deposited was situated near the border between warm-humid and hot-arid climate zones. Although Mongolia was situated in midlatitude during early Cretaceous, the tropical-subtropical climate promoted thermal stratification and therefore bottom water anoxia in the freshwater lakes. The degree of development of bottom anoxia was likely controlled by nutrient supply from the surrounding area.

1. Introduction

The Lower Cretaceous Züünbayan Group is distributed in the eastern Mongolian Mesozoic basins (Fig. 1) and is composed of lacustrine sedimentary sequences with thick oil shale horizons and coal measures (Bat-erdene and Enkhtugs, 1987). The oil shale of the Züünbayan Group (Züünbayan oil shale) is undoubtedly a petroleum source rock of waxy oil of the Züünbayan oil field (1941-1969) in the East-Gobi basin (*e.g.*, Petzet, 1990). The Züünbayan Group is correlated to the Lower Cretaceous lacustrine source beds distributed in Chinese territory.

The basins where the Züünbayan oil shales were deposited are developed in the accretional terrain on

the southern margin of the Siberian craton, and were formed by rift and graben deformations initiated in late Jurassic time (Petzet, 1990). After the rift filling with conglomerates, breccias and volcanics during late Jurassic time (Sharilin Group), lacustrine sediments (Tsagaantsav and Züünbayan Groups) were deposited during early Cretaceous time (Fig. 2; Petzet, 1990). Based on the similarity of the timing and mechanisms of basin developments, the East Mongolian Province is regarded as the northern extension of the East China Petroleum Province defined by Zhai *et al.* (1988).

The geological and geochemical investigations on the Züünbayan oil shales had been conducted by some Mongolian and Estonian institutes; nevertheless the

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"Züünbayan" was expressed as "Dsunbayan" in our previous papers (Yamamoto *et al.*, 1993; Yamamoto *et al.*, 1998)

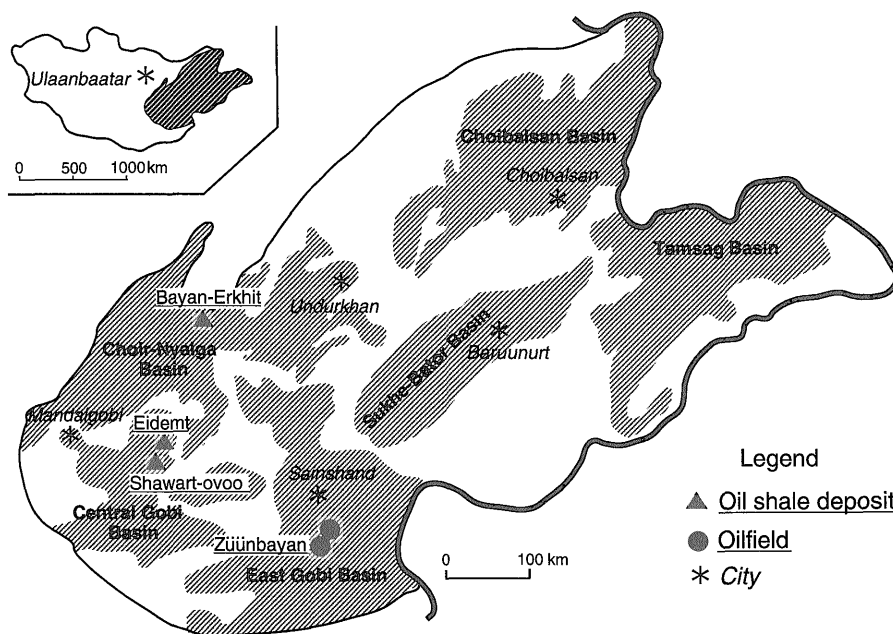


Fig. 1 Map showing the distribution of Mesozoic basins and the sampling locations in the East Mongolia coal and oil shale province. Modified from Bat-erdene and Enkhtugs (1987). After Yamamoto *et al.* (1993).

System	Period	Stage	Stratigraphic unit	
Cretaceous	Lower	Albian	Züünbayan Group	Barunbayan Formation
		Aptian		Khukhteg Formation
		Barremian Hauterivian		Shinekhudag Formation
Jurassic	Upper	Valanginian Berriasian Tithonian	Tsagaantsav Group	
		Tithonian Kimmeridgian	Sharilin Group	
	Lower-Middle	Bathonian Lias	Khamarkhoovor Group	

Fig. 2 Generalized stratigraphic column in eastern Mongolian Mesozoic basins. Modified from Petzet (1990) and Bat-erdene (1992). After Yamamoto *et al.* (1993).

results have not been published. Little published data is available about the geochemical aspects of the Züünbayan oil shales except for a few studies such as Yamamoto *et al.* (1993, 1998).

This paper reports the variations in the distribution of biomarkers and the compositions of spores and pollens in oil shales of the Züünbayan Group (Züünbayan oil shales) from the Bayan-Erkhit, Eidemt and Shawart-ovoo oil shale deposits, and discusses their geochemical characteristics and depositional environment. The oil shale samples provided for this study were taken by some of the authors (M. Y., D. B. and P. U.) during the field survey in August 1991.

2. Samples and analytical methods

Twenty-six Züünbayan oil shales from the Shinekhudag Formation (four samples from the Bayan-Erkhit oil shale deposit, ten from the Eidemt deposit and twelve from the Shawart-ovoo deposit) were collected for this study (Fig. 3 and Table 1).

The rock samples were crushed and milled to a particle size of about 200 mesh. More than 1 kg of sample was crushed at the same time and homogenized to eliminate the centimeter and decimeter scale heterogeneity of the sample.

The powdered sample (c. 1-5 g) was extracted three times by ultrasonification with benzene/methanol (7/3 v/v) for 15 minutes. The solvent extract (bitumen) was chromatographed by thin layer chromatography with a silica gel plate (Whatman, PLKC 18 F 20 × 20 cm, 1000 μm) and hexane as a development solvent. The band of R_f 0.7-1.0 was scraped off from the plate and re-extracted with a mixture of benzene/methanol (1/1 v/v). This fraction is called "Hydrocarbon fraction."

Molecular distributions were determined using a Hewlett Packard 5890A+5970B gas chromatography-mass spectrometry (GC/MS) system equipped with a fused silica capillary column coated (Ultra-1, length = 25 m, i.d. = 0.20 mm, film thickness = 0.33 μm thick). Hydrocarbon fraction was dissolved in benzene and then injected into the splitless injection system at 300 °C with helium carrier gas. The oven temperature was programmed from 60 °C to 160 °C at 20 °C/min., from 160 °C to 300 °C at 4 °C/min., and then isothermal at 300 °C for 30 minutes. The mass spectrometer was

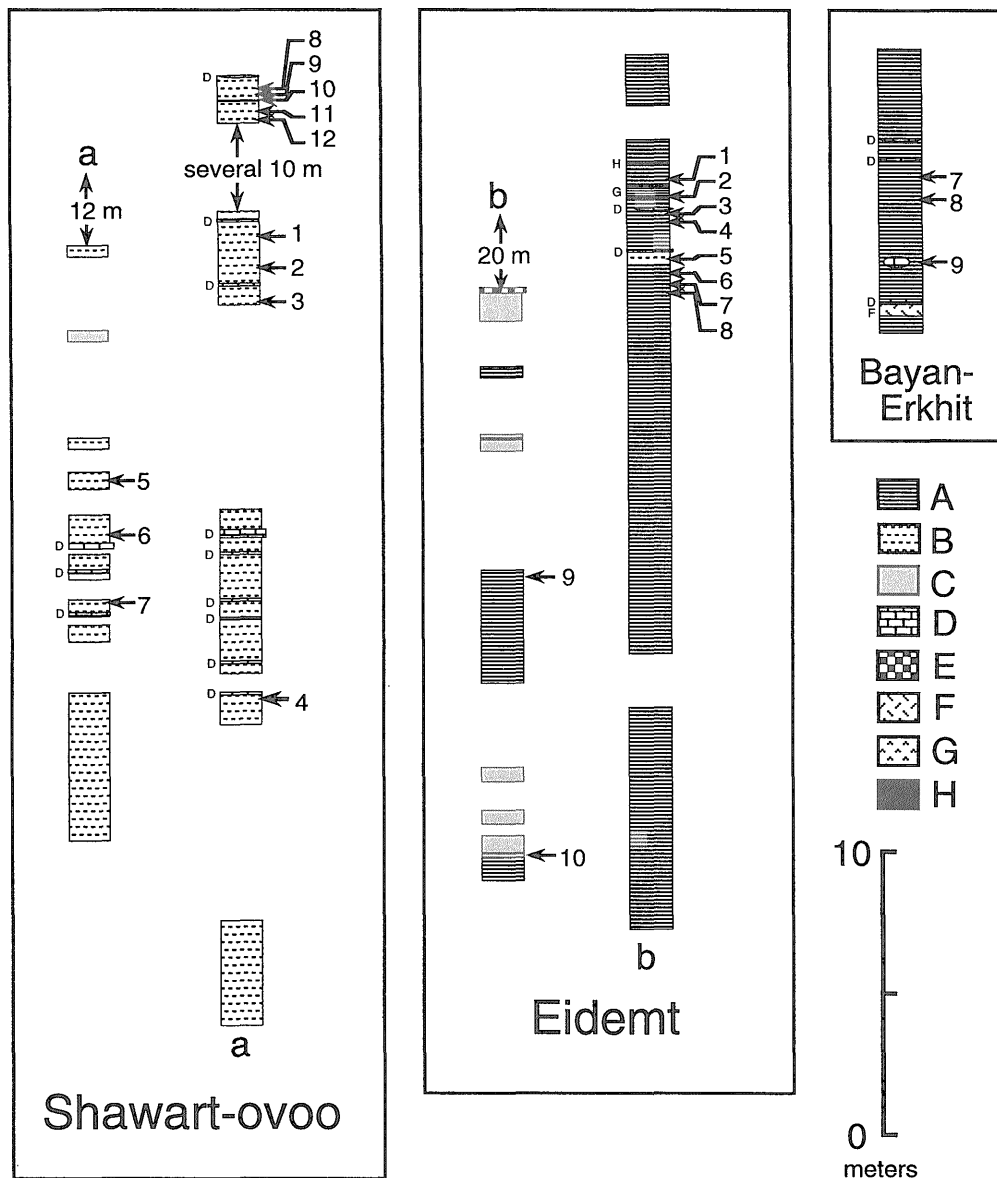


Fig. 3 Stratigraphic and lithologic sections of the Bayan-Erkit, Eidemt and Shawart-ovoo deposits. The numbers in the column indicate sampling positions and sample numbers. A=mudstone, B=calcareous mudstone/siltstone, C=fine grained sandstone, D=dolomite nodule, E=conglomerate, F=tuffaceous mudstone, G=tuff, H=gypsum. After Yamamoto *et al.* (1998).

run in the full scan ion monitoring mode (m/z 50-550) or in the selected ion monitoring mode (SIM; m/z 99, 125, 177, 191, 205, 217 and 231), with an ionizing-electron energy of 70 eV. Assignment of peaks on the gas chromatograms was carried out by comparison with those of standards and in literature, *e.g.*, Philp (1985) and Peters and Moldowan (1993). Abundances of the compounds were represented by their peak areas in the specific fragmentograms, *i.e.*, m/z 99 for n-alkanes, m/z 125 for β -carotane, m/z 191 for triterpanes and m/z 217 for steranes. Relative abundances of biomarkers were calculated according to the formula in Appendix I.

The analysis of spores and pollens in three se-

lected samples was conducted by Palynosurvey Co. Ltd., Tokyo.

3. Results and discussion

3.1 Biomarker distributions and sources of organic matter

The hydrocarbons extracted from the Züünbayan oil shales consist mainly of n-alkanes, isoprenoid alkanes, hopanes, hop-17(21)-enes, isohop-13(18)-enes, steranes, gammacerane, gammacer-2-ene and β -carotane (Fig. 4, Table 2). Little sulfur compound was detected. The relative abundances of each compound classes are shown in Table 3. The correlation coefficients (r)

Table 1 List of oil shale samples from the Shinekhudag Formation of the Lower Cretaceous Züünbayan Group

Sample name	Rock type	color	Bioturbation
<i>Bayan-Erkhit</i>			
no.5	mudstone	dark brownish gray	none
no.7	mudstone	dark brownish gray	none
no.8	mudstone	dark brownish gray	none
no.9	mudstone	dark brownish gray	none
<i>Eidemt</i>			
no.1	mudstone	dark brownish gray	none
no.2	mudstone	dark brownish gray	none
no.3	mudstone	dark brownish gray	none
no.4	mudstone	dark brownish gray	none
no.5	calcareous mudstone	beige gray	none
no.6	mudstone	dark brownish gray	none
no.7	mudstone	dark brownish gray	none
no.8	mudstone	dark brownish gray	none
no.9	mudstone	dark brownish gray	none
no.10	mudstone	dark brownish gray	none
<i>Shawart-ovoo</i>			
no.8	calcareous mudstone	bluish gray	none
no.9	calcareous mudstone	bluish gray	none
no.10	calcareous mudstone	bluish gray	none
no.11	calcareous mudstone	bluish gray	none
no.12	phosphatic calcareous siltstone	bluish gray	bioturbated
no.1	calcareous mudstone	bluish gray	none
no.2	calcareous mudstone	bluish gray	none
no.3	calcareous mudstone	bluish gray	none
no.4	calcareous mudstone	bluish gray	none
no.5	calcareous mudstone	bluish gray	none
no.6	calcareous mudstone	bluish gray	none
no.7	calcareous mudstone	bluish gray	none

for Rock-Eval and biomarker parameters are shown in Table 4.

3.1.1 Maturity

The presence of thermally unstable compounds, *e.g.*, 5 β (H), 14 α (H), 17 α (H)-steranes, 17 β (H), 21 β (H)-hopanes, hop-17(21)-enes, isohop-13(18)-enes and gammacer-2-ene and low concentrations of diagenetically-generated compounds, *e.g.*, 20 S-steranes and 22 S-hopanes in samples (Table 3) indicate that they are in an immature stage below the oil generation window.

The ratio of gammacer-2-ene to gammacerane is slightly higher in Shawart-ovoo samples than the others (Fig. 5). Since the gammacerane is thought to be formed from tetrahymanol *via* gammacer-2-ene (ten Haven *et al.*, 1989), the ratio of gammacer-2-ene to gammacerane must decrease with increasing maturity. Thus the higher ratios of the Shawart-ovoo samples indicate that they are less mature than the others.

$\beta\beta$ -hopane (%) ($\beta\beta/(\beta\beta+\beta\alpha+\beta\alpha)$ hopane \times 100), often used as a maturity parameter (Seifert and Moldowan, 1980), varies largely among samples (Fig. 5). Interestingly, the samples with low $\beta\beta$ -hopane (%) (Bayan-Erkhit no. 9, Eidemt no. 4, Shawart-ovoo nos. 2 and 3) have high hop-17(21)-enes/ $\beta\beta$ -hopane ratio (Fig. 5).

Since hop-17(21)-ene yields abundant $\beta\alpha$ - and $\alpha\beta$ -hopanes on hydrogenation during early diagenesis (ten Haven *et al.*, 1988), the hop-17(21)-ene might be a precursor of the abundant $\beta\alpha$ - and $\alpha\beta$ -hopane. It indicates that the $\beta\beta$ -hopane (%) does not reflect maturity but source differences in these samples.

3.1.2 Sources of organic matter

About half of samples show a dominant n-heptadecane (n-C₁₇ alkane) on n-alkane distribution. The n-heptadecane anomaly (expressed in $2 \times C_{17}/(C_{16} + C_{18})$ n-alkane ratio) is extremely high in two samples (Eidemt nos. 3 and 4) (Fig. 5). Although the dominant n-heptadecane is often attributed to algal contribution (Tissot *et al.*, 1978; Dean and Anders, 1991), its origin is still questionable. A dominance of C₁₇ straight chain hydrocarbons has been reported in some photosynthetic and non-photosynthetic bacteria as well as marine algae (compiled in Hunt, 1979). A good correlation exists between n-heptadecane anomaly and isohop-13(18)-ene/ $\beta\beta$ -hopane ratio ($r=0.72$; Table 4), which suggests that both n-heptadecane and isohop-13(18)-ene have a common origin (Fig. 6). Since hopanoids are biosynthesized mostly by prokaryotic microorganisms (Ourrison *et al.*, 1979, 1984), the dominant n-heptadecane was most likely

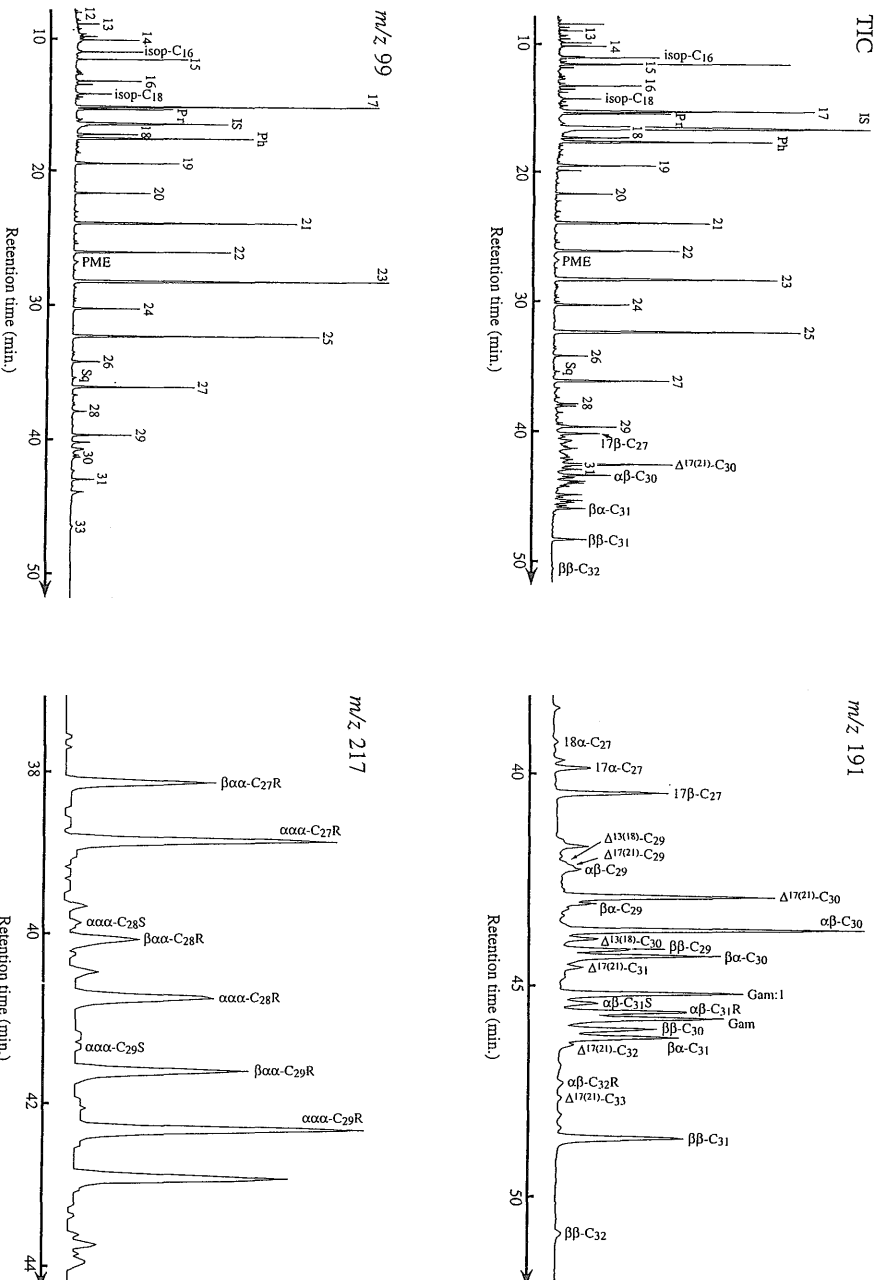


Fig. 4 Total ion chromatogram (TIC; m/z 50–550) and mass fragmentograms of acyclic alkanes (m/z 99) triterpenoid hydrocarbons (m/z 191) and steranes (m/z 217) of hydrocarbon fraction from an oil shale sample (Eidemnt no. 3). The numbers in the figure indicate the carbon number of n-alkanes. IS=internal standard (benzo (h) quinoline). The compounds identified are listed in Table 2.

derived from a specific blooming prokaryote which produced the precursor of isohop-13(18)-ene as well.

A dominant n-heptadecane was also found in Green River oil shales (Tissot *et al.*, 1978; Dean and Anders, 1991; Collister *et al.*, 1994). The $\delta^{13}\text{C}$ of the n-heptadecane is 1–2 per mil lower than those of steroids and the other mid-chain length n-alkanes in Green River oil shales, which suggests that the dominant n-heptadecane derive mainly from prokaryotes such as cyanobacteria (Collister *et al.*, 1994).

Since hopanoids are biosynthesized mostly by prokaryotes, while steroids by eukaryotes, hopane/sterane ratio reflects the relative contribution of prokaryotes to eukaryotes (Seifert and Moldowan, 1978). Prokaryotes act as either producers or decomposers in aquatic environment. Thus the variation of hopane/sterane ratio reflects either the productivity of autotrophic prokaryotes, *i.e.*, cyanobacteria, photosynthetic bacteria and chemioautotrophic bacteria, or the activity of heterotrophic bacteria as decomposers (*e.g.*, Yamamoto and Watanabe, 1994). Three major types can be recognized based on the variations in n-heptadecane anomaly and hopane/sterane ratio (Fig. 6). Type A is

characterized by high values of the n-heptadecane anomaly (above 2), a big scatter of the hopane/sterane ratios, and covariation of the two indices. Type B is characterized by moderate n-heptadecane anomaly (from 1 to 2) and low hopane/sterane ratio. Type C is characterized by low n-heptadecane anomaly (below 1) and high hopane/sterane ratio (Fig. 6). While β -carotane is under detection limit in Type C and most Type B samples, it is abundant in most Type A samples (Fig. 6). The precursor of β -carotane is β -carotene, and is easily degraded by aerobic bacteria (Adam *et al.*, 1993). It indicates that the depositional environment of Type A samples was highly reducing and the high hopane/sterane ratio resulted from the large contribution of a blooming autotrophic prokaryote. In Type B samples, the hopane/sterane ratios are relatively low, which indicates the contribution of eukaryotic algae as well as the autotrophic prokaryote. Type C samples are lacking in β -carotane, which suggests that high activity of heterotrophic bacteria in relatively oxygenated environment resulted in the high hopane/sterane ratios.

Gammacerane and gammacer-2-ene occur ubiqui-

Table 2 List of identified compounds shown in Fig. 4

Peak name	Compound name
isop-C ₁₆	2,6,10-trimethyltridecane
isop-C ₁₈	2,6,10-trimethylpentadecane
Pr	pristane
Ph	phytane
PME	2,6,10,15,19-pentamethyleicosane
Sq	squalane
18 α -C ₂₇	18 α -22,29,30-trisnorneohopane
17 α -C ₂₇	17 α -22,29,30-trisnorhopane
17 β -C ₂₇	17 β -22,29,30-trisnorhopane
$\Delta^{13(18)}$ -C ₂₉	30-norisohop-13(18)-ene
$\Delta^{17(21)}$ -C ₂₉	30-norhop-17(21)-ene
$\alpha\beta$ -C ₂₉	17 α ,21 β -30-norhopane
$\Delta^{17(21)}$ -C ₃₀	hop-17(21)-ene
$\beta\alpha$ -C ₂₉	17 β ,21 α -30-norhopane
$\alpha\beta$ -C ₃₀	17 α ,21 β -hopane
$\Delta^{13(18)}$ -C ₃₀	isohop-13(18)-ene
$\beta\beta$ -C ₂₉	17 β ,21 β -30-norhopane
$\beta\alpha$ -C ₃₀	17 β ,21 α -moretane(hopane)
$\Delta^{17(21)}$ -C ₃₁	22R-homohop-17(21)-ene
Gam:1	gammacer-2-ene
$\alpha\beta$ -C ₃₁ S	22S-17 α ,21 β -homohopane
$\alpha\beta$ -C ₃₁ R	22R-17 α ,21 β -homohopane
Gam	gammacerane
$\beta\beta$ -C ₃₀	17 β ,21 β -hopane
$\beta\alpha$ -C ₃₁ R	22R-17 β ,21 α -homohopane
$\Delta^{17(21)}$ -C ₃₂	22R-bishomohop-17(21)-ene
$\alpha\beta$ -C ₃₂ R	22R-17 α ,21 β -bishomohopane
$\Delta^{17(21)}$ -C ₃₃	22R-trishomohop-17(21)-ene
$\beta\beta$ -C ₃₁	17 β ,21 β -homohopane
$\beta\beta$ -C ₃₂	17 β ,21 β -bishomohopane
$\beta\beta$ -C ₃₃	17 β ,21 β -trishomohopane
$\beta\alpha\alpha$ C ₂₇ R	20R-5 β ,14 α ,17 α (H)-cholestane
$\alpha\alpha\alpha$ C ₂₇ R	20R-5 α ,14 α ,17 α (H)-cholestane
$\alpha\alpha\alpha$ C ₂₈ S	20S-5 α ,14 α ,17 α (H)-24-methylcholestane
$\beta\alpha\alpha$ C ₂₈ R	20R-5 β ,14 α ,17 α (H)-24-methylcholestane
$\alpha\alpha\alpha$ C ₂₈ R	20R-5 α ,14 α ,17 α (H)-24-methylcholestane
$\alpha\alpha\alpha$ C ₂₉ S	20S-5 α ,14 α ,17 α (H)-24-ethylcholestane
$\beta\alpha\alpha$ C ₂₉ R	20R-5 β ,14 α ,17 α (H)-24-ethylcholestane
$\alpha\alpha\alpha$ C ₂₉ R	20R-5 α ,14 α ,17 α (H)-24-ethylcholestane

tously in samples (Table 3). They are thought to be formed from tetrahymanol (ten Haven *et al.*, 1989) which were reported in a fern (Zander *et al.*, 1969), photosynthetic sulfur bacteria (Kleeman *et al.*, 1990) and bacterivorous ciliates (Harvey and McManus, 1991). In lacustrine systems, gammacerane and gammacer-2-ene are supposed to derive from bacterivorous ciliates that feed on prokaryotes based on stable carbon isotopic compositions (Sinninghe Damsté *et al.*, 1995). Gammacerane/n-alkane ratio is high in the Types A and B samples with high n-heptadecane anomaly,

supporting that the gammacerane originates from bacterivorous ciliates.

Long chain n-alkanes (>C₂₃) occur as a dominant compound class in all samples. Long chain n-alkanes are biosynthesized mainly by higher plants (compiled in Hunt, 1979) and some species of nonmarine algae (Gelpi *et al.*, 1970). Long chain straight hydrocarbons (C₁₃-C₃₁) are also generated from resistant aliphatic biomacromolecules by pyrolysis and are common in matured rocks and crude oils (Tegelaar *et al.*, 1989). Higher plant n-alkanes show strong odd carbon number

Table 3 Relative abundances of biomarkers in Zitiinbayan oil shales

Sample name	Bitumen wt%	Relative abundances to n-alkanes					n-Alkane				
		Isop.alkanes	Steranes	Hopanes	β -Carotane	gammacerane	Hopane/sterane	C ₂₉ /C ₁₉	CPI	n-C ₁₇ anomaly	Pr/Ph
<i>Bayan-Erkhii</i>											
no.5	0.47	0.25	0.95	0.17	0.0052	0.049	0.17	1.33	6.40	1.43	0.11
no.7	0.35	0.03	0.04	0.06	0.0000	0.004	1.42	1.06	11.14	1.16	0.10
no.8	0.35	0.15	0.17	0.42	0.0000	0.059	2.51	2.23	4.97	1.48	0.09
no.9	0.48	0.17	0.21	0.46	0.0000	0.133	2.21	2.24	4.52	1.18	0.08
<i>Eidemt</i>											
no.1	0.31	0.09	0.14	0.08	0.0000	0.005	0.58	0.87	5.43	1.22	0.17
no.2	0.70	0.10	0.13	0.43	0.0010	0.061	3.35	1.65	4.37	1.25	0.24
no.3	3.12	0.17	0.03	0.23	0.0042	0.096	6.62	0.69	6.43	5.71	0.33
no.4	2.63	0.19	0.06	0.17	0.0031	0.023	3.03	0.87	4.63	6.26	0.26
no.5	0.92	0.04	0.03	0.03	0.0000	0.001	0.94	0.64	5.39	1.50	0.23
no.6	1.93	0.11	0.06	0.12	0.0215	0.011	1.97	0.46	4.58	2.78	0.23
no.7	0.21	0.10	0.04	0.08	0.0019	0.010	1.99	0.50	5.17	3.02	0.28
no.8	0.91	0.09	0.18	0.09	0.0059	0.011	0.51	1.19	8.29	1.46	0.13
no.9	1.22	0.07	0.09	0.10	0.0032	0.009	1.12	0.64	8.10	2.46	0.13
no.10	0.71	0.17	0.07	0.13	0.0039	0.025	1.95	0.39	4.56	2.03	0.14
<i>Shawart-ovoo</i>											
no.8	0.23	0.03	0.02	0.08	0.0001	0.001	3.80	3.68	2.84	0.76	0.00
no.9	0.28	0.03	0.02	0.10	0.0000	0.001	6.18	3.14	2.89	0.65	0.00
no.10	0.25	0.03	0.01	0.06	0.0000	0.001	7.81	2.16	2.99	0.68	0.00
no.11	0.26	0.04	0.03	0.11	0.0000	0.001	4.16	2.45	3.41	0.81	0.00
no.12	0.04	0.05	0.02	0.04	0.0000	0.000	2.01	1.08	3.35	1.35	0.65
no.1	1.23	0.01	0.02	0.05	0.0000	0.002	2.00	6.96	4.46	1.20	0.00
no.2	1.87	0.09	0.03	0.24	0.0000	0.009	6.75	3.06	4.38	4.59	0.07
no.3	0.85	0.06	0.03	0.11	0.0000	0.005	3.92	2.99	4.47	3.22	0.06
no.4	0.73	0.03	0.03	0.07	0.0000	0.003	2.66	3.57	4.43	1.31	0.00
no.5	0.26	0.01	0.01	0.06	0.0000	0.001	5.00	3.69	3.73	0.65	0.00
no.6	0.52	0.04	0.01	0.03	0.0001	0.001	5.75	1.33	1.98	0.93	0.07
no.7	0.90	0.05	0.01	0.07	0.0000	0.001	5.60	2.81	3.15	1.93	0.05

Isop.alkanes = acyclic isoprenoid alkanes, CPI = carbon preference index, n-C₁₇ anomaly = n-heptadecane anomaly, Pr/Ph = pristane/phytane, Calculated according to the formula in Appendix I.

Table 3 continued

Sample name	Hopane			Homohopane	Bishomohopane	Hopanes			Relative abundances to hopane	
	$\beta\beta$ (%)	$\beta\alpha$ (%)	$\alpha\beta$ (%)	22S/22R	22S/22R	C ₂₇ /C ₃₀	C ₂₉ /C ₃₀	Σ (C ₃₁ -C ₃₅)/C ₃₀	Hop-17(21)-ene	Isohop-13(18)-ene
<i>Bayan-Erkhii</i>										
no.5	9.89	13.44	76.66	0.12	0.00	2.18	1.53	1.64	0.12	0.08
no.7	28.10	20.96	50.94	0.09	0.00	1.59	0.76	2.93	0.36	0.12
no.8	25.49	24.58	49.93	0.10	0.58	0.94	0.65	1.86	0.69	0.11
no.9	20.59	27.72	51.68	0.10	0.41	2.07	1.26	3.71	1.07	0.17
<i>Eidemt</i>										
no.1	21.03	27.35	51.63	0.14	0.21	2.25	1.17	0.76	0.04	0.23
no.2	30.70	23.42	45.88	0.33	0.69	0.91	0.73	0.91	0.09	0.24
no.3	19.81	28.72	51.48	0.30	0.71	0.96	0.65	1.66	0.06	0.36
no.4	17.54	27.72	54.74	0.22	0.76	3.29	1.06	1.35	1.16	0.44
no.5	33.31	25.03	41.65	0.10	0.00	1.36	0.81	0.95	0.00	0.08
no.6	23.58	25.00	51.42	0.16	0.00	1.70	0.68	1.85	0.05	0.23
no.7	19.73	26.67	53.60	0.20	0.76	2.15	0.72	1.86	0.12	0.27
no.8	22.46	20.86	56.68	0.17	0.53	1.99	0.95	0.92	0.05	0.35
no.9	21.56	24.59	53.86	0.31	0.49	1.30	1.04	0.59	0.13	0.44
no.10	17.07	27.71	55.23	0.22	0.48	1.93	1.06	0.79	0.11	0.16
<i>Shawart-ovoo</i>										
no.8	28.03	48.57	23.40	0.11	0.27	4.24	1.08	2.83	0.05	0.19
no.9	39.48	41.57	18.95	0.10	0.17	2.14	0.75	3.20	0.02	0.10
no.10	44.42	34.43	21.14	0.09	0.31	1.86	0.73	1.64	0.02	0.09
no.11	29.70	53.94	16.36	0.07	0.32	1.84	0.75	2.76	0.05	0.15
no.12	24.75	29.31	45.94	0.41	0.56	1.53	0.42	1.31	0.16	0.10
no.1	7.82	62.60	29.59	0.09	0.00	4.00	2.09	4.56	0.31	0.22
no.2	11.43	65.53	23.04	0.35	0.00	3.28	4.52	2.42	2.16	0.48
no.3	11.00	59.72	29.28	0.17	0.37	2.83	2.43	2.58	1.08	0.15
no.4	17.55	56.82	25.63	0.14	0.15	2.92	1.20	3.51	0.06	0.05
no.5	33.93	39.20	26.87	0.09	0.36	2.61	0.93	3.42	0.04	0.11
no.6	40.09	41.04	18.87	0.15	0.40	2.44	0.89	2.74	0.04	0.10
no.7	33.99	47.35	18.66	0.11	0.08	2.97	1.12	1.82	0.06	0.14

Table 3 continued

Sample name	Gam. index	Gammacer-2-ene C ₂₉ Sterane		C ₂₈ Sterane		C ₂₉ Sterane			Steranes			Steranes Type
		/gammacerane	$\beta\alpha\alpha/\alpha\alpha\alpha$	20S/20R	20S/20R	20S/20R	C ₂₇ (%)	C ₂₈ (%)	C ₂₉ (%)	C ₂₇ /C ₂₉		
Bayan-Erkhit												
no.5	18.59	0.15	0.39	0.08	0.12	25.9	32.6	41.5	0.62	B		
no.7	13.16	0.87	0.55	0.02	0.04	15.0	39.0	45.9	0.33	B		
no.8	16.15	0.73	0.53	0.06	0.03	40.8	26.9	32.3	1.27	B		
no.9	48.24	0.62	0.72	0.06	0.08	44.6	26.9	28.6	1.56	B		
Eidemt												
no.1	6.19	0.99	0.36	0.03	0.04	26.8	33.2	40.0	0.67	B		
no.2	15.44	0.84	0.36	0.38	0.03	28.6	21.3	50.1	0.57	B		
no.3	35.50	1.01	0.61	0.09	0.00	34.6	23.8	41.6	0.83	A		
no.4	15.91	0.65	0.47	0.07	0.06	42.1	22.0	35.9	1.18	A		
no.5	3.06	1.41	0.34	0.03	0.02	22.7	40.2	37.2	0.61	B		
no.6	11.52	0.88	0.50	0.05	0.04	41.0	28.8	30.2	1.36	A		
no.7	15.03	0.93	0.64	0.04	0.06	44.8	25.8	29.4	1.52	A		
no.8	12.93	0.73	0.37	0.05	0.04	41.7	21.4	37.0	1.13	B		
no.9	7.42	0.98	0.36	0.03	0.05	18.2	34.7	47.1	0.39	A		
no.10	15.61	0.64	0.38	0.34	0.03	19.3	43.3	37.4	0.52	A		
Shawart-ovoo												
no.8	3.48	1.37	0.65	0.04	0.19	35.3	32.1	32.6	1.08	C		
no.9	3.90	1.13	0.58	0.05	0.16	34.4	26.6	39.0	0.88	C		
no.10	3.01	2.35	0.45	0.00	0.08	44.3	19.0	36.6	1.21	C		
no.11	2.51	1.68	0.57	0.00	0.17	37.4	24.8	37.8	0.99	C		
no.12	0.00	n.d.	0.61	0.00	0.19	28.3	31.9	39.8	0.71	B		
no.1	4.93	0.89	0.87	0.00	0.17	42.4	17.8	39.7	1.07	?		
no.2	5.06	1.39	0.91	0.00	0.00	47.9	19.4	32.7	1.46	A		
no.3	4.13	1.26	0.68	0.00	0.15	35.6	12.9	51.5	0.69	A		
no.4	7.08	0.78	0.76	0.00	0.08	41.2	18.6	40.2	1.03	B		
no.5	5.43	0.85	0.77	0.05	0.08	34.0	25.1	40.9	0.83	C		
no.6	5.67	1.18	0.51	0.00	0.14	50.4	22.7	26.9	1.87	C		
no.7	3.67	1.26	0.73	0.04	0.16	42.9	26.8	30.4	1.41	?		

Gam.index = gammacerane index.

preference, while resistant biomacromolecule-derived n-alkanes show no odd carbon number preference (Tegelaar *et al.*, 1989). The long chain n-alkanes of the Züünbayan oil shales have strong odd carbon number preference, which indicates that the long-chain n-alkanes were derived mainly from terrestrial higher plants.

C₂₇-C₂₈-C₂₉ Sterane distribution (Fig. 7) shows that most samples have sterane compositions close to those of petroleum of nonmarine algal origin (Area N in Fig. 7, Moldowan *et al.*, 1985), while some samples have intermediate compositions of petroleum between nonmarine algal (Area N) and higher plant (Area L) origins. This suggests that the steranes were derived mainly from nonmarine algae and partly from higher plants.

As shown in Fig. 8, a negative correlation exists between C₂₇/C₂₉ sterane ratio and odd carbon number preference (Carbon Preference Index: CPI) of long chain n-alkanes (C₂₄-C₃₄). Since C₂₇ steroids are abundant in algae, while C₂₉ steroids are dominant in higher plants (Huang and Meinschein, 1979), C₂₇/C₂₉ sterane ratio is used as a parameter indicating the relative contribution of algae and higher plants. On the other hands, CPI of long chain n-alkanes are high in higher plant waxes (Eglinton *et al.*, 1962). Thus the negative correlation between C₂₇/C₂₉ sterane ratio and the CPI of long chain n-alkanes most likely resulted from the variation in the contribution of higher plants in each sample.

3.2 Pollen-spore compositions and the climate of the environment where Züünbayan oil shales were deposited

The pollen-spore compositions for three selected samples are shown in Fig. 9. Fern spores and gymnosperm pollens are recognized, while no angiosperm pollen is recognized. Gymnosperm pollens predominate over fern spores (Fig. 9). The spore-pollen compositions show a common assemblage of the Neocomian sediments belonging to the Boreal palynofloral Province (Herngreen and Chlonova, 1981) that covered present eastern Europe and northern Asia.

Herngreen and Chlonova (1981) recognized the differences on the palynoflora between Siberian and Chinese areas in the eastern part of the Boreal palynofloral Province, and divided it into the two types; the Boreal-Siberian subprovince which is characterized by the presence of *Pilosiporites*, *Impardecispora*, *Aequitriradites*, and the southern adjacent subprovince ("Chinese subprovince" called tentatively here) which is characterized by a dominant *Classopollis*. A comparison between these palynofloral subprovinces and the floral provinces proposed by Kimura (1979, 1980) indicates that the palynoflora of the Boreal-Siberian subprovince reflects the "Tetori" type flora indicating a warm-humid climate, while that of the "Chinese subprovince" reflects the "Ryoseki" type flora indicating a hot-arid climate. The presence of *Classopollis* (but not dominant) and the absence of *Pilosiporites*, *Impardecispora*, *Aequitriradites* in the Züünbayan oil shales

Table 4 Correlation coefficients (r) for Rock-Eval parameters and the relative abundances of biomarkers in Zütünbayan oil shales

	org. C	C/S	T _{max}	S ₁	S ₂	S ₃	H.I.	O.I.	P.I.	S ₂ /S ₃	EOM	I/N A	S/NA	H/NA	β-C/NA	Gam/NA	H/S	C ₂₉ /C ₁₉ NA	CPI	C ₁₇ NA	Pr/Ph	HH/H	Δ17(21)H/H	Δ13(18)H/H	Gam.I	
C/S	0.43																									
T _{max}	-0.59	-0.30																								
S ₁	0.80	0.39	-0.87																							
S ₂	0.99	0.40	-0.59	0.80																						
S ₃	0.93	0.33	-0.58	0.76	0.92																					
H.I.	0.53	-0.08	-0.22	0.38	0.60	0.51																				
O.I.	-0.13	-0.28	0.09	-0.09	-0.12	0.19	0.15																			
P.I.	0.36	0.24	-0.70	0.78	0.33	0.37	0.08	0.02																		
S ₂ /S ₃	0.23	0.08	-0.12	0.14	0.28	-0.06	0.36	-0.80	-0.11																	
Bitumen content	EOM	0.59	0.32	-0.86	0.80	0.56	0.63	0.28	0.05	0.66	0.58															
Isoprenoid/normal alkane	I/N A	0.57	0.23	-0.35	0.52	0.53	0.55	0.08	0.02	0.24	-0.02	0.39														
Sterane/n-alkane	S/NA	0.67	0.06	0.22	-0.10	0.03	-0.01	-0.04	-0.08	-0.20	0.07	-0.10	0.66													
Hopane/n-alkane	H/NA	0.07	-0.07	-0.07	0.14	0.01	0.19	-0.19	0.35	0.21	-0.40	0.16	0.58	0.26												
β-Carotane/n-alkane	β-C/NA	0.44	0.44	-0.16	0.22	0.42	0.48	0.18	-0.01	0.05	0.02	0.43	0.35	0.18	0.00											
gammacerane/n-alkane	Gam/NA	0.17	-0.08	-0.26	0.23	0.13	0.23	-0.08	0.22	0.11	-0.23	0.26	0.69	0.36	0.84	0.06										
Hopane/sterane	H/S	-0.17	-0.03	-0.27	0.21	-0.15	-0.12	0.11	0.07	0.49	-0.02	0.17	-0.28	-0.43	0.01	-0.25	-0.05									
C ₂₉ /C ₁₉ n-alkane	C ₂₉ /C ₁₉ NA	-0.51	-0.52	0.11	-0.29	-0.50	-0.39	-0.04	0.03	0.10	-0.23	-0.15	-0.48	-0.17	-0.06	-0.39	-0.18	0.29								
CPI		0.26	0.13	-0.02	0.12	0.19	0.17	-0.03	-0.09	-0.03	0.01	0.18	0.22	0.26	0.03	0.17	0.14	-0.55	-0.37							
n-heptadecane anomaly	C ₁₇ NA	0.69	0.36	-0.85	0.89	0.65	0.65	0.17	-0.10	0.76	0.07	0.87	0.49	-0.09	0.18	0.26	0.23	0.15	-0.29	0.17						
Pr/Ph		0.29	0.52	-0.36	0.25	0.27	0.18	-0.40	-0.52	0.00	0.24	0.22	0.29	-0.01	0.04	0.23	0.16	-0.28	-0.58	0.13	0.36					
Σ(C ₃₁ -C ₃₅)/C ₃₀ hopane	HH/H	-0.46	-0.53	0.15	-0.29	-0.44	-0.37	0.02	0.27	-0.03	-0.14	-0.16	-0.39	-0.17	-0.04	-0.26	-0.01	0.28	0.78	-0.25	-0.26	-0.54				
Hop-17(21)-ene/hopane	Δ17(21)H/H	0.08	-0.18	-0.26	0.35	0.02	0.11	-0.20	0.05	0.60	-0.20	0.34	0.26	-0.02	0.44	-0.15	0.23	0.17	0.16	0.01	0.53	-0.06	0.18			
Isoprop-13(18)-ene/hopane	Δ13(18)H/H	0.60	0.48	-0.63	0.70	0.55	0.55	0.17	-0.11	0.69	0.05	0.69	0.29	-0.12	0.20	0.23	0.13	0.01	-0.19	0.30	0.72	0.20	-0.32	0.46		
Gammacerane index	Gam.I.	0.34	-0.04	-0.32	0.33	0.30	0.38	0.09	0.20	0.12	-0.14	0.32	0.70	0.32	0.69	0.17	0.94	-0.13	-0.27	0.29	0.30	0.14	0.03	0.20	0.21	
C ₂₇ /C ₂₉ sterane	C ₂₇ /C ₂₉ S	-0.03	-0.04	-0.11	0.03	0.01	0.09	0.19	0.33	0.14	-0.17	0.08	0.00	-0.18	0.13	0.08	0.09	0.39	0.18	-0.50	0.10	-0.18	0.33	0.27	0.08	0.13

Note: bold value means the correlation coefficient (r) below -0.50 and above 0.50 (within 99% confidence interval).

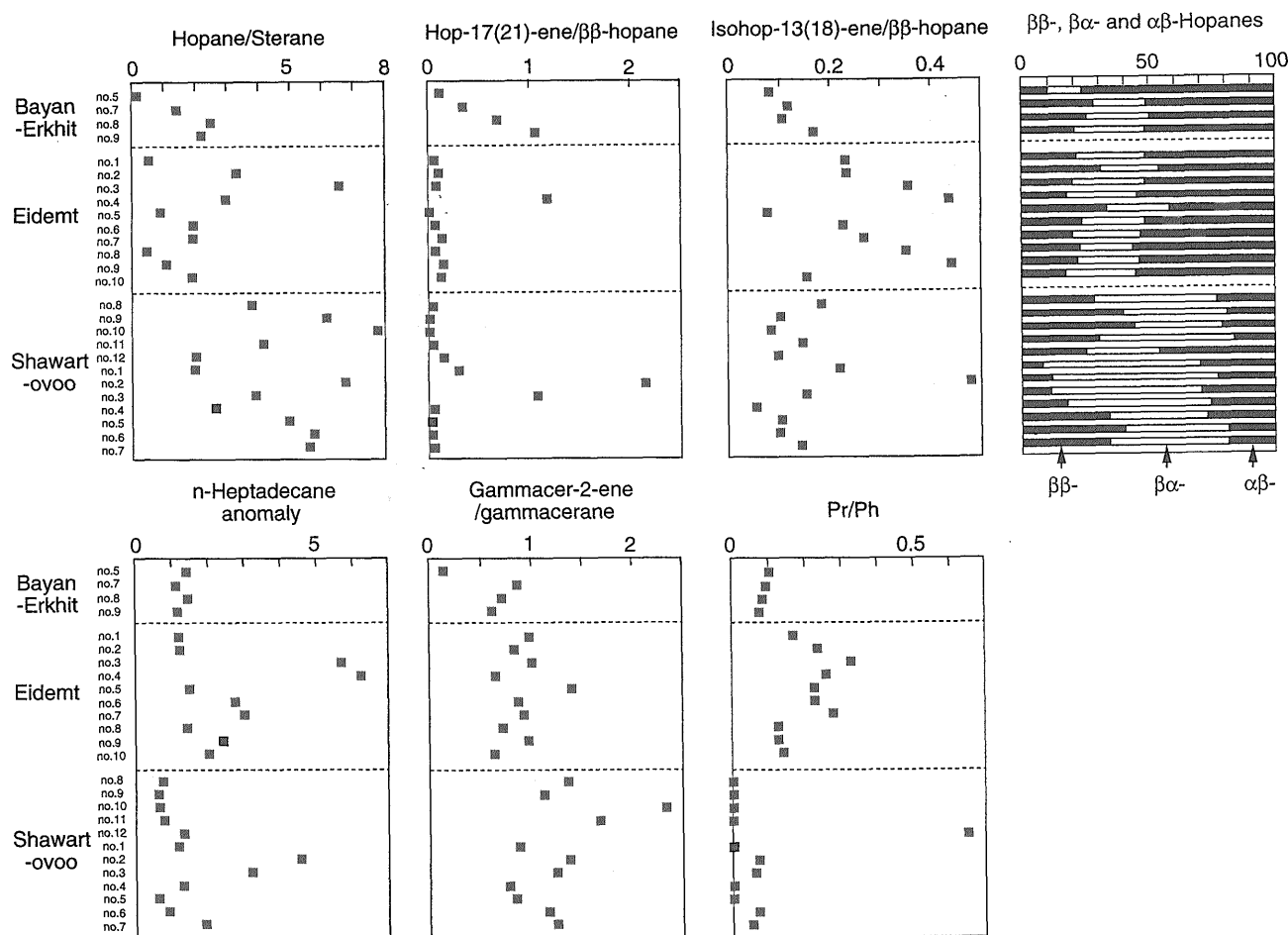


Fig. 5 Stratigraphic variations in hopane/sterane ratio, hop-17(21)-ene/ $\beta\beta$ -hopane ratio, hop-13(18)-ene/ $\beta\beta$ -hopane ratio, the relative abundances of $\beta\beta$ -, $\beta\alpha$ - and $\alpha\beta$ -hopanes, n-heptadecane anomaly (n-C₁₇ anomaly), gammacer-2-ene/gammacerane ratio and Pr/Ph ratio in Zütünbayan oil shales.

(Table 4; Fig. 9) indicate that they have an intermediate palynofloral composition between the Boreal-Siberian and the Chinese subprovinces. It suggests that this area was situated near the border between warm-humid and hot-arid climate zones.

3.3 Rock-Eval pyrolysis and source rock characteristics

The results of Rock-Eval pyrolysis are listed in Yamamoto *et al.* (1993). The stratigraphic variations of the parameters are shown in Fig. 10.

Hydrogen Index-Oxygen Index (H.I.-O.I.) diagram shows that most samples are plotted in the region of Type II kerogens (Fig. 11). In contrast, T_{max} -H.I. diagram shows that they are plotted in the region of Type I kerogens (Fig. 11). Since the combination of constantly high T_{max} and high H.I. is typical in Type I kerogens, the kerogens of the samples are classified into Type I kerogens (lacustrine oil shale type). Although the O.I. values of the samples are slightly higher than that of typical Type I kerogen, it can be explained by the weathering at the outcrop surface.

Most samples show an almost identical T_{max} value

around 450°C, and Production Index (P.I. = $S_1/(S_1 + S_2)$) below 0.05. Exceptionally, Eidemt nos. 3 and 4 samples show significantly lower T_{max} values (ca. 420–430°C) and higher P.I. values (above 0.05) than the others. T_{max} and P.I. generally increase with increasing thermal maturity, and are often used as maturity indices (Bordenave *et al.*, 1993). In this case, however, the T_{max} and P.I. of both samples are different from those of the other samples located very closely in stratigraphic column (Fig. 3), which is a negative evidence for the maturity control. A high P.I. is also often attributed to the contamination of migrated matured oil (Bordenave *et al.*, 1993). Yet, biomarker distribution of both samples indicates that the bitumens are immature. In this case, both samples contain significantly high amount of bitumen (Table 3), and good correlations exist among T_{max} , P.I. and bitumen content (Fig. 12). This suggests that the anomalous P.I. value is attributed to the abundant indigenous bitumen in the samples. It is also possible that the anomalous T_{max} value is attributed to the contribution of heavy fraction of the bitumen to S_2 peak, because the S_2 peak

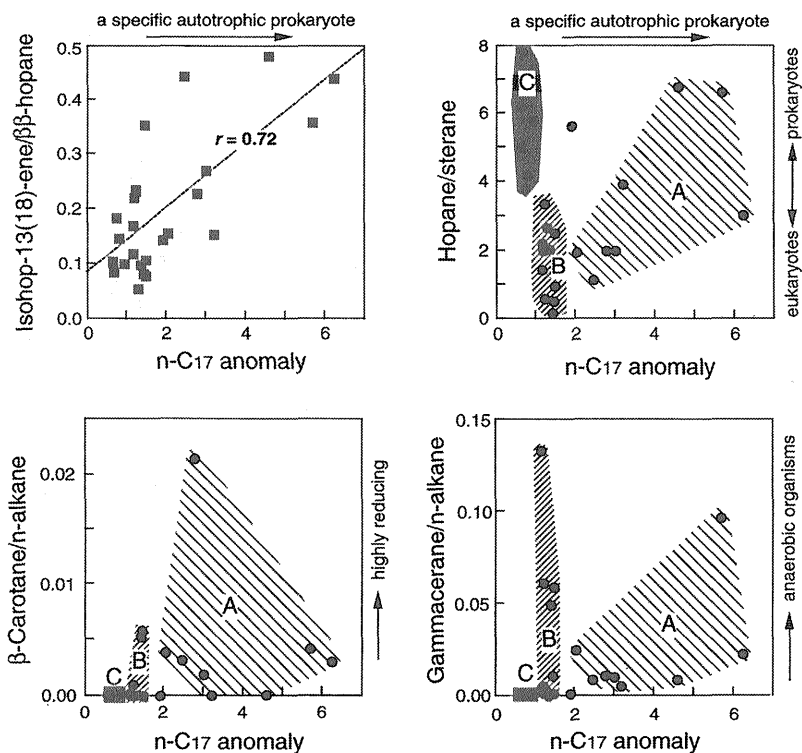


Fig. 6 Plots of isohop-13(18)-ene/ $\beta\beta$ -hopane, hopane/sterane, β -carotane/n-alkane and gammacerane/n-alkane ratios against n-heptadecane anomaly ($n\text{-C}_{17}$ anomaly) in Züünbayan oil shales.

represents partly the heavy hydrocarbons, resins and asphaltenes vaporized (Bordenave, 1993).

The Hydrogen Index (H.I., defined as $S_2/\text{org. C}$) of most samples ranges from c. 500 to c. 800 mgHC/gC (Fig. 10). The range indicates that the samples are in immature and/or early mature stages (Bordenave *et al.*, 1993). Exceptionally, Shawart-ovoo no. 12 sample shows a rather lower H.I. value (235 mgHC/gC) than the others. The bioturbated sedimentary structure of the sample (Table 1) suggests that the lower H.I. resulted from the degradation of organic matter in the oxic depositional environment.

Interestingly, n-heptadecane anomaly seems to be related to the petroleum source rock potentiality of the Züünbayan oil shales. The n-heptadecane anomaly has good correlations with organic carbon contents ($r=0.69$), oil yields ($r=0.40$), bitumen content ($r=0.87$) and P.I. ($r=0.76$) and a negative correlation with T_{max} ($r=-0.85$) (Fig. 13, Table 4). It means that the Type A oil shales with the highest n-heptadecane ratio are most excellent as a source rock. This suggests that the potentiality was controlled by primary production.

3.4 Depositional environment of Züünbayan oil shales

An organic carbon-total sulfur diagram (Fig. 14) shows that the Züünbayan oil shales are distributed in the region of freshwater environment (Berner and Raiswell, 1984). Also, the low concentration of organic

sulfur compounds in the samples is a characteristic of freshwater sediments (de Leeuw and Sinninghe Damsté, 1990). These results along with the occurrence of freshwater benthic fauna (Bat-erdene, 1992) indicate that the Züünbayan oil shales were deposited in a freshwater environment.

All but one samples have a well laminated texture with no significant bioturbation, which indicates a reducing bottom water environment (Savdra and Bottjer, 1991). Pristane over phytane ratios (Pr/Ph ratios) of all samples are below 0.65 (Fig. 5). Since the Pr/Ph ratio below 0.6 is common in the sediments deposited in anoxic environments (Peters and Moldowan, 1993), an anoxic depositional environment is also suggested. Shawart-ovoo no. 12 sample shows relatively high Pr/Ph ratio (Pr/Ph=0.65). Since only this sample has bioturbated structure (Table 1), the relatively high Pr/Ph ratio most likely reflects the relatively oxygenated environment. The occurrence of the gammacerane and gammacer-2-ene which originate from anaerobic ciliates and/or bacteria also indicates the presence of anoxic water mass (Schoell *et al.*, 1994; Sinninghe Damsté *et al.*, 1995).

Permanent stratification promotes the development of anoxic bottom water in the large, deep lake with more than 100 meter depth (Demaison and Moore, 1980). Lake Malawi and Lake Tanganyika are examples of the recent freshwater lakes where permanent stratification promotes stagnant anoxic bottom water

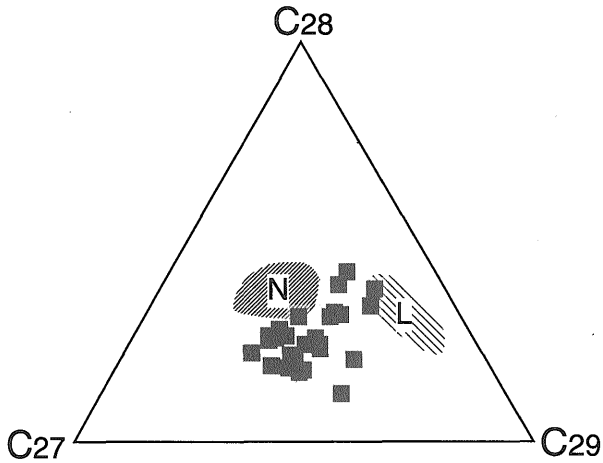


Fig. 7 C₂₇-C₂₈-C₂₉ Sterane (5 α , 14 α , 17 α , 20 R-isomer) distribution for Züünbayan oil shales. Areas N and L refer to petroleum sourced mainly from nonmarine algal and higher plant organic matters, respectively (Moldowan *et al.*, 1985). After Yamamoto *et al.* (1998).

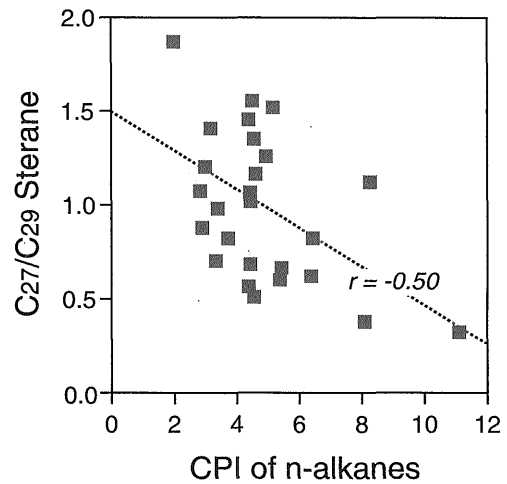


Fig. 8 Carbon number preference (CPI) of C₂₄-C₃₄ n-alkanes versus C₂₇/C₂₉ sterane ratio in Züünbayan oil shales.

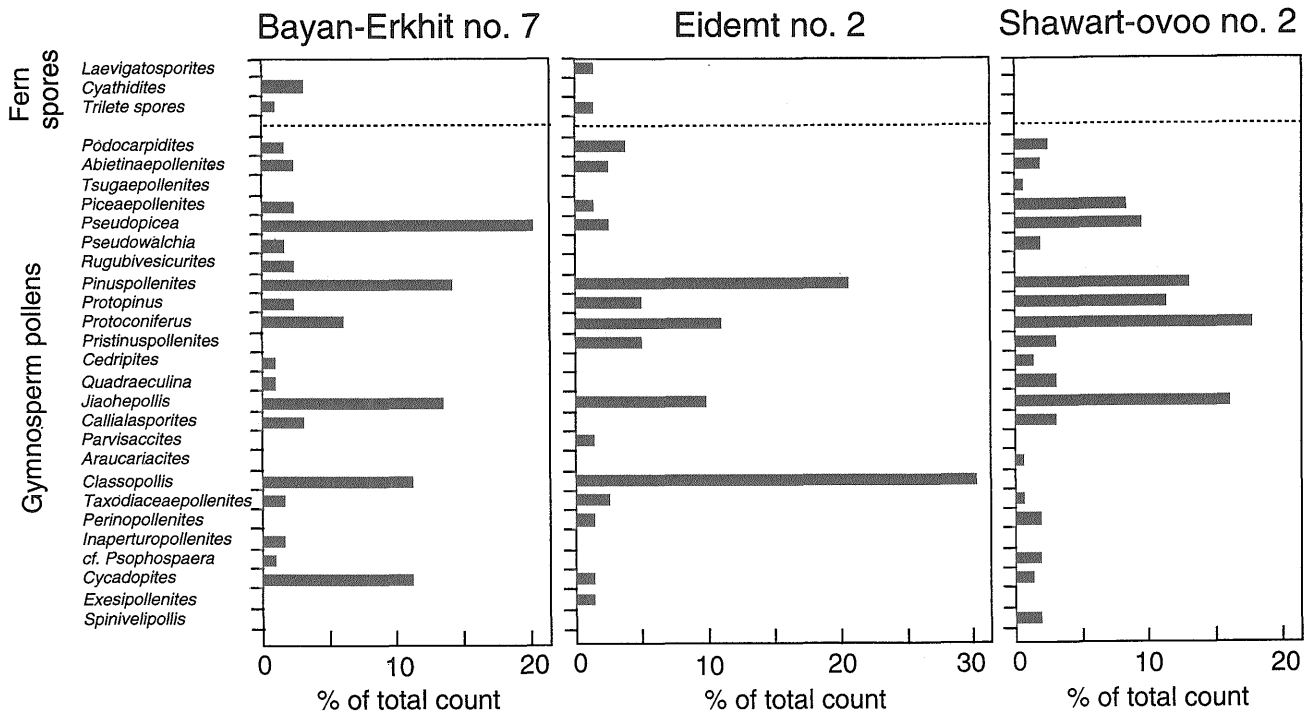


Fig. 9 Relative abundances of fern spores and gymnosperm pollens identified in Bayan-Erkhit no. 7, Eident no. 2 and Shawart-ovoo no. 2 oil shale samples.

and organic-rich bottom sediments (Degens *et al.*, 1971 ; Demaison and Moore, 1980 ; Talbot, 1988). In these tropical lakes, little seasonal temperature change and moderate to high rainfall, year round, tend to promote permanent water column stratification and therefore anoxia. On the other hands, in cold and temperate climates, seasonal overturning of water, the high capacity of cold water to dissolve oxygen, and density underflows of cold river waters all enhance

oxic conditions in bottom waters (Demaison and Moore, 1980). Early Cretaceous Mongolia was situated at midlatitude (35° N to 40° N) (Smith and Briden, 1977). Nevertheless, as discussed in previous section, the palynoflora of the Züünbayan oil shales suggests hot-arid to warm-humid climate. Also, tropical-subtropical flora was distributed in early Cretaceous Mongolia, and the southern limit of temperate flora was 50° N. (Vakhrameev, 1964). Crocodile fossils found in Creta-

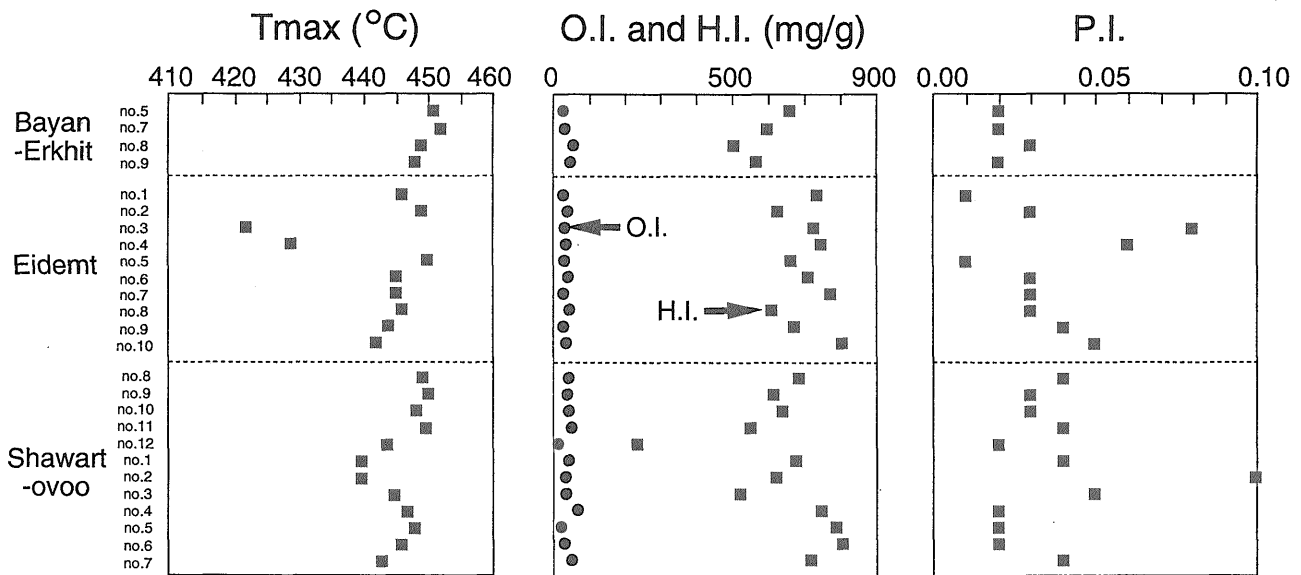


Fig. 10 Stratigraphic variations of Rock-Eval parameters in Zütünbayan oil shales.

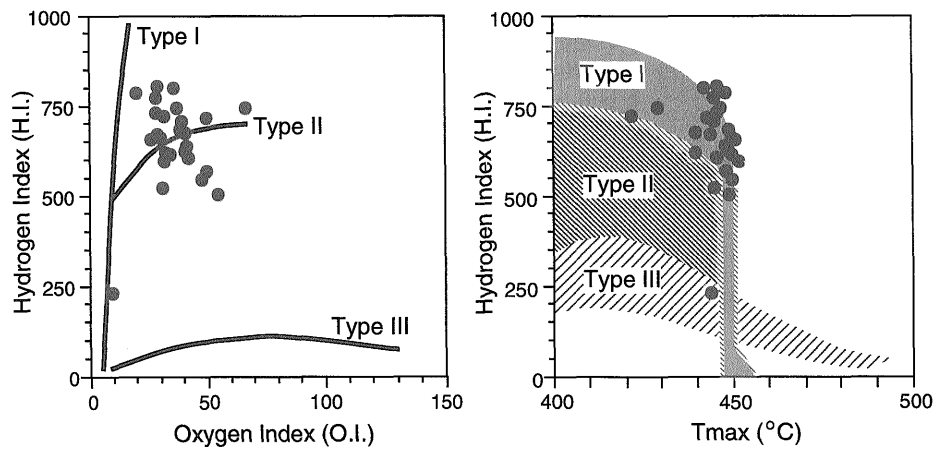


Fig. 11 Hydrogen Index-Oxygen Index (H.I.-O.I.) and H.I.- T_{max} diagrams for Zütünbayan oil shales. After Yamamoto *et al.* (1998).

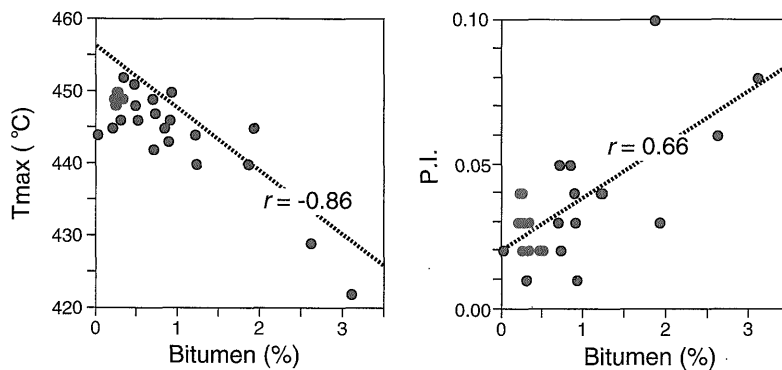


Fig. 12 Plots of T_{max} and Production Index (P.I.) against bitumen content for Zütünbayan oil shales.

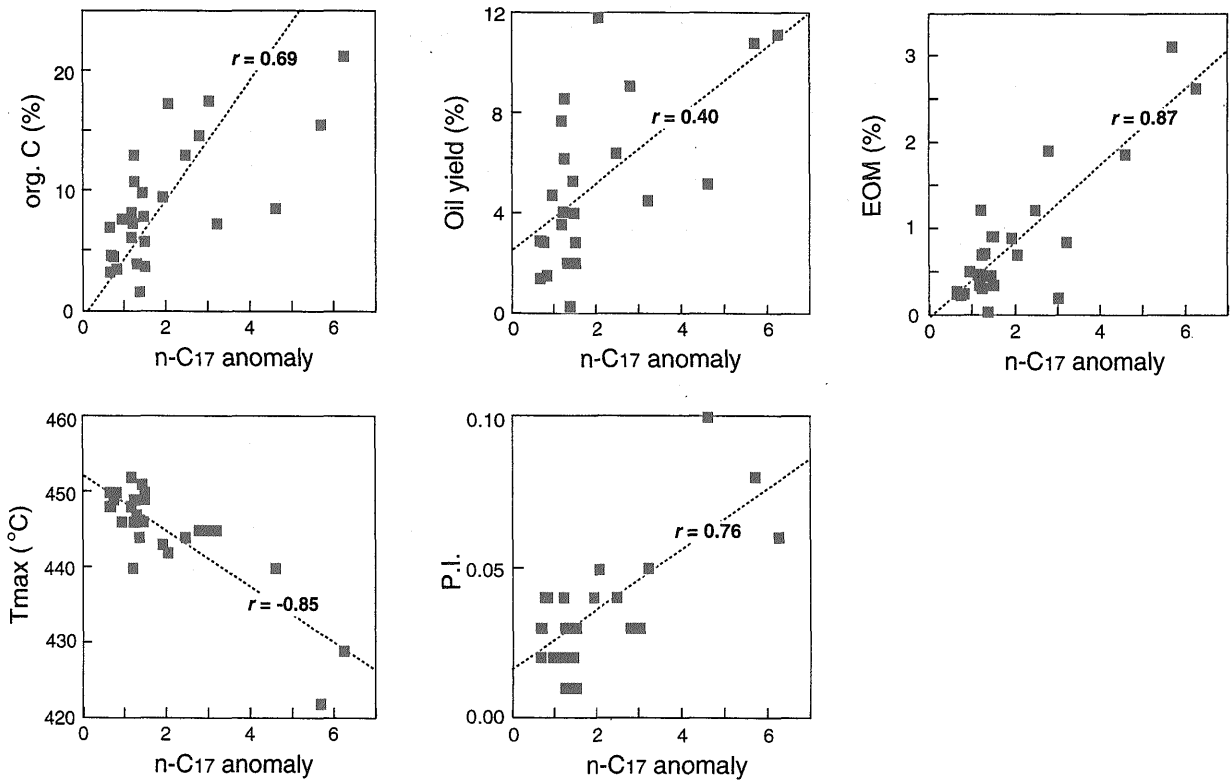


Fig. 13 Plots of organic carbon content (org. C), oil yield, bitumen (EOM), T_{max} and Production Index (P.I.) against n-heptadecane anomaly (n-C₁₇ anomaly) in Zütünbayan oil shales.

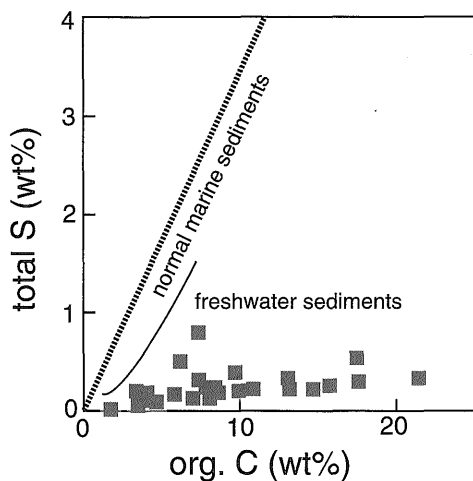


Fig. 14 Distribution of organic carbon and sulfur contents in Zütünbayan oil shales. Areas of normal marine and freshwater sediments refer to Berner and Raiswell (1984). After Yamamoto *et al.* (1998).

ceous sediments in Mongolia also suggests tropical-subtropical climate (Lefield, 1971). It is therefore possible that the temperature in winter season was rather high in the early Cretaceous Mongolia, and permanent stratification was maintained year round.

Variation in the abundance of β -carotane suggests the changes in the degree of development of bottom

water anoxia (Table 3). In the case of tropical fresh-water lakes, organic-rich sediments occur in early Holocene horizon (Talbot, 1988). The formation of organic-rich beds probably resulted from enhanced primary productivity caused by the nutrient supply promoted by chemical weathering in the densely vegetated area around the lake (Talbot, 1988).

On the analogy of the modern cases, it is possible that the Type A of the Zütünbayan oil shales represents eutrophic environment, while the Type C represents oligotrophic environment. The depositional environment of each type oil shale was supposed as follows. In the Type A deposition, the massive supply of nutrient in a humid climate enhanced the productivity of a blooming autotrophic prokaryote such as a cyanobacterium, and formed highly reducing stagnant bottom-water below thermocline. In the Type B deposition, the decreased supply of nutrient in a relatively dry climate reduced the primary productivity, and the algae succeeded the blooming prokaryote. As the result, the bottom-water anoxia was weaker than that of Type A. In the Type C deposition, the little supply of nutrient in dry climate resulted in low primary productivity and relatively oxygenated bottom water. The organic matter was degraded by heterotrophic bacteria, and consequently relatively organic-lean sediments were deposited.

4. Conclusions

Biomarker distribution indicates (1) the ubiquitous contributions of a blooming autotrophic prokaryote such as a cyanobacterium, nonmarine algae, terrestrial higher plants, heterotrophic bacteria and bacterivorous ciliates, (2) low maturity of organic matter in samples, (3) freshwater depositional environment and (4) the development of bottom water anoxia.

The palynoflora shows a common assemblage of the Neocomian sediments belonging to the Boreal palynofloral Province, and suggests that the area where the Zuunbayan oil shales were deposited was situated near the border between warm-humid and hot-arid climate zones.

Good correlations among organic carbon content, oil yield, bitumen content and n-heptadecane anomaly suggests that the degree of bottom water anoxia controlled organic carbon content and oil yield, and was related to the contribution of a blooming autotrophic prokaryote which sourced dominant n-heptadecane.

The tropical-subtropical climate promoted thermal stratification and therefore bottom water anoxia in the freshwater lakes. The degree of development of bottom anoxia was likely controlled by nutrient supply from the surrounding area.

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Appendix I

Isoprenoid/n-alkane ratio = (2,6,10-trimethyltridecane + 2,6,10-trimethylpentadecane + pristane + phytane + 2,6,10,15,19-pentamethyleicosane + squalane) (*m/z* 99)/C₁₄-C₃₅ n-alkanes (*m/z* 99).

Sterane/n-alkane ratio = C₂₇-C₂₉ 5 α , 14 α , 17 α , 20 R-steranes (*m/z* 217)/C₁₄-C₃₅ n-alkanes (*m/z* 99).

Hopane/n-alkane ratio = (17 β -C₂₇ + C₂₉-C₃₅ 17 β , 21 β -hopanes (*m/z* 191)/C₁₄-C₃₅ n-alkanes (*m/z* 99).

β -Carotane/n-alkane ratio = β -carotane (*m/z* 125)/C₁₄-C₃₅ n-alkanes (*m/z* 99).

Gammacerane/n-alkane ratio = gammacerane (*m/z* 191)/C₁₄-C₃₅ n-alkanes (*m/z* 99).

Hopane/sterane ratio = (17 β -C₂₇ + C₂₉-C₃₅ 17 β , 21 β -hopanes (*m/z* 191)/C₂₇-C₂₉ 5 α , 14 α , 17 α , 20 R-steranes (*m/z* 217).

C₂₉/C₁₉ n-Alkane ratio = C₂₉/C₁₉ n-alkanes (*m/z* 99).

CPI = 1/2{(C₂₅ + C₂₇ + C₂₉ + C₃₁ + C₃₃)/(C₂₄ + C₂₆ + C₂₈ + C₃₀ + C₃₂) + (C₂₅ + C₂₇ + C₂₉ + C₃₁ + C₃₃)/(C₂₆ + C₂₈ + C₃₀ + C₃₂ + C₃₄)} n-alkanes (*m/z* 99).

n-Heptadecane anomaly = 2 × C₁₇/(C₁₆ + C₁₈) n-alkanes (*m/z* 99).

Pristane/phytane ratio = pristane (*m/z* 99)/phytane (*m/z* 99).

$\beta\beta$ -Hopane (%) = 17 β , 21 β -hopane (*m/z* 191)/(17 β , 21 β - + 17 β , 21 α - + 17 α , 21 β -) hopanes (*m/z* 191) × 100.

$\beta\alpha$ -Hopane (%) = 17 β , 21 α -hopane (*m/z* 191)/(17 β , 21 β - + 17 β , 21 α - + 17 α , 21 β -) hopanes (*m/z* 191) × 100.

$\alpha\beta$ -Hopane (%) = 17 α , 21 β -hopane (*m/z* 191)/(17 β , 21 β - + 17 β , 21 α - + 17 α , 21 β -) hopanes (*m/z* 191) ×

100.

22 S/22 R Homohopane ratio = 22 S/22 R 17 α , 21 β -C₃₁ hopanes (*m/z* 191).

22 S/22 R Bishomohopane ratio = 22 S/22 R 17 α , 21 β -C₃₂ hopanes (*m/z* 191).

C₂₇/C₃₀ Hopane ratio = 17 β -22, 29, 30-trisnorhopane (*m/z* 191)/17 β , 21 β -hopane (*m/z* 191).

C₂₉/C₃₀ Hopane ratio = 17 β , 21 β -30-norhopane (*m/z* 191)/17 β , 21 β -hopane (*m/z* 191).

Σ (C₃₁-C₃₅)/C₃₀ Hopane ratio = (C₃₁-C₃₅)/C₃₀ 17 β , 21 β -hopanes (*m/z* 191).

Hop-17(21)-ene/hopane ratio = hop-17(21)-ene (*m/z* 191)/17 β , 21 β -hopane (*m/z* 191).

Isohop-13(18)-ene/hopane ratio = isohop-13(18)-ene (*m/z* 191)/17 β , 21 β -hopane (*m/z* 191).

Gammacerane index = gammacerane (*m/z* 191)/(17 β , 21 β - + 17 β , 21 α - + 17 α , 21 β -) hopanes (*m/z* 191).

Gammacerane/n-alkane ratio = gammacerane (*m/z* 191)/C₁₄-C₃₅ n-alkanes (*m/z* 99).

Gammacer-2-ene/gammacerane ratio = gammacer-2-ene (*m/z* 191)/gammacerane (*m/z* 191).

$\beta\alpha\alpha/\alpha\alpha\alpha$ C₂₉ Sterane ratio = 5 β /5 α 14 α , 17 α , 20 R-C₂₉ steranes (*m/z* 217).

20 S/20 R C₂₈ Sterane ratio = 20 S/20 R 5 α , 14 α , 17 α -C₂₈ steranes (*m/z* 217).

20 S/20 R C₂₉ Sterane ratio = 20 S/20 R 5 α , 14 α , 17 α -C₂₉ steranes (*m/z* 217).

C_n Sterane (%) = C_n/C₂₇-C₂₉ 5 α , 14 α , 17 α , 20 R-sterane (*m/z* 217) × 100. n = 27, 28 and 29.

C₂₇/C₂₉ Sterane ratio = C₂₇/C₂₉ 5 α , 14 α , 17 α , 20 R-steranes (*m/z* 217).