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PRELIMINARY RESULTS OF PETROLEUM SOURCE ROCK EVALUATION OF MONGOLIAN MESOZOIC OIL SHALES

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Abstract

Jurassic and Cretaceous oil shale samples, collected from northern and central Mongolian basins, have been analyzed to determine their petroleum source rock potential. The contents of total organic carbon (TOC) and total sulfur, and source rock screening data were obtained by Rock-Eval pyrolysis. Cretaceous oil shales contain up to 17.4 wt.% TOC and Hydrogen Index (HI) values range from 638-957 mg HC/g TOC. Jurassic oil shale samples have similar TOC contents, ranging from 10.7 to 17.3 wt.%. HI values of Jurassic Tsagaan-Ovoo oil shale vary between 270-313 mg HC/g TOC. Average Tmax values of Cretaceous and Jurassic samples are 437^0C and 423^0C, respectively. This observed data indicates that both Jurassic and Cretaceous oil shales are excellent source rock. Cretaceous oil shales contain type I kerogen (highly oil prone), while Jurassic Tsagaan-Ovoo oil shale has mixed type II/III kerogen (mixed oil and gas prone). Based on Tmax and Production Index values, both Jurassic and Cretaceous oil shales are immature. Overall, the result of this study contributes organic geochemistry database of Mongolian oil shale and encourages source rock potential of both Jurassic and Cretaceous oil shale.

Key words: Jurassic oil shale, Mesozoic source rock, Rock-Eval analysis

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1.Introduction

Petroleum exploration in Eastern Mongolia has been focused only on Lower Cretaceous sedimentary rocks, because it is accounted as the only one Independent Petroleum System (Pentilla, 1994). The oil shale hosted in Lower Cretaceous sedimentary rocks is undoubtedly source rocks of the known oil fields in Eastern Mongolia (Yamamoto et al., 1998; Johnson et al., 2003). In addition, oil shale has been categorized as a ‘superb oil-prone world-class source rock’, which under the right geological conditions (adequate seals and reservoir quality coupled with large structures and proper maturity) could give rise to ‘billions of barrels of oil’ (Penttila, 1994). Mongolian Cretaceous oil shale and its shale oil resources were estimated to be 787 Bt and 22.7 Bt, respectively (Bat-Erdene, 2009). This huge number implies that Mongolian sedimentary basins have great potential for both oil shale and petroleum, as well.

Previously, it was thought that all oil shales in Mongolia is hosted in Early Cretaceous sedimentary unit and can be divided into 13 oil shale-bearing basins (Bat-Erdene and Jargal, 1994) (Fig.1). Recently, Li et al. (2014) revealed that the age of Khuut oil shale in Middle Gobi basin, previously accounted as Lower Cretaceous, is Early-Middle Jurassic. After this age-revision, several additional Jurassic oil shales have catalogued in central and north Mongolia (Erdenetsogt and Jargal, 2014). This is important because ‘mega’ petroleum systems with Jurassic source rocks contain one-fourth of the World’s discovered petroleum (Klemme, 1994).

On the other hand, geological survey of Mongolian oil shale is very poor. For instance, above mentioned Cretaceous oil shale resource estimation was based on scarce data; only ~8% of known deposits/occurrences were sampled for lab assays (Bat-Erdene, 2009). Moreover, the organic geochemistry database for Mongolian oil and source rocks is also limited (Jonhson et al., 2003). Only few papers have been published so far.

This study aims to improve understanding of the source rock potential of Cretaceous and Jurassic oil shale. To do this, oil shale samples from several different locations are collected and analyzed. The results provide new insights into petroleum systems of Mongolia and source rock potential of Jurassic oil shale.

2.Regional geology

Mesozoic sedimentary successions in Southeastern Mongolia is divided into four sequence stratigraphic megasequences, bounded by unconformities and tied to tectonic episodes (Graham et al., 2001). The first megasequence, Lower to Middle Jurassic Pre-rift Megasequence, is represented by Khamarkhoovor Formation. The second Upper Jurassic–Lower Cretaceous Synrift Megasequence is subdivided into several synrift sequences and characterized by Upper Jurassic Sharyl, Lower Cretaceous Tsagaantsav, Shinekhudag, and Khukhteeg Formations (Graham et al., 2001, Johnson, 2004). The third megasequence is Mid Cretaceous Inversion Megasequence, which is assigned to Baruunbayan Formation. The megasequence represents basin inversion during late Early Cretaceous time. The thickness of eroded section due to inversion was estimated to be 1.7 km (Johnson, 2004). The fourth megasequence is Upper Cretaceous Postrift Megasequence, characterized by several formations, including Sainshand and Bayanshiree.

Currently only few Jurassic oil shales in central and northern Mongolia, closely related to previously known Jurassic coal seams, have been documented so far. However, it is quite certain that more oil shale can be discovered in Jurassic sedimentary rocks at western and eastern Mongolia, where relatively bigger basins lie compared with central and northern Mongolia. Known Jurassic oil shales at Tsagaan-Ovoo, Khuut, and Shariin Gol mines are hosted in Bakhar, Eedemt, and Shariin Gol Formations, respectively. In general, the Formations belong to Lower-Middle Pre-rift Megasequence, composed of sandstone and conglomerate layers at the base and fine-grained sequence of shale, carbonaceous shale, sandstone, and coal seams at the middle and top. The Megasequence is hypothesized to be part of the early Mesozoic foreland basin developed in south-central Mongolia (Hendrix et al., 1996, Graham et al., 2001, Lamb et al., 2008, Erdenetsogt et al., 2009).

Cretaceous oil shale suits to Upper Jurassic–Lower Cretaceous Synrift Megasequence. According to Johnson (2004), the Forth Synrift Sequence of the Megasequence (SR4) is characterized by oil shale-bearing Shinekhudag Formation. The Formation consists of sandy conglomerates (at bottom), siltstone and mudstone with subordinate sandstone, limestone, siderite nodules, dolomite, and marl siltstone (Bat-Erdene, 2009). The overlying Fifth Synrift sequence (SR5) is composed of conglomerate, gross bedded sandstone, siltstone, coaly shale with up to 110 m thick coal measures of Khukhteeg Formation.

The sediments of Lower Cretaceous oil shales bearing Shinekhudag Formation were accumulated in relatively deep lakes of rift valleys, when extension was intense. Afterwards, due to decreased subsidence rate at the late stage of rifting, water level lowered and shallow lakes were filled with Khukhteeg coal-bearing formation. Thick coal seams were formed in extensively developed peatlands during this time (Erdenetsogt et al., 2009). Therefore, Cretaceous oil shale-bearing unit always underlies coal-bearing unit. This feature is common for rift valleys (Watson et al., 1987, Diessel,1992). In contrast, known Jurassic oil shales are on the top of coal seams (e.g., Tsagaan-Ovoo, Shariin Gol and Khuut). Furthermore, both Jurassic and Cretaceous oil shales are rhythmically alternated with carbonates (dolomite, calcite and marl), which can be explained by changes in lake-level and lake productivity. Carbonate layers were formed during low lake levels, whereas oil shale layers were deposited during high lake levels (Hitoshi et al., 2014).

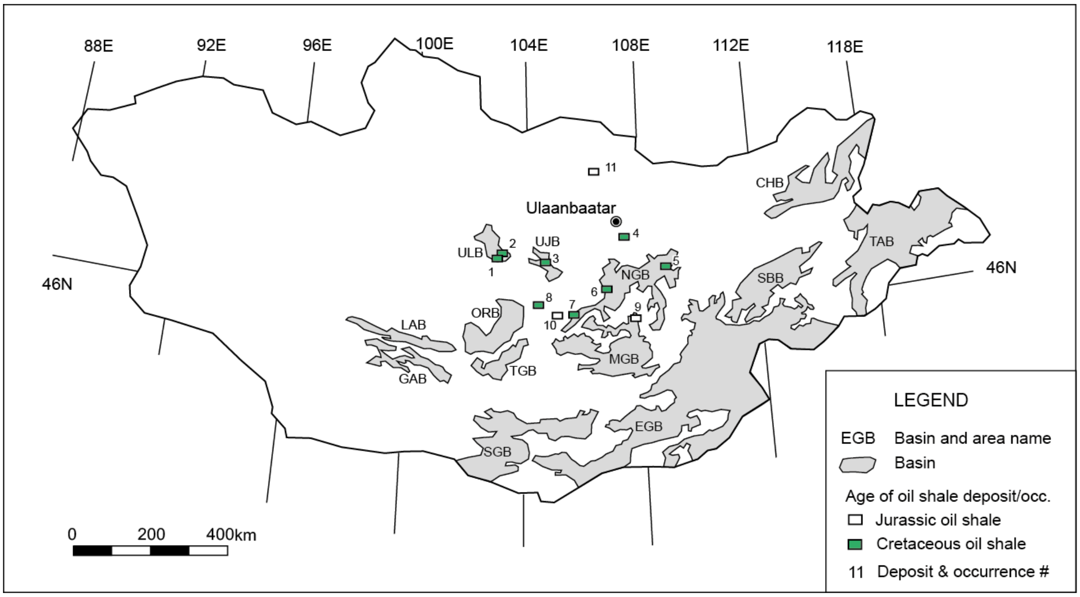

Fig. 1. Schema of Mongolian oil shale-bearing basins (modified after Bat-Erdene and Jargal, 1994). Oil shale sample localities are shown. See Table 1 for addition information. Basins: LAB – Nuuruudiin Khotgor, GAB – Gobi-Altai, ORB – Ongi River, TGB – Tugrug, ULB – Ugii Lake, UJB – Uvurjargalant, NGB – Nyalga, MGB – Middle Gobi, SGB – South Gobi, EGB – East Gobi, SBB – Sukhbaatar, TAB – Tamsag, CHB – Choibalsan; Sampled localities: 1 – Khugshin Gol, 2 – Zuunbulag, 3 – Uvurjargalant, 4 – Nalaikh, 5 – Bayan-Erkhet, 6 – Beeliin Jas, 7 – Ulaankhooloin Gobi, 8 – Ergenegiin Gobi, 9 – Khuut, 10 – Tsagaan-Ovoo, 11 – Shariin Gol.

3.Samples and methods

A total of 57 samples, including 7 carbonate samples, were collected from eleven different locations in 2012 and 2016 (Fig 1). Most of the samples are taken from outcrops of oil shale seams and intercalated carbonate layers, but also include 17 core samples from a borehole drilled in Uvurjargalant area (Table 1). Samples collected in 2012 were analyzed at Ben Gurion University (BGU) in Israel, while samples taken in 2016 were analyzed at Korea Institute of Geoscience and Mineral resources (KIGAM) in South Korea (Table 2). All samples were stored in plastic bags and shipped to laboratories, where the samples were cleaned with water, dried at room temperature and crushed by hand (70 mesh sieve). Homogenized powder samples were selected for further analyses.

Total organic carbon (TOC) and total sulfur (TS) contents were analyzed using Leco SC-632 carbon and sulfur determinator at BGU in 2012. Rock-Eval pyrolysis/TOC analyses of the all samples were performed using Rock-Eval 6 instrument equipped with TOC module at BGU and KIGAM in 2012 and 2016, respectively.

Table 1. List of sample abbreviations, locality names, and location

Sample abbreviation	Locality	Age	Longitude	Latitude
KHG	Khugshin gol	Lower Cretaceous	102.98	47.09
ZB	Zuunbulag	Lower Cretaceous	103.20	47.27
NL	Nalaikh	Lower Cretaceous	107.33	47.79
HU	Bayan-Erkhet	Lower Cretaceous	108.64	46.97
BJ	Beeliin Jas	Lower Cretaceous	106.72	46.31
TG	Ulaankhooloin gobi	Lower Cretaceous	105.71	45.76
EG	Ergenegiin Gobi	Lower Cretaceous	104.47	45.97
OB	Uvurjargalant	Lower Cretaceous	-*	-
KH	Khuut	Middle Jurassic	107.72	45.68433
SHG	Shariin gol	Lower-Middle Jurasssic	106.4211	49.22147
TSO	Tsagaan-Ovoo	Middle-Upper Jurassic	105.18	45.73

*Coordinates not shown due to permission

Table 2.Rock-Eval and TOC data of Mesozoic oil shale samples

Sample	Lithology	Lab	Sampled type	TOC	S1	S2	S3	Tmax	HI	OI	S2/S3	PI	TS
KHG-1602	Oil shale	1	Outcrop	12.61	1.70	86.33	4.71	432	685	37	18.33	0.02	-
KHG-1604	Oil shale	1	Outcrop	15.97	2.76	112.67	5.26	431	706	33	21.42	0.02	-
KHG-1605	Calcite	1	Outcrop	1.92	0.23	10.68	2.16	431	556	112	4.94	0.02	-
ZB-1601	Oil shale	1	Outcrop	4.02	1.50	28.24	1.43	427	702	36	19.75	0.05	-
ZB 1602	Marl	1	Outcrop	0.27	0.10	1.02	0.57	414	378	211	1.79	0.09	-
ZB-1603	Oil shale	1	Outcrop	13.56	2.70	94.37	5.61	422	696	41	16.82	0.03	-
ZB-1604	Oil shale	1	Outcrop	16.32	3.45	113.92	7.03	424	698	43	16.20	0.03	-
NL-1601	Oil shale	1	Outcrop	8.94	0.55	57.69	3.72	430	645	42	15.51	0.01	-
NL-1602	Calcite	1	Outcrop	1.33	0.10	6.17	1.93	433	464	145	3.20	0.02	-
NL-1201	Oil shale	2	Outcrop	19.38	-	-	-	-	-	-	-	-	0.53
NL-1202	Oil shale	2	Outcrop	12.47	-	-	-	-	-	-	-	-	0.32
NL-1203	Oil shale	2	Outcrop	11.46	-	-	-	-	-	-	-	-	0.25
HU-1601	Oil shale	1	Outcrop	8.87	0.76	66.70	3.28	435	752	37	20.34	0.01	-
HU-1602	Dolomite	1	Outcrop	1.43	0.07	3.61	1.40	435	252	98	2.58	0.02	-
BJ-1602	Calcite	1	Outcrop	0.27	0.04	0.76	0.59	440	281	219	1.29	0.05	-
BJ-1603	Oil shale	1	Outcrop	9.62	3.05	64.21	4.58	429	667	48	14.02	0.05	-
BJ-1604	Calcite	1	Outcrop	1.56	0.43	9.17	1.28	429	588	82	7.16	0.04	-
TG-1601	Oil shale	1	Outcrop	17.38	0.81	129.9	7.06	438	747	41	18.40	0.01	-
TG-1602	Oil shale	1	Outcrop	18.17	0.98	139.48	7.3	440	768	40	19.11	0.01	-
OBDH-416	Oil shale	2	Core	14.26	0.82	133.25	0.66	447	934	5	201.89	0.61	0.47
OBDH-421	Oil shale	2	Core	10.28	0.76	98.35	0.44	447	957	4	223.52	0.01	0.39
OBDH-430	Oil shale	2	Core	10.79	0.69	91.56	0.91	441	849	8	100.62	0.01	0.28
OBDH-441	Oil shale	2	Core	6.11	0.18	48.56	0.80	445	795	13	60.70	0.004	0.42
OBDH-455	Oil shale	2	Core	4.27	0.34	29.39	0.65	438	688	15	45.22	0.01	0.40
OBDH-467	Oil shale	2	Core	10.69	2.37	86.76	0.59	434	812	6	147.05	0.03	0.34
OBDH-481	Oil shale	2	Core	7.71	0.42	66.25	0.53	441	859	7	125.00	0.01	2.52
OBDH-490	Oil shale	2	Core	7.31	0.55	58.88	0.66	443	805	9	89.21	0.01	0.29
OBDH-502	Oil shale	2	Core	2.71	0.47	17.28	0.37	438	638	14	46.70	0.03	0.75
OBDH-517	Oil shale	2	Core	11.18	1.38	92.29	0.75	437	825	7	123.05	0.01	3.48
OBDH-530	Oil shale	2	Core	14.77	2.45	130.95	0.46	445	887	3	284.67	0.02	1.00
OBDH-540	Oil shale	2	Core	9.62	0.50	78.70	0.60	442	818	6	131.17	0.01	0.14

OBDH-553	Oil shale	2	Core	4.14	0.58	30.41	0.40	440	735	10	76.03	0.02	0.11
OBDH-567	Oil shale	2	Core	5.57	0.95	40.50	1.01	442	727	18	40.10	0.02	0.08
OBDH-604	Oil shale	2	Core	12.23	3.64	101.58	1.04	442	831	9	97.67	0.03	0.31
OBDH-619	Oil shale	2	Core	7.96	0.67	55.96	1.19	436	703	15	47.03	0.01	0.48
OBDH-642	Oil shale	2	Core	15.72	3.47	129.17	3.19	441	822	20	40.49	0.03	0.32
OB-1255	Oil shale	2	Outcrop	10.24	-	-	-	-	-	-	-	-	0.23
OB-1256	Oil shale	2	Outcrop	12.45	-	-	-	-	-	-	-	-	0.31
OB-1257	Oil shale	2	Outcrop	14.22	-	-	-	-	-	-	-	-	0.37
OB-1259	Oil shale	2	Outcrop	11.3	-	-	-	-	-	-	-	-	0.27
OB-1260	Oil shale	2	Outcrop	7.48	-	-	-	-	-	-	-	-	0.18
EG-12004	Oil shale	2	Outcrop	5.47	-	-	-	-	-	-	-	-	0.09
EG-12005	Oil shale	2	Outcrop	6.15	-	-	-	-	-	-	-	-	0.15
EG-12009	Oil shale	2	Outcrop	11.49	-	-	-	-	-	-	-	-	0.20
TSO-1604	Marl	1	Outcrop	1.44	0.06	2.54	0.88	423	176	61	2.89	0.02	-
TSO-1605	Oil shale	1	Outcrop	17.30	0.54	51.92	3.43	422	300	20	15.14	0.01	-
TSO-1606	Oil shale	1	Outcrop	15.18	0.57	44.14	3.71	422	291	24	11.90	0.01	-
TSO-1607	Oil shale	1	Outcrop	13.70	0.56	37.95	4.24	424	277	31	8.95	0.01	-
TSO-1608	Oil shale	1	Outcrop	10.98	0.48	29.67	3.01	422	270	27	9.86	0.02	-
TSO-1609	Oil shale	1	Outcrop	11.43	0.56	35.74	2.59	425	313	23	13.80	0.02	-
TSO-1610	Oil shale	1	Outcrop	10.73	0.56	31.46	3.01	424	293	28	10.45	0.02	-
KH-8/18	Oil shale	2	Outcrop	15.13	-	-	-	-	-	-	-	-	0.33
KH-8/19	Oil shale	2	Outcrop	16.56	-	-	-	-	-	-	-	-	0.35
KH-8/20	Oil shale	2	Outcrop	6.08	-	-	-	-	-	-	-	-	0.14
SHG-1205	Oil shale	2	Outcrop	4.42	-	-	-	-	-	-	-	-	0.15
SHG-1206	Oil shale	2	Outcrop	8.1	-	-	-	-	-	-	-	-	0.29
SHG-1207	Oil shale	2	Outcrop	3.96	-	-	-	-	-	-	-	-	0.09

Note: Locations and age of the samples are shown in Table 1. Laboratories are denoted as follows: 1 - KIGAM; 2 -BGU.

Briefly, the Rock-Eval pyrolysis method uses programmed temperature heating to (i) thermally distil 'free' or adsorbed hydrocarbons (S1 peak) from the sample, (ii) pyrolyze the kerogen to produce hydrocarbons (S2 peak) and CO2 (S3 peak) and, (iii) in a second oven, oxidize the residual organic matter. The total organic carbon (TOC) is determined by summing the pyrolyzed and residual carbon fractions. The temperature at the top of the S2 peak, coinciding with maximum generation of hydrocarbons, is referred to as Tmax (Sykes and Snowdon, 2002). Detailed description of the newest version (Rock-Eval 6) of the instrument, its operation, measured parameters, and applications to petroleum exploration can be found in Lafargue et al. (1998), Behar et al. (2001), McCarthy et al. (2011). In addition, based on pyrolysis data, several important indices are calculated and used in the interpretation of source rock characteristics such as hydrogen index [HI=S2*100/TOC], oxygen index [OI=S3*100/TOC] and production index [PI=S1/(S1+S2)] etc.

Sedimentary rocks that are, or may become, or have been able to generate petroleum are source rocks (Tissot and Welte, 1984). The source rocks satisfy three geochemical requirements such as quantity (amount of organic matter), quality (type of organic matter or kerogen type) and thermal maturity (extent of burial heating) (Peters and Cassa, 1994). In this study, the quantity of organic matter was measured as TOC (wt.%), S1 (mg HC/g rock) and S2 (mg HC/g rock), the quality was determined by HI (mgHC, g TOC), OI (mgHC/g TOC) and, S2/S3 and thermal maturation assessed by Tmax (^{0}C) and PI (Tables 3-5).

Table 3. Geochemical Parameters Describing the petroleum potential (quantity) of an immature source rock (Peters and Cassa, 1994)

Petroleum potential	Organic matter			Bitumen		Hydrocarbons
	TOC	Rock-Eval pyrolysis				
	(wt.%)	S1*	S2*	(wt.%)	(ppm)	(ppm)
Poor	0-0.5	0-0.5	0-2.5	0-0.05	0-500	0-300
Fair	0.5-1	0.5-1	2.5-5	0.05-0.1	500-1000	300-600
Good	1-2	1-2	5-10	0.1-0.2	1000-2000	600-1200
Very Good	2-4	2-4	10-20	0.2-0.4	2000-4000	1200-2400
Excellent	>4	>4	>20	>0.4	>4000	>2400

*mg HC/g dry rock

Table 4. Geochemical Parameters Describing kerogen type (quality) and the character of expelled products (Peters and Cassa, 1994)

Kerogen type	HI*	S2/S3	Atomic H/C	Main expelled product at peak maturity
I	>600	>15	>1.5	Oil
II	300-600	10-15	1.2-1.5	Oil
II/III	200-300	5-10	1.0-1.2	Mixed oil and gas
III	50-200	1-5	0.7-1.0	Gas
IV	<50	<1	<0.7	None

*mg HC/g TOC

Table 5. Geochemical Parameters Describing level of thermal maturation (Peters and Cassa, 1994)

Stage of thermal maturity for oil	Maturation			Generation		
	Ro (%)	Tmax (^{0}C)	TAI*	Bitumen/ TOC	Bitumen (mg/g rock)	PI [S1/ (S1+S2)]
Immature	0.2-0.6	<435	1.5-2.6	<0.05	<50	<0.1
Mature						
Early	0.6-0.65	435-445	2.6-2.7	0.05-0.1	50-100	0.1-0.15
Peak	0.65-0.9	445-450	2.7-2.9	0.15-0.25	150-250	0.25-0.4
Late	0.9-1.35	450-470	2.9-3.3	-	-	>0.4
Postmature	>1.35	>470	>3.3	-	-	-

*TAI - Thermal alteration index

4.Results and Discussion

4.1. Organic richness

Total organic carbon (TOC) contents of 34 samples (out of 57 samples) were measured by Leco method, whereas that of remaining samples were determined by Rock-Eval. In addition, TOC contents of 17 core samples were analyzed by both Leco and Rock-Eval methods. For organic carbon determination, Rock-Eval 6 is reliable technique and the data from Rock-Eval correlates well (R^2=0.99) with element analyses and Leco methods (Behar et al., 2001). For our 17 core samples, almost perfect correlation was obtained, as well (Fig 2, TOC vs TOC comparison). Thus, in this study, TOC contents of the outcrop samples measured by two different methods are used simultaneously.

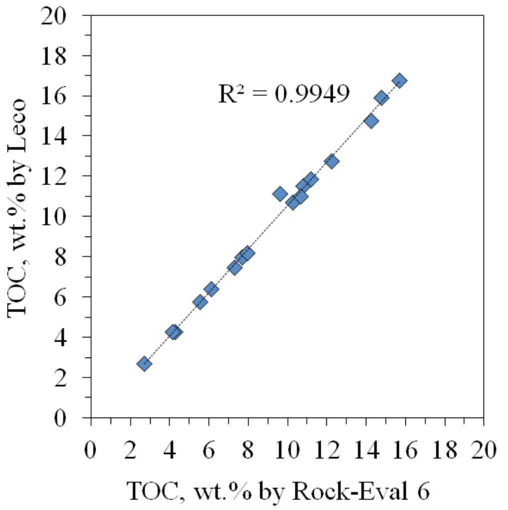

Fig.2. *Correlation between TOC contents of core samples measured by Rock-Eval 6 and Leco.*

TOC contents of oil shale samples range from 2.67 wt.% to 19.38 wt.%, whereas that of carbonate samples vary from 0.27 wt.% to 1.92 wt.% (Table 2). For outcrop samples, Jurassic Shariin gol (SHG) and Cretaceous Ergenegiin gobi (EG) samples have relatively lower TOC contents, ranging from 3.96 wt.% to 8.1 wt.% and 5.47 wt.% to 11.49 wt.%, respectively. Other outcrop samples have high TOC contents, varying between 6.08 wt.% and 19.38 wt.%. The organic richness of Jurassic and Cretaceous samples does not have much difference with an average of 11.13 wt.% and 11.79 wt.%, respectively.

The S1 and S2 values of Cretaceous oil shales range from 0.18 to 3.64 mgHC/g rock (average 1.42 mgHC/g rock) and from 17.28 to 139.50 mgHC/g (average 80.89 mgHC/g rock), respectively. For Jurassic oil shales, only Tsagaan-Ovoo samples have been analyzed by Rock-Eval. The observed S1 and S2 values of the sample range from 0.48 to 0.57 mgHC/g rock and from 29.67 to 51.92 mgHC/g rock, respectively.

TOC and Rock–Eval data indicates that the both Jurassic and Cretaceous oil shales are excellent petroleum source rocks. Moreover, the measurements of carbonate samples reveal that the carbonate layers intercalated with oil shale seams also have pair to good petroleum potential (Fig 3). This data for high organic richness of Mesozoic oil shales agrees well with previously reported results of Yamamoto et al. (1993), Slaydon and Traynor (2000) and Jonhson et al. (2003).

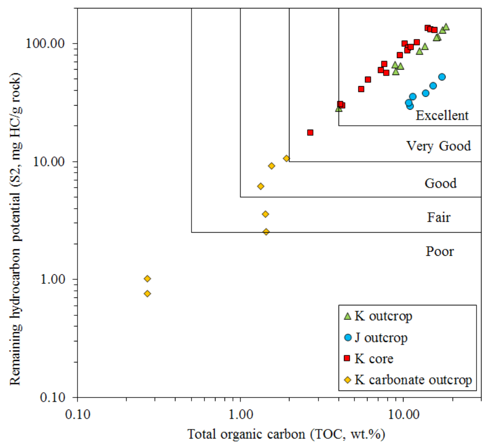

Fig 3. *S2 value vs. TOC contents for oil shale and carbonate samples. S2 and TOC cut-off values based on Peters and Cassa, (1994). Majority of oil shale samples have excellent source rock generative potential, whereas carbonate samples have fair to good potential.*

The distribution of sulfur contents in outcrop samples seems to be dependent on TOC contents (Fig 4). In the case of outcrop samples, including both Jurassic and Cretaceous, total sulfur (TS) contents have strong relationship with TOC (R^2 0.86; 0.024xTOC). Furthermore, several core samples (OBDH) fall on the same trend, while the rest fall above it. This relationship suggests that the samples, which fall on the linear trend, contain mainly organic sulfur (TOS) in the proportion TOS/TOC=0.024. The samples, laying above this trend, contain both organic and inorganic sulfur. This is probably due oxidation and weathering of inorganic sulfur, which lead preservation of only the organic sulfur fraction in the outcrop samples.

Fig 4 also demonstrates that the oil shales are deposited in lacustrine condition without marine influences. This is consistent with a fact that the closure of Mongol-Okhotsk Ocean was evidenced in the Early Permian and Mongolian portion was closed completely by Early Jurassic (e.g., Zorin, 1999). After closure of the Ocean, entire Mongolia was dominated by continental condition and oil shales were accumulated in intercontinental lakes.

The organic richness and sulfur content of Jurassic and Cretaceous oil shales are quite identical for the studied samples. It may suggest that biological productivity level and preservation and dilution conditions of oil shale forming paleo-lakes were similar during Jurassic and Cretaceous time. More detailed studies are required to check this prediction.

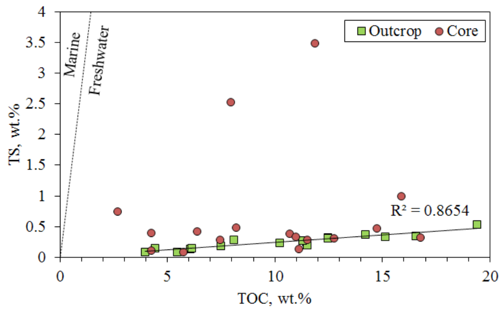

Fig 4. *Total sulfur vs. total organic carbon content plot for Jurassic and Cretaceous outcrop and Cretaceous core samples. The C/S ratio (dashed line) distinguishing marine from freshwater (or slightly brackish) sedimentary rocks is adopted from Berner and Raiswell (1983).*

4.2. Kerogen types

Kerogen types can be distinguished using atomic H/C versus O/C diagram or van Krevelen diagram (Tissot et al., 1974). Rock-Eval method can also define kerogen type by using Hydrogen index (HI) and Oxygen index (OI) and is more rapid and less expensive than elemental analysis (Peters, 1986).

Using Rock-Eval data, Cretaceous outcrop samples fall on region for Type II kerogen (Fig 5), whereas Cretaceous core samples fall on Type I kerogen region. Type I and II kerogens are rich in hydrogen and low in oxygen and expel mainly oil. However, it depends largely on thermal evolution.

It is well known that type I kerogen (HI is >600 mg HC/g TOC) is predominantly originated from lacustrine environment. In contrast, type II kerogen (HI is 300-600 mg HC/g TOC) is typically generated in reducing environment found in deep marine setting (e.g., Peters and Cassa, 1994, McCarthy et al., 2011). On the other hand, all types of organic matter subject to oxidation during transportation, deposition and diagenesis. Oxidation tends to remove hydrogen and add oxygen to the kerogen (e.g., Peters, 1986). In addition, thermal maturity of source rock depends on kerogen type. Type I kerogen requires much higher thermal maturation to expel oil than type II kerogen. By judging above mentioned facts, it can be concluded that Cretaceous outcrop samples suffer from oxidation effects (exposure to atmospheric O_2, water flow, wet-dry cycles etc.), which results in a decrease in hydrogen (and sulfur) and an increase in oxygen. This oxidation effect might mislead to think the oil shale samples have type II kerogen, when in actuality it contains oxidized type I kerogen.

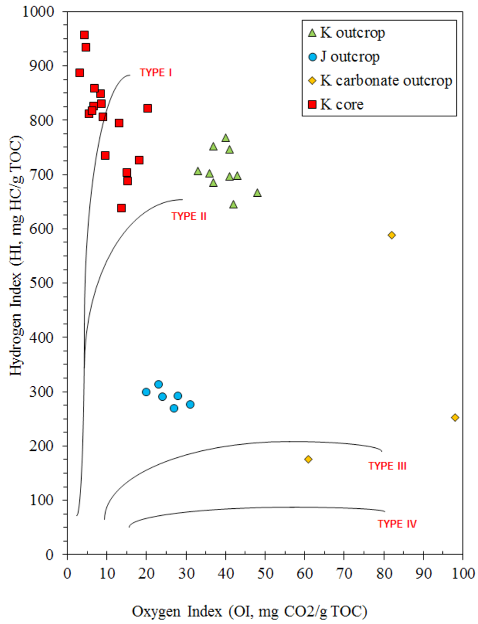

Fig 5. *HI versus OI diagram (modified van Krevelen) based on Rock-Eval pyrolysis describing type of organic matter in source rock (Peters and Cassa, 1994). See Table 2 for data.*

Kerogen type is also defined by a plot of S2 versus TOC diagram (Fig. 6). This approach is effective, because it avoids the problems in S3 (Langford and Blanc-Valleron, 1990). The plot clearly indicates that all Cretaceous samples have Type I kerogen. Yamamoto et al. (1998) made same conclusion, which stated that the studied Mongolian Cretaceous oil shales have Type I kerogen, because of high HI and Tmax values. Observed higher OI can be explained by weathering at the outcrop surface.

Jurassic Tsagaan-Ovoo samples have mixed type II/III kerogen (HI is 270-313 HC/gTOC), suggesting that the oil shale has potential for mixed oil and gas (Figs. 5 and 6). It also reveals that the oil shale has significantly increased proportion of type III kerogen (or higher land plant derived material). Yamamoto et al. (1993) studied Jurassic Khuut oil shale. In this paper, Khuut was named as Eedemt and age was assigned as Early Cretaceous. However, the age of Eedemt oil shale was later revised to Middle Jurassic by Li et al. (2014). Similar to Cretaceous oil shales, Jurassic Khuut oil shale have quite high HI, ranging from 610 to 805 mg HC/gTOC (average 714 mg HC/gTOC), which suggests type I kerogen (Fig 6). According to Johnson et al. (2003), Mongolian Jurassic source rock can be divided into two different groups distinguished by kerogen type and maturity. The first group has type II and III kerogen and the second group has type I kerogen. The Tsagaan-Ovoo oil shale may belong to the first group, whereas Khuut oil shale can represent the highly oil prone second group.

The observed S2/S3 values of Jurassic Tsagaan-Ovoo samples vary from 9 to 15, which demonstrates that main expelling products at peak maturity is oil and gas. Cretaceous outcrop samples have S2/S3 values, ranging from 14 to 21 with an average of 18. It corresponds to type I kerogen. In contrast, Cretaceous core samples have much higher 40-285 S2/S3 values (average 111) compared with outcrop samples. It clearly shows that the S3 values of outcrop samples are increased because of oxidation, which leads to decrease the ratio (Table 2). The increased S3 values of outcrop samples also affect plots on HI vs. OI diagram (Fig. 5).

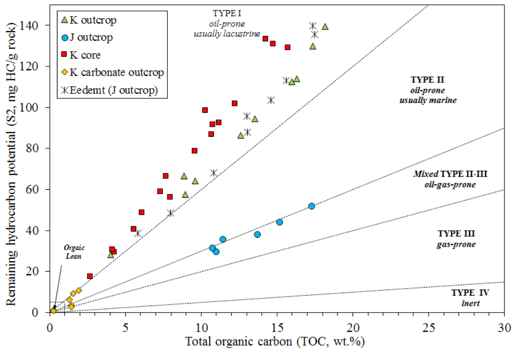

Fig 6. S2 versus TOC plot of the samples. Boundary between kerogen types are from Peters and Cassa (1994). See Table 2 for data. Eedemt data is from Yamamoto et al. (1993).

4.3. Thermal maturity

Besides organic richness and kerogen types, thermal maturity of organic matter is vital factor for source rock characterization. Thermal maturation is evaluated based on several methods such as vitrinite reflectance, thermal alteration index, Tmax and Production index etc. In this study, only Rock-Eval derived Tmax and PI are used. However, thermal maturity should be supported by vitrinite reflectance or thermal alteration index (Peters, 1986). Moreover, maturation parameter T max depends on kerogen type. For type I kerogen, oil formation begins at mean Tmax of about 442^{0}C (corresponding at Ro of about 0.7%). For type II and III kerogen, the beginning of oil formation starts much earlier at Tmax values of between 430 and 435^{0}C (Espitalie, 1986). In general, Tmax and Production index (PI) values less than about 435^{0}C and 0.1, respectively, indicate immature kerogen (Peters, 1986).

Jurassic and Cretaceous outcrop samples have quite low PI, ranging from 0.01 to 0.09 (average 0.03), suggesting the samples are immature. Similarly, Tmax values of samples range between 414^{0}C and 440^{0}C with an average of 428^{0}C, indicating immature level. Compared with outcrop samples, the core samples have slightly elevated Tmax and PI values. Tmax ranges from 434^{0}C to 447^{0}C with an average of 441^{0}C and PI ranges from 0.004 to 0.03 with an average of 0.02, indicating that Uvurjargalant core samples are immature, too. However, according to observed Tmax, thermal maturity is close to the top of oil window for type I kerogen.

5.Conclusion

In total 57 oil shale samples collected from eleven different locations are studied and the petroleum source rock potential of Jurassic and Cretaceous oil shale is evaluated. On the basis of the geochemical results, the following conclusions can be drawn:

1. Both Jurassic and Cretaceous oil shales are excellent source rock potential, containing 2.67-19.38 wt.% TOC. The carbonate layers intercalated with oil shale seams also have pair to good petroleum potential, characterized by average 1.2 wt.% TOC. Observed S1 and S2 values of the samples support above mentioned conclusion, as well.
2. Cretaceous oil shale have highly oil prone type I kerogen, derived mainly from lacustrine organic matter, indicated by high HI value ranging from 638 to 957 mgHC/g rock with an average of 769 mgHC/g rock. Jurassic Tsagaan-Ovoo oil shale is characterized by mixed type II/III kerogen, which has potential for oil and gas. Due to oxidation and weathering, OI of outcrop samples is increased. For core samples, this effect is not observed.
3. According to measured Tmax and PI values, both Jurassic and Cretaceous oil shales are immature. However, Tmax values of core samples, taken from 400 m to 640 m depth interval of a borehole drilled in Uvurjargalant, are slightly elevated compared to outcrop samples.
4. Total sulfur contents of the oil shales are low ranging from 0.08 wt.% to 3.48wt.%, indicating that oil shales were deposited in fresh to slightly brackish lacustrine condition without marine influence. In addition, total sulfur (TS) contents of outcrop samples have strong relationship with TOC, which suggest that inorganic sulfur fraction was oxidized and only organic sulfur was preserved in the samples.
5. This study shows that not only Cretaceous but also Jurassic oil shale have excellent petroleum potential. Although Jurassic oil shales have been identified (and studied) in relatively small basins in terms of petroleum exploration, the geological settings of the basins are similar to others. Therefore, it is believed that more Jurassic oil shale can be discovered from East and West of Mongolia and the quality of oil shale should be similar. Further comprehensive studies of Jurassic sedimentary rocks, hosted in bigger basins in eastern and western Mongolia, should be completed. This is critically important for complete evaluation of petroleum potential of Mesozoic sedimentary unit.

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