

Article

Source-Rock Potential of Jurassic Deposits on the Northern and South-Western Flanks of the Kosbulak Trough (North Ustyurt Basin, Kazakhstan): Evidence from Rock-Eval Pyrolysis of Two Exploration Wells

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Abstract

The Kosbulak Trough, in the eastern part of the North Ustyurt Basin in western Kazakhstan near the border with Uzbekistan, is one of the deepest Mesozoic depocentres of the basin, yet published organic geochemical data on its source rocks remain scarce. This study evaluates Rock-Eval pyrolysis data from two exploration wells located on opposite flanks of the trough: Well N on the northern flank (11 cuttings samples, 1657–1975 m depth) and Well S on the south-western flank (752 cuttings samples, 450–4688 m depth). Formation tops from well logs and palynology were used to compare the same stratigraphic units in both wells. In Well N, the Middle Jurassic coal-bearing interval (1685–1875 m depth) has median TOC of 5.81 wt.% (up to 32.2 wt.% in coal), S_2 of 1.08–31.59 mg HC/g rock and HI of 43–189 mg HC/g TOC, indicating gas-prone Type III organic matter; T_{max} of 424–429 °C and measured vitrinite reflectance of 0.43–0.44% show that it is thermally immature. In Well S, the Middle Jurassic (3242–4010 m depth) is leaner (median TOC 1.06 wt.%, median S_2 1.16 mg HC/g rock), but its richest coaly beds at 3522–3563 m depth (TOC 3.32–4.93 wt.%, S_2 5.41–8.34 mg HC/g rock) have T_{max} of 435–441 °C, corresponding to the onset of the oil window. In the Lower Jurassic and Triassic of Well S (below 4010 m depth), T_{max} decreases to about 407 °C; this is attributed to low S_2 , oil-based-mud contamination and bitumen impregnation observed in core, rather than to decreasing maturity. Regional vitrinite reflectance and palaeotemperature data support this interpretation. The results indicate that Middle Jurassic source rocks are richer but immature on the northern flank and leaner but more mature on the deeper south-western flank; the deeper axial part of the trough, not sampled here, is suggested as the most probable gas-prone generation area.

Keywords: North Ustyurt Basin; Kosbulak Trough; source rock; Rock-Eval pyrolysis; total organic carbon; kerogen type; thermal maturity; vitrinite reflectance; burial history; Jurassic



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1. Introduction

The North Ustyurt Basin of western Kazakhstan and Uzbekistan is a Mesozoic–Cenozoic sag basin developed on the heterogeneous Palaeozoic basement of the Turan Platform, and the Jurassic is regarded as its principal petroleum system [1–3]. Exploration in the Kazakh part of the basin, and particularly in the Kosbulak Trough, is still at an early stage, and the location, richness and maturity of effective source rocks remain the main uncertainties in assessing hydrocarbon charge. Without reliable source-rock data, prospects

on the flanks of the trough cannot be ranked by charge risk, and exploration wells are likely to continue targeting structures with uncertain access to mature source rocks.

Middle Jurassic coaly shales and coals, with lacustrine mudstones locally carrying Type II kerogen, are considered the main source rocks of the basin, and most of their generation is dated to the Tertiary [1]. Regional geochemical studies of 476 rock samples from twelve areas of the North Ustyurt identified source intervals in all three Jurassic series [4]. In the deepest part of the Kosbulak depression, where the base of the Middle Jurassic lies at 3750–4500 m depth, Middle Jurassic source rocks have been placed in the oil window on the basis of palaeotemperature and vitrinite reflectance data [4,5]; Paleogene clinoform gas reservoirs have also been mapped in the Ustyurt region [6]. Coal-bearing Jurassic successions are proven sources in other Central Asian basins [7], but their Rock-Eval evaluation requires specific criteria [8,9]. In Kazakhstan, Rock-Eval, vitrinite reflectance and basin-modelling studies have characterised source rocks of the Precaspian and Pre-Uralian basins [10–12] and Jurassic Type III source rocks of the South Turgay Basin [13], geochemical studies have addressed the oils of the South Mangyshlak Basin [14,15], and integrated lithophysical analysis of deep-borehole data has been applied to other sedimentary sequences of the country [16]. A further difficulty is data quality: most regional pyrolysis data come from drill cuttings, often drilled with oil-based mud (OBM), which raises S_1 , lowers S_2 and suppresses T_{max} [17–20].

The objective of this study is to characterise the organic richness, kerogen type and thermal maturity of the Jurassic succession on the northern and south-western flanks of the Kosbulak Trough. We use Rock-Eval data from two exploration wells, Well N and Well S, together with formation tops, core descriptions, measured vitrinite reflectance in Well N and simple one-dimensional burial histories. The novelty of the study lies in the first stratigraphically controlled comparison of source-rock properties on opposite flanks of the trough, in which apparent maturity anomalies in contaminated deep cuttings are separated from the burial-related maturity trend using independent maturity data. The study contributes new, previously unpublished source-rock data for the Kosbulak Trough and constraints on where Jurassic source rocks may have reached the generation window.

2. Geological Setting

The Kosbulak Trough lies in the eastern part of the North Ustyurt Basin, between the South Emba Uplift and Shomyshty structures to the north-west, the Samsky Trough and Aktumsuk Uplift to the south and the Kyzylkum Swell to the east (Figure 1). On the structure map of the base of the Jurassic, the surface deepens from about -1.8 to -2.2 km on the northern flank to -4.2 to -4.4 km on the south-western flank and -4.6 km in the trough axis. Cretaceous rocks reach about 2600 m and Palaeocene-lower Miocene rocks about 1400 m in thickness in the Kosbulak depression [1]. The basement beneath the depression lies at about 11–12 km depth, and the platform cover reaches 4.5–5 km [4]. The depression has subsided continuously, without significant uplift or erosion, from the Jurassic to the present [4,5].

The stratigraphy of both wells, based on well logs and, in Well N, on palynological dating of 42 cuttings samples, is shown in Table 1 and Figure 2. In Well N (rotary table elevation 54 m), the Cretaceous is underlain by the Upper Jurassic (1507.5–1685 m depth), the Middle Jurassic (1685–1875 m depth) and Lower Jurassic plus Upper Triassic deposits (1875–2025 m depth, total depth). The Middle Jurassic has a three-part structure: siltstones and fine-grained sands with clay interlayers at the top, two massive sandstone units separated by a 25 m coaly–clayey interval with metre-thick coal beds at its base in the middle, and argillaceous siltstones and silty clays at the bottom. Kaolinite dominates the clay fraction in the Middle and Lower Jurassic (35–53.5%), consistent with continental depo-

sition. In Well S (rotary table elevation 133.77 m), the Upper Jurassic lies at 2920–3242 m depth, the Middle Jurassic at 3242–4010 m depth, the Lower Jurassic at 4010–4420 m depth and the Triassic at 4420–4750 m depth (total depth). Cores from the Middle Jurassic (3493.5–3553.7 m depth) consist of dark-grey siltstones and sandstones with coal inter-layers and abundant coalified plant material, whereas cores from 4057–4075 m depth are sandstones saturated with bituminous material, with a persistent hydrocarbon odour and 30–60% yellow natural fluorescence.

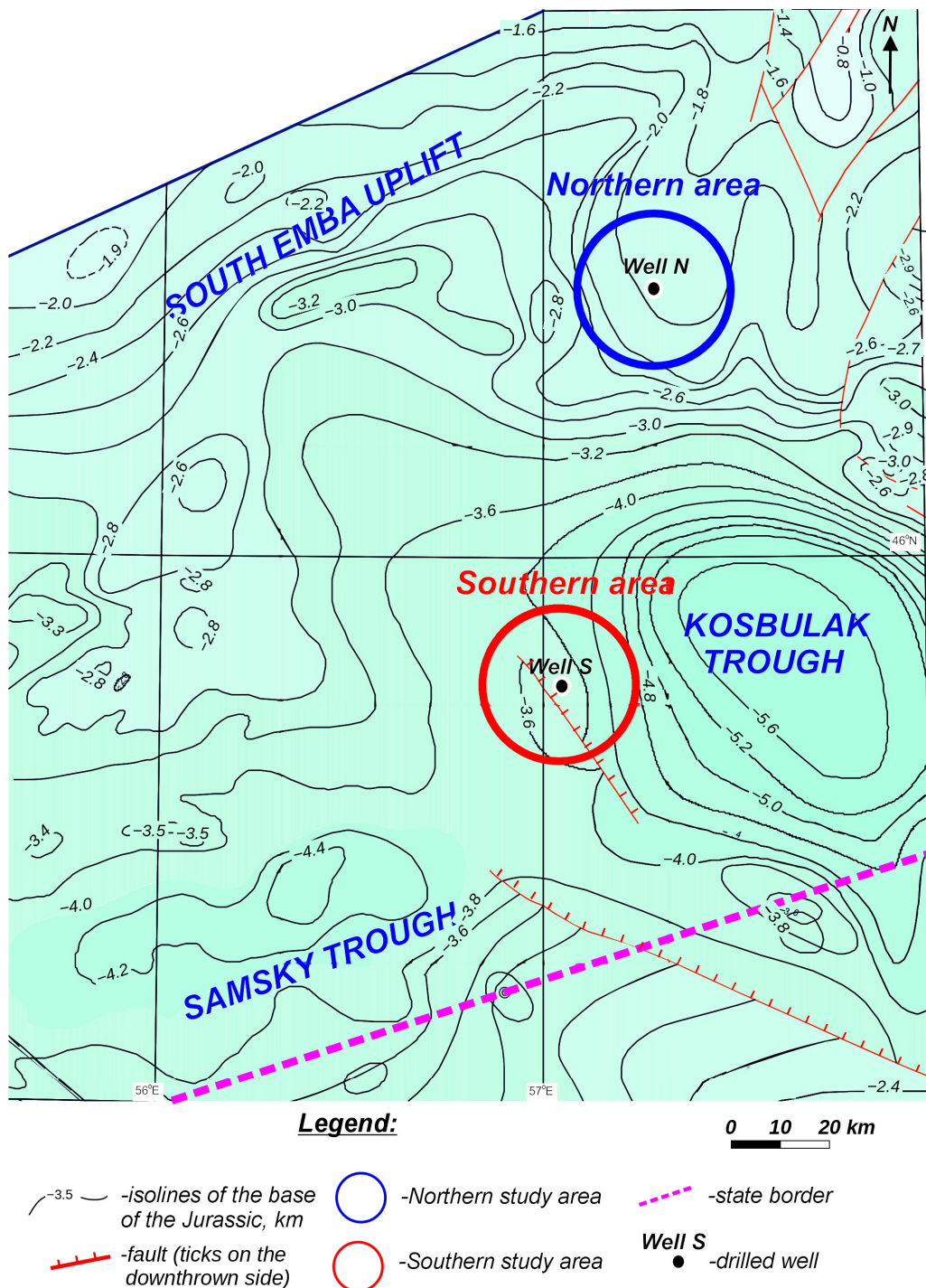
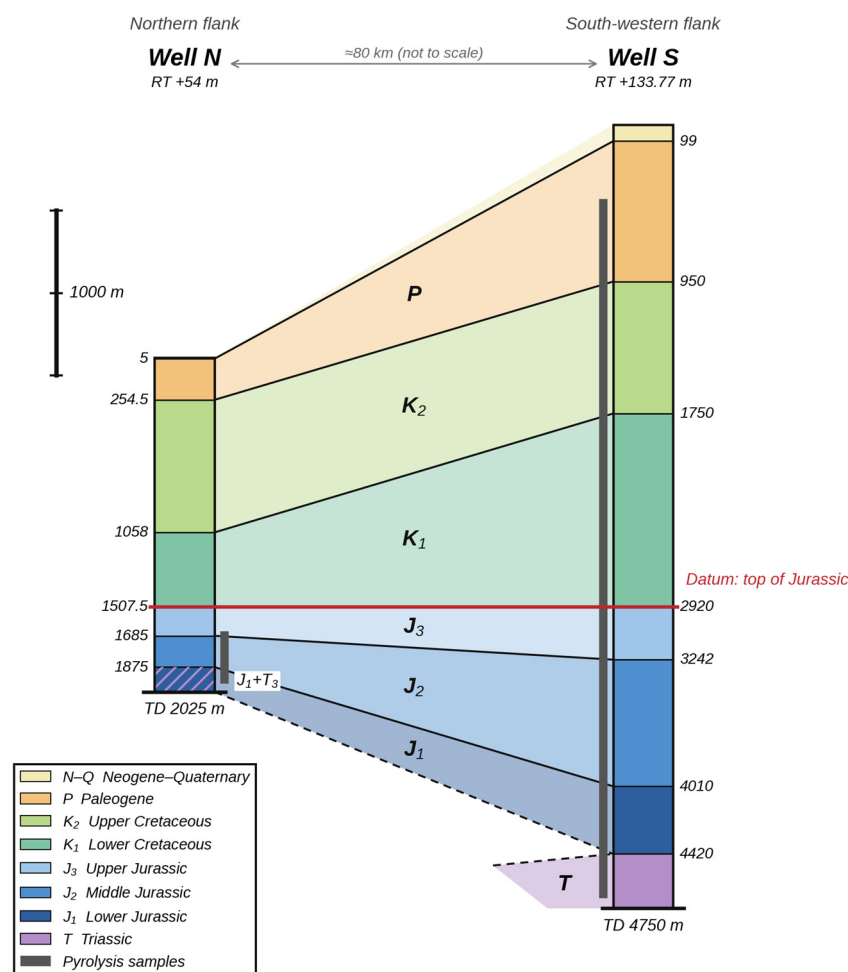


Figure 1. Structure map of the base of the Jurassic in the Kosbulak Trough area (isolines in km), showing the northern and south-western study areas and the schematic positions of Well N and Well S. The inset shows the position of the map within the North Ustyurt Basin. Map modified from a regional industry structure map of the base of Jurassic.

Table 1. Formation tops in the studied wells (depth below rotary table, m).

Well S, Thickness	Well S, Top-Base	Well N, Thickness	Well N, Top-Base	Unit
950	0–950	249.5	5–254.5	Neogene-Paleogene
800	950–1750	803.5	254.5–1058	Upper Cretaceous
1170	1750–2920	449.5	1058–1507.5	Lower Cretaceous
322	2920–3242	177.5	1507.5–1685	Upper Jurassic (J3)
768	3242–4010	190	1685–1875	Middle Jurassic (J2)
410	4010–4420	150 *	1875–2025 *	Lower Jurassic (J1)
330	4420–4750	—	—	Triassic (T)

* Lower Jurassic and Upper Triassic undivided; total depth 2025 m.

**Figure 2.** Stratigraphic correlation of Well N and Well S flattened on the top of the Jurassic (datum). Numbers are depths of formation tops (m); dark bars show the intervals of pyrolysis samples; the vertical bar is 1000 m; the distance between the wells is about 80 km and is not to scale. Data from well logs, palynology and laboratory reports; compiled by the authors.

3. Materials and Methods

3.1. Samples and Analytical Procedure

All pyrolysis data are from drill cuttings (Table 2). In Well N, 11 cuttings samples from 1657–1975 m depth were analysed on a Rock-Eval 6 instrument (Vinci Technologies, Nanterre, France); no core was taken because no hydrocarbon shows were observed. In Well S, 752 unwashed cuttings samples from 450–4688 m depth were analysed on a Weatherford Source Rock Analyzer (SRA TPH/TOC; Weatherford Laboratories, Houston, TX, USA); 63 m of core was recovered from the Jurassic and was used for lithological description only. Both instruments follow the same programmed-pyrolysis principle [21,22]: S₁ is released

during a 3 min isothermal step at 300 °C, S_2 during heating from 300 to 600 °C at 25 °C/min, and TOC is obtained by oxidation of the pyrolysis residue [23]. $HI = S_2 \times 100/TOC$ and $PI = S_1/(S_1 + S_2)$ were calculated for both wells; $OI = S_3 \times 100/TOC$ was available only for Well S, because S_3 was not measured in Well N [24].

Table 2. Sample sets and analytical data.

Well S (South-Western Flank)	Well N (Northern Flank)	Parameter
Cuttings (unwashed); core for lithology	Cuttings	Sample type
752 (450–4688 m depth)	11 (1657–1975 m depth)	Pyrolysis samples
Weatherford SRA TPH/TOC	Rock-Eval 6	Instrument
$S_1, S_2, S_3, T_{max}, TOC$	S_1, S_2, T_{max}, TOC	Measured
Calculated from T_{max}	Measured, 2 samples	Vitrinite reflectance
Logs and core description	Logs and palynology (42 samples)	Stratigraphy

Vitrinite reflectance was measured in Well N on 10 cuttings samples using an MSF-30U microphotometer; only two samples (1855 and 1930 m depth) contained vitrinite particles suitable for measurement. In Well S, calculated vitrinite reflectance was derived from T_{max} as $\%Ro = 0.0180 \times T_{max} - 7.16$ [25].

3.2. Interpretation Criteria

Organic richness was assessed from TOC and remaining generation potential from S_2 separately, following Peters and Cassa [26]. Kerogen type and maturity were classified as shown in Table 3 [24,26,27]; S_2 -TOC plots were used to reduce the matrix effect on HI [28]. For coaly organic matter, the onset of oil generation at T_{max} of about 420–430 °C and of efficient expulsion at about 430–440 °C were also considered [8].

Table 3. Criteria used for source-rock evaluation [24,26].

$T_{max}, ^\circ C$	Maturity	HI, mg HC/g TOC	Kerogen Type	S_2 , mg HC/g Rock	TOC, wt. %	Class
<435	Immature	>600	I	<2.5	<0.5	Poor
435–470	Oil window	300–600	II	2.5–5	0.5–1	Fair
>470	Gas window	200–300	II/III	5–10	1–2	Good
		50–200	III	10–20	2–4	Very good
		<50	IV	>20	>4	Excellent

3.3. Data Screening

T_{max} and PI were interpreted only where $S_2 \geq 0.5$ mg HC/g rock and $380 < T_{max} < 480$ °C [19,20,24]. In Well S, 472 of 752 samples passed this screening; values flagged -1 (36 samples) and T_{max} above 480 °C with near-zero S_2 (43 samples) were excluded. The number of screened samples in each stratigraphic unit is given in Table 4. In Well N, one sample (1657 m depth, T_{max} 336 °C) was excluded. A few depth labels in the Well S report are out of sequence and were used as reported.

Table 4. Rock-Eval results by stratigraphic unit: range (median). T_{max} is the median of screened samples ($S_2 \geq 0.5$ mg HC/g rock, 380–480 °C); n screened/ n total is given in brackets; “—”, no samples passed the screening.

PI	$T_{max}, ^\circ C$	HI, mg HC/g TOC	S_2 , mg HC/g	TOC, wt. %	n	Well, Unit (Depth, m)
0.20	— (0/1)	261	0.73	0.28	1	N, J3 (1657)
0.08	428 (6/6)	43–189 (142)	1.08–31.59 (4.95)	0.57–32.20 (5.81)	6	N, J2 (1687–1858)
0.12	430 (4/4)	144–213 (168)	2.09–4.03 (2.32)	1.17–2.79 (1.27)	4	N, J1 + T3 (1876–1975)
0.34	427 (5/24)	1–193 (39)	0.02–2.52 (0.33)	0.22–2.04 (0.79)	24	S, Paleogene (450–950)
0.32	419 (31/95)	0–166 (39)	0.01–1.28 (0.32)	0.22–2.58 (1.01)	95	S, K2 (950–1750)
0.32	425 (53/180)	0–293 (52)	0.01–2.10 (0.34)	0.06–4.40 (0.62)	180	S, K1 (1750–2920)

Table 4. Cont.

PI	T _{max} , °C	HI, mg HC/g TOC	S ₂ , mg HC/g	TOC, wt.%	n	Well, Unit (Depth, m)
0.27	428 (84/92)	4–441 (119)	0.09–13.76 (0.91)	0.31–3.12 (0.89)	92	S, J3 (2920–3242)
0.23	432 (171/199)	6–284 (115)	0.12–8.34 (1.16)	0.29–5.95 (1.06)	199	S, J2 (3242–4010)
0.29	408 (107/133)	15–283 (111)	0.19–2.02 (0.68)	0.12–1.78 (0.65)	133	S, J1 (4010–4420)
0.30	406 (21/29)	13–201 (114)	0.22–1.49 (0.82)	0.47–1.75 (0.77)	29	S, T (4420–4688)

3.4. Burial-History Reconstruction

One-dimensional burial histories were constructed from the formation tops in Table 1 and the chronostratigraphic ages of the units [29], assuming continuous deposition within each unit and no erosion, as indicated by the regional subsidence history [4]. Decompaction was not applied, so the curves show present-day thicknesses projected back in time and give minimum burial rates for older intervals. Present-day temperatures were estimated from the regional geothermal gradient of the Kosbulak depression (30–36.6 °C/km) [4].

4. Results

4.1. Organic Richness and Generation Potential

Rock-Eval results by stratigraphic unit are summarised in Table 4 and Figure 3. In Well N, the Middle Jurassic (six samples) is organic-rich: TOC ranges from 0.57 to 32.2 wt.% (median 5.81 wt.%), including coal at 1855 m depth (TOC 32.2 wt.%, S₂ 31.59 mg HC/g rock) and carbonaceous shales at 1756, 1828 and 1858 m depth (TOC 4.17–9.48 wt.%). By S₂, its remaining generation potential ranges from poor to excellent (median 4.95 mg HC/g rock, fair). The Lower Jurassic–Upper Triassic (four samples) has TOC of 1.17–2.79 wt.% (good) and S₂ of 2.09–4.03 mg HC/g rock (poor to fair).

(a) Well N, northern flank

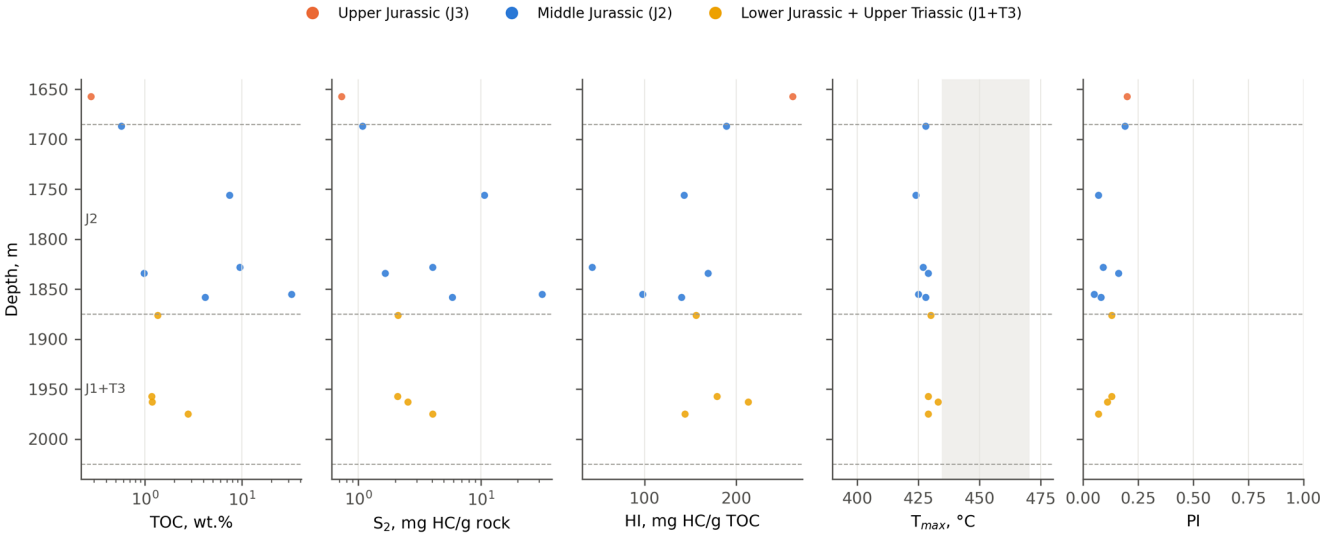


Figure 3. Cont.

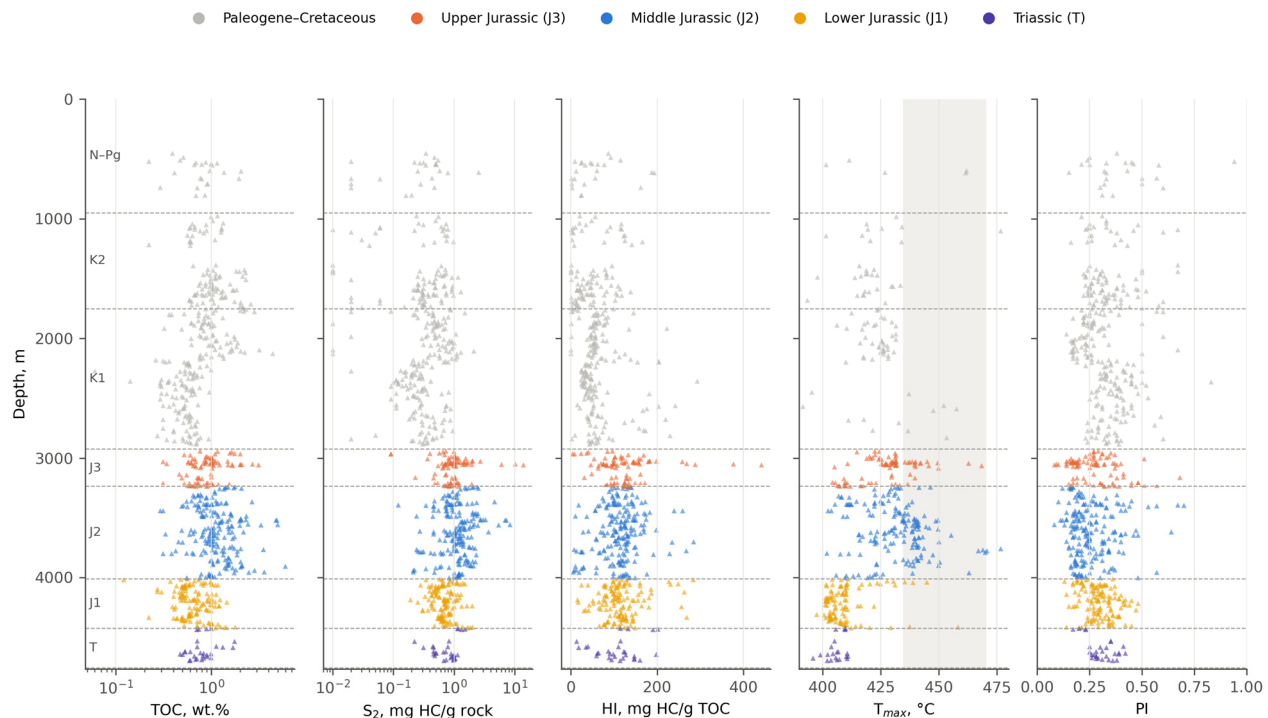
(b) Well S, south-western flank

Figure 3. Depth profiles of TOC, S_2 , HI, T_{max} and PI coloured by stratigraphic unit: (a) Well N; (b) Well S. Dashed lines are formation boundaries; the grey band on the T_{max} panel marks the oil window. T_{max} panels show screened samples only. Data from industry Rock-Eval reports; plotted by the authors.

In Well S, the Paleogene and Cretaceous are lean: median TOC is 0.62–1.01 wt.%, but S_2 is below 2.5 mg HC/g rock in all but one of 299 samples, so their generation potential is poor. The Middle Jurassic is the richest unit (median TOC 1.06 wt.%, median S_2 1.16 mg HC/g rock); 10 of 199 samples reach fair to good S_2 . The richest beds are coaly siltstones at 3522–3563 m depth (TOC 3.32–4.93 wt.%, S_2 5.41–8.34 mg HC/g rock, HI 146–169 mg HC/g TOC), which correspond to the cored coal-bearing interval. The highest TOC in this unit (5.95 wt.% at 3906 m depth) has S_2 of only 0.61 mg HC/g rock and HI of 10 mg HC/g TOC and represents inert or reworked organic matter. The highest S_2 in the well (13.76 mg HC/g rock, TOC 3.12 wt.%, HI 441 mg HC/g TOC) occurs at 3055 m depth in the Upper Jurassic, close to cored siltstones with hydrocarbon shows, so part of this S_2 may come from heavy migrated hydrocarbons. The Lower Jurassic and Triassic have median TOC of 0.65–0.77 wt.% and S_2 below 2.1 mg HC/g rock in all samples.

4.2. Kerogen Type

In both wells, the Jurassic plots mainly in the Type III field (HI 50–200 mg HC/g TOC), with a minor Type II/III tail (Figures 4 and 5). The Middle Jurassic has a median HI of 142 mg HC/g TOC in Well N and 115 mg HC/g TOC in Well S. On the S_2 -TOC plot, most Well N samples follow the HI 100–200 trend, and the coal at 1855 m depth falls near HI 100, typical of humic coals [8,9]. Only two Upper Jurassic samples in Well S, at 3048 and 3055 m depth, reach the Type II field. The Paleogene and Cretaceous of Well S have median HI of 39–52 mg HC/g TOC and are effectively inert (Type III–IV).

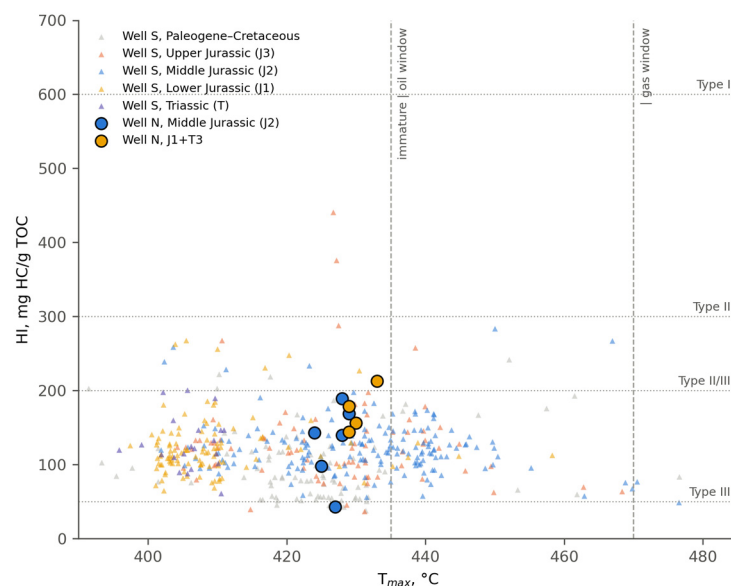


Figure 4. HI versus $T_{\max}$ diagram by well and stratigraphic unit (screened samples). Data from industry Rock-Eval reports; plotted by the authors.

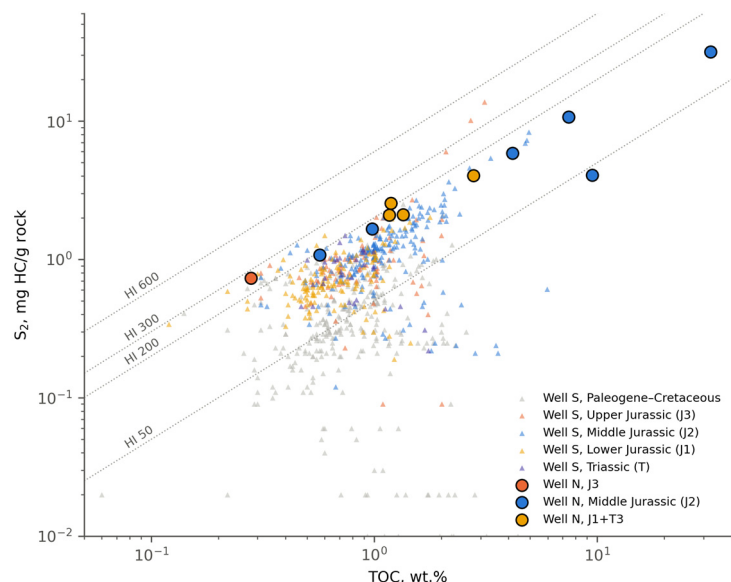


Figure 5. S_2 versus TOC with HI isolines, by well and stratigraphic unit. Data from industry Rock-Eval reports; plotted by the authors.

4.3. Thermal Maturity

In Well N, $T_{\max}$ of the Middle Jurassic is 424–429 °C and that of the Lower Jurassic–Upper Triassic 429–433 °C; PI is 0.05–0.19. Measured vitrinite reflectance is 0.43% at 1855 m depth (Middle Jurassic) and 0.44% at 1930 m depth (Lower Jurassic–Upper Triassic). Both indicators show that the Jurassic in Well N is immature. In Well S, the median $T_{\max}$ of screened samples increases from 419–428 °C in the Cretaceous and Upper Jurassic to 432 °C in the Middle Jurassic; the richest Middle Jurassic beds at 3522–3563 m depth, where S_2 is high and $T_{\max}$ most reliable, have $T_{\max}$ of 435–441 °C (calculated Ro 0.67–0.78%), i.e., the onset of the oil window. In the Lower Jurassic and Triassic, the median $T_{\max}$ falls to 408 and 406 °C, while PI remains 0.29–0.30 (Figure 6).

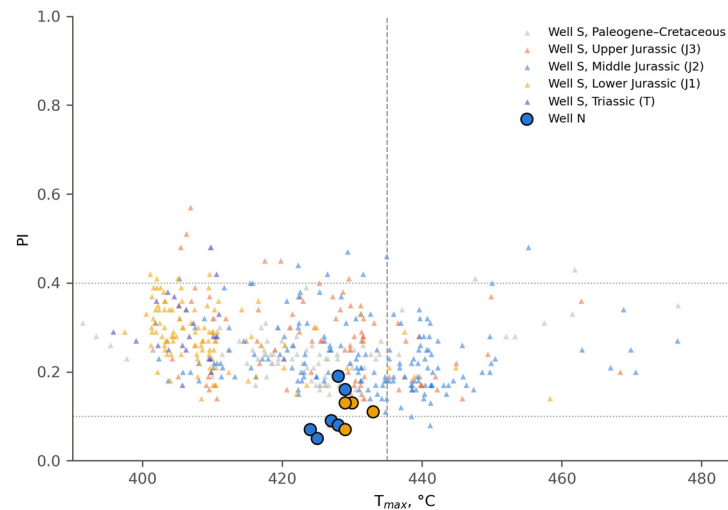


Figure 6. Production index versus T_{max} by well and stratigraphic unit (screened samples). The dashed vertical line marks 435 °C (onset of the oil window); the dotted lines mark $PI = 0.1$ and 0.4 . Data from industry Rock-Eval reports; plotted by the authors.

4.4. Burial History

Both wells show continuous burial since the Jurassic (Figure 7). In Well N, the base of the Middle Jurassic reached about 1.6 km depth by the end of the Cretaceous and lies at 1.9 km depth today. In Well S, the base of the Middle Jurassic reached about 3.1 km depth by the end of the Cretaceous and was buried by a further 0.95 km during the Cenozoic, about half of it in the Oligocene, to its present depth of 4.0 km. Using the regional present-day gradient, the Middle Jurassic of Well N is at about 70–75 °C today, whereas that of Well S is at about 120–160 °C.

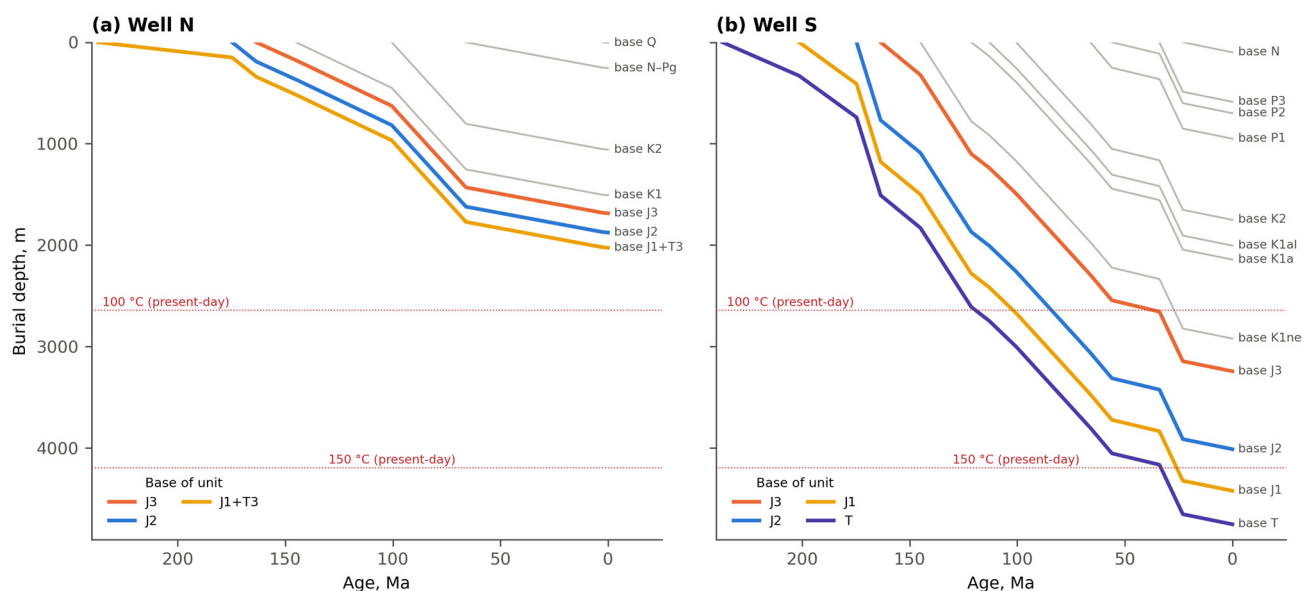


Figure 7. One-dimensional burial histories (without decompaction) of (a) Well N and (b) Well S, based on formation tops (Table 1) and chronostratigraphic ages [29]. Dotted lines show present-day isotherms for a gradient of 32.2 °C/km [4]. Plotted by the authors.

5. Discussion

5.1. Comparison of Equivalent Stratigraphic Units

Because the two datasets differ in sample number and depth range, they were not treated as statistically equivalent populations. Instead, the comparison was restricted to

the same stratigraphic units, mainly the Middle Jurassic, which was sampled in both wells and is the main regional source interval [1,4]. Each well represents one location on its flank, so the results describe local conditions rather than the whole northern or south-western part of the trough.

The Middle Jurassic shows a trade-off between richness and maturity. On the northern flank (Well N), it contains coal and carbonaceous shale with high TOC and S_2 but is immature at 1.7–1.9 km depth (T_{max} 424–429 °C, Ro 0.43%). For coaly organic matter, this corresponds to the very beginning of oil generation, before efficient expulsion [8], and the low PI (median 0.08) agrees with this. On the south-western flank (Well S), the Middle Jurassic lies about 1.5–2.1 km deeper (3.2–4.0 km depth), is thicker (768 m vs. 190 m) and leaner, but its coaly beds have reached the onset of the oil window. In both wells, the kerogen is dominantly gas-prone, in line with the regional view of continental coaly Middle Jurassic sources [1,4] and with Jurassic coal-bearing analogues in Central Asia [7,13]. The lower richness in Well S may reflect a more distal or more diluted depositional setting; facies analysis of the Middle Jurassic in both wells is needed to test this.

5.2. Low T_{max} in the Lower Jurassic and Triassic of Well S

In a continuously buried section, T_{max} should not decrease with depth, yet in Well S the median T_{max} drops from 432 °C in the Middle Jurassic to 408 °C in the Lower Jurassic and 406 °C in the Triassic. Three factors likely act together. First, the samples are unwashed cuttings drilled with OBM; contamination adds a low-temperature shoulder to the S_2 peak and lowers T_{max} , while raising S_1 and reducing S_2 [17]. Second, cores from 4057–4075 m depth are sandstones saturated with bituminous material and show strong natural fluorescence, indicating migrated hydrocarbons; heavy hydrocarbons and bitumen are a known cause of T_{max} suppression [18]. Third, median S_2 below 4010 m depth is only 0.68–0.82 mg HC/g rock, close to the threshold below which T_{max} becomes unreliable [19,24]. The elevated PI of 0.29–0.30 in these units is also consistent with added free hydrocarbons. The low T_{max} values below 4010 m depth are therefore treated as analytical minima rather than as evidence of decreasing maturity, although 107 of 133 Lower Jurassic samples passed the screening and the data quality remains the weakest in the well.

5.3. Comparison with Measured and Regional Vitrinite Reflectance

Vitrinite reflectance is a more robust maturity indicator than T_{max} in contaminated cuttings [30], and kinetic models show that it integrates the full time-temperature history of burial [31,32]. In Well N, measured vitrinite reflectance (0.43–0.44%) agrees with T_{max} (424–433 °C) and confirms that the Jurassic on the northern flank is immature. No vitrinite reflectance data are available for Well S, so its maturity is assessed from T_{max} of the rich, high- S_2 beds and is compared with regional data, which do not come from Well S itself. More than 1200 vitrinite reflectance measurements are available for the North Ustyurt sedimentary cover [4]. Across the basin, Ro of the Jurassic and Upper Triassic increases from 0.6–0.7% at 2500 m depth to 1.0–1.1% at 4000 m depth [4]. In the Kosbulak depression, the vitrinite reflectance gradient is 7.5–11.4‰ Ra per km, the palaeogeothermal gradient 37.5–44 °C/km and the present-day geothermal gradient 30–36.6 °C/km [4]. Ra denotes reflectance measured in air and expressed in per mille, as used in the regional studies; it is higher than reflectance in oil immersion (Ro) for the same vitrinite.

At the base of the Middle Jurassic (3750–4100 m depth), palaeotemperatures rise from 160–175 °C on the north-western flank of the depression to about 190 °C on its southern flank [4,5], and present-day formation temperatures at 3700–4100 m depth in the south-western part of the depression are 155–175 °C [4,5]. These regional data support the interpretation that the Middle Jurassic of Well S is in the oil window and that the Lower

Jurassic below 4010 m depth is at least as mature. North-west of the depression, Jurassic vitrinite at 2300–2400 m depth has R_a of 65% (i.e., 6.5% reflectance in air), corresponding to the brown-coal stage of coalification, with a present formation temperature of 72 °C [4,5]. This regional value is consistent with the R_o of 0.43–0.44% measured in Well N.

5.4. Implications for Exploration

The burial histories (Figure 7) show that the Middle Jurassic of Well S reached its present depth only during the Cenozoic, so hydrocarbon generation on the south-western flank is likely to be young, in agreement with the Tertiary generation proposed for the basin [1]. The trough axis, where the base of the Jurassic lies at about −4.6 km, was not sampled in this study; by analogy with Well S and regional palaeotemperatures of 175–200 °C at the base of the Middle Jurassic [4,5], we suggest that it is the most probable gas-prone generation area, with possible condensate. The immature but rich Middle Jurassic of the northern flank would act as a source only where it is buried deeper toward the trough, so charge to northern-flank traps would rely on lateral migration. The Paleogene of the Kosbulak Trough may also have generation potential, which is relevant to the Paleogene clinoform gas reservoirs mapped in the region [4,6].

5.5. Limitations

Well N is represented by only 11 samples, compared with 752 in Well S, so its statistics are less robust. All pyrolysis data come from cuttings, and the two wells were analysed on different instruments. Vitrinite reflectance was measured only in Well N; maturity in Well S relies on T_{max} and regional data. The burial histories are not decompacted and do not include a calibrated thermal model. No biomarker or extract data were available to correlate the source rocks with oils and gases of the region [33].

6. Conclusions

Measured results:

- In Well N (northern flank), the Middle Jurassic at 1685–1875 m depth is coal-bearing and organic-rich (median TOC 5.81 wt.%, up to 32.2 wt.%), with gas-prone Type III kerogen (HI 43–189 mg HC/g TOC).
- In Well N, T_{max} of 424–433 °C and measured R_o of 0.43–0.44% show that the Jurassic is thermally immature.
- In Well S (south-western flank), the Middle Jurassic at 3242–4010 m depth is leaner (median TOC 1.06 wt.%, median S_2 1.16 mg HC/g rock), with Type III kerogen; its richest coaly beds (3522–3563 m depth) have T_{max} of 435–441 °C.
- In Well S, the Paleogene and Cretaceous have poor generation potential ($S_2 < 2.5$ mg HC/g rock in 298 of 299 samples).
- In Well S, median T_{max} decreases to 406–408 °C below 4010 m depth, where cores show bitumen-saturated sandstones.

Interpretation:

- The Middle Jurassic is richer but immature on the northern flank and leaner but at the onset of the oil window on the deeper south-western flank.
- The low T_{max} below 4010 m depth in Well S most likely reflects OBM contamination, bitumen impregnation and low S_2 rather than decreasing maturity; regional vitrinite reflectance and palaeotemperature data support this, but direct R_o measurements in Well S are needed to confirm it.
- The unsampled axial part of the trough is suggested as the most probable gas-prone generation area; this hypothesis should be tested by wells or basin modelling.

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