

Article

Characteristics and Exploration Potential Evaluation of Lower Cambrian Source Rocks in the Southern Keping Area, Tarim Basin

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Abstract

Despite recent Cambrian subsalt gas discoveries in the Keping fault-uplift, northwestern Tarim Basin, organic abundance, type, maturity, and depositional setting of Lower Cambrian source rocks remain poorly documented. We evaluated the Yuertusi and Lower Xiaerbulake Formations using total organic carbon (TOC) analysis, Rock-Eval pyrolysis, kerogen microscopy, solid bitumen reflectance, X-ray diffraction, and ICP-MS trace-element analysis of samples from 11 wells and 6 outcrops. The Yuertusi Formation is organic-rich in northern Keping (TOC = 0.13–28.20%) but thins and deteriorates southward. The Lower Xiaerbulake Formation (TOC = 0.10–9.68%; 70–160 m thick) is a widespread, moderate-to-good source rock, challenging the view that the Yuertusi Formation is the only Cambrian source rock. Sapropelinite-dominated kerogen (>80%) indicates Type I–II organic matter; equivalent vitrinite reflectance (2.28–3.50%) confirms overmature, gas-prone rocks. The Yuertusi Formation reflects upwelling-fed high productivity and anoxic–euxinic waters; the Lower Xiaerbulake Formation, moderately high productivity and dysoxic waters. The subsalt gas is oil-cracked gas from marine sapropelic source rocks of either formation. Chloroform bitumen “A” estimates give in-place gas resources of $1121.4 \times 10^9 \text{ m}^3$; the static share for southern Keping ($20.1 \times 10^9 \text{ m}^3$) understates its dynamic potential. A lower-generation/upper-reservoir, fault-controlled, near-source model favors Trap 1-1 for future drilling.

Keywords: Lower Cambrian; source rock; organic geochemistry; exploration potential; southern Keping area; Tarim Basin



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1. Introduction

1.1. Research Background and Significance

Hydrocarbon resources hosted in ancient deeply buried marine carbonate strata represent a current frontier of global petroleum exploration. As conventional reserves at shallow and intermediate depths decline, exploration targets are extending into deep strata (burial depths > 4500 m). The Cambrian (ca. 541–485 Ma) was the period of the Cambrian Explosion of life. Planktonic organisms and algae (including cyanobacteria and other microbes) flourished in the oceans, and large quantities of organic matter were

deposited on the seafloor. Under specific tectono-sedimentary settings, such as passive continental margins, rifts, and intra-cratonic depressions, this organic matter formed multiple marine source-rock successions of regional significance [1–5]. These source rocks have undergone hundreds of millions of years of geological evolution, and their organic matter is highly mature, with vitrinite reflectance (R_o) values mostly exceeding 2.0%, corresponding to the overmature stage. For reference, $R_o < 0.5\%$ indicates the immature stage, and R_o of 0.5–1.3% indicates the mature oil-generation stage, during which liquid petroleum is the main product. At such high maturity, the kerogen and the liquid hydrocarbons generated earlier have been largely cracked, so that gas is the main product. These rocks therefore constitute an important source for deep gas accumulations. Large gas and oil fields have been discovered in Lower Cambrian strata in the Oman Basin, the Siberian Basin, and the Middle East, demonstrating the exploration potential of this stratigraphic interval [6–10].

The Tarim Basin, located in northwestern China, covers an area of approximately 560,000 km² and is the largest petroliferous basin in China. The basin contains thick Mesoproterozoic–Neoproterozoic to Paleozoic marine strata, in which the Cambrian succession exceeds 1000 m in thickness [11]. The Cambrian strata consist of carbonate rocks with interbedded fine-grained rocks such as black shale and siliceous rocks, and they form one of the oldest source-rock successions in the basin [12,13]. In recent years, advances in deep drilling technology have led to a series of breakthroughs in Cambrian subsalt exploration in the Tarim Basin. Well Zhongshen-1 in the northern Tarim Basin encountered hydrocarbon accumulations beneath the Cambrian salt, and Well Luntan-1 made a hydrocarbon discovery at a depth of 8882 m [14,15]. These discoveries confirm that ancient deep marine carbonate strata can host large oil and gas fields, and they have made the Cambrian subsalt a strategic target for reserve replacement in the Tarim Basin.

The Keping fault-uplift is located at the northwestern margin of the Tarim Basin. The term “fault-uplift” is used in Chinese petroleum geology to denote a first-order tectonic unit bounded by faults and uplifted over an extended period; it describes the position of the unit within the basin architecture rather than its deformation style. In terms of structural style, the Keping fault-uplift is a Cenozoic foreland fold-and-thrust belt. Deformation is dominated by thin-skinned thrusting along the Middle Cambrian gypsum-salt detachment, and the belt overrides the Bachu Uplift to the south. This style differs fundamentally from basement-involved thick-skinned uplifts of the Laramide type in North America and is closer to salt-related thin-skinned thrust belts [16,17]. The Keping fault-uplift is a first-order tectonic unit within the “five uplifts and five depressions” framework of the Paleozoic Tarim cratonic basin [12]. It borders the South Tianshan Mountains to the north, the Bachu Uplift to the south, the Awati Sag to the east, and the Kashi Sag to the west, and it covers an area of more than 20,000 km². The surface is characterized by high mountains and deep gullies, with elevations of 1500–2300 m. The climate is arid, vegetation is sparse, and access is difficult. Owing to these natural conditions and the difficulty of data acquisition, both exploration and research in this area remain at a low level. Nevertheless, previous studies have addressed outcrop stratigraphy and sedimentary facies [18–21] and regional structural characteristics [22] in the Keping area, providing a basis for the present work. Since 2018, petroleum industry reform in China has allowed companies such as Jingneng, Shenergy, and Boyuan to acquire exploration rights in the Keping area and to drill a number of wells. Well KT1(JN) tested a gas rate of 104.03×10^4 m³/d from the Cambrian Wusonggeer Formation, and Well BY1 tested 34.6×10^4 m³/d from the same formation. Well KPN1 achieved a successful ignition test in the Cambrian subsalt interval. These results provide the first confirmation of hydrocarbon accumulations in the previously unexplored Keping thrust belt. The Keping fault-uplift has accordingly become a focus of gas exploration

in the Tarim Basin. Proven geological reserves of 55.56 million tons of oil equivalent have been reported, and a 180 km long hydrocarbon enrichment zone has been identified, extending from the Wensu Bulge through the Shajingzi structural belt to the Keping thrust belt [22].

1.2. Scientific Problems and Controversies

Despite these exploration breakthroughs, a comprehensive evaluation of the Lower Cambrian source rocks in the Keping area is still lacking. Researchers disagree on the stratigraphic position of the principal source rocks [23–26], the lithological role of the Xiaoerbulake Formation [27–29], and the origin and source of the natural gas [14,15]. These disagreements limit the accuracy of resource assessments and the optimization of exploration deployment.

Controversy 1: Is the traditional understanding of the principal source-rock interval complete?

The black shale of the Lower Cambrian Yuertusi Formation has been widely regarded as the principal Cambrian source rock in the northwestern Tarim Basin. Based on evidence from siliceous rock geochemistry, depositional environments, and trace-element, iron-speciation, and Mo-isotope proxies, Sun et al. [23], Li et al. [24], Fang et al. [25], and Zhu et al. [26] demonstrated that this source rock is well developed in Well Luntan-1 in the northern Tarim Basin and in the central Tarim Basin, with TOC contents of 2–16% and thicknesses of 10–55 m. The kerogen is dominated by Type I–II₁, that is, sapropelic to humic-sapropelic kerogen. The source organisms were lower aquatic organisms such as algae (including cyanobacteria and other microbes), which are hydrogen-rich and have a high oil-generation potential [23–26]. In the Keping area, however, the Yuertusi Formation is thin and of poor quality [30–32]. During deposition of the Yuertusi Formation, a nearly E–W-trending paleo-land existed in the Bachu–Tazhong area, and the southern Keping area occupied a shallow-water platform along its northern margin [30,33]. Wells KPN1, KT1(CNPC), KT1(JN), and PT1 show that the formation is only 4–5 m thick and consists of brown mudstone. Its position near the paleo-land accounts for the oxidized color, and the TOC contents are low, indicating a limited hydrocarbon-generating potential. The contrast between high-rate gas flows and the weak source rock has raised doubts about whether the source rock is sufficient [22,31,34]. On the one hand, wells such as KPN1 confirm that the Yuertusi Formation is thin (4–5 m) and of poor quality in the Keping area, so the volume of hydrocarbons it could have generated is limited [32]. On the other hand, high-rate discoveries such as Well KT1(JN) ($104.03 \times 10^4 \text{ m}^3/\text{d}$) and Well BY1 ($34.6 \times 10^4 \text{ m}^3/\text{d}$), together with the reported proven geological reserves, require a hydrocarbon supply far greater than the local Yuertusi Formation could provide [22]. This raises the question of where the gas in the Keping area originated, that is, whether it was generated locally or migrated from external source areas. This contradiction is the direct motivation for re-evaluating the source-rock potential of the lower member of the Xiaoerbulake Formation.

Controversy 2: The lithological classification of the Xiaoerbulake Formation

The interpretation of the Xiaoerbulake Formation as a carbonate reservoir has been widely adopted, and it is also the basic hypothesis tested in this study. This interpretation originates from early reservoir-focused studies. Jiang et al. [27], Liu et al. [28], Song et al. [29], Zheng et al. [35–37], and Shen et al. [38] characterized the reservoir properties and origin of the formation in detail. However, almost all of their samples were taken from the upper member (Members 3 and 4), which hosts the main producing interval, whereas the lower member was rarely involved. Its hydrocarbon-generating potential has therefore remained unevaluated [27–29,31]. According to the Dunham (1962) [39] textural

classification of carbonate rocks, the upper member consists of dolomitized grainstone–packstone and microbial bindstone (stromatolites and thrombolites), in which dissolution pores, vugs, and fractures are well developed. The reservoir quality is correspondingly good. Porosity ranges from 0.87% to 6.25% (mean 3.18%), and the mean permeability is $1.64 \times 10^{-3} \mu\text{m}^2$. In the interval of very finely crystalline dolostone with relic grain texture, porosity reaches 3.48–22.49% (mean 10.77%) [33]. Well KPN1-recorded hydrocarbon shows in 25 layers in this formation and a successful ignition test [32]. In contrast, the lower member (Members 1 and 2) consists of lime mudstone and argillaceous limestone (mudstone–wackestone, locally dolomitized). Core-measured porosity is only 0.10–2.50%, and no fractures have been observed [31]. In Well KPN1, the neutron-density interpreted porosity is close to 0 in Member 1 and only 0.3–1.9% in Member 2 [32]. The rock is tight, has no reservoir capacity, and forms only a tight intraformational baffle bed, that is, a low-permeability interlayer that restricts fluid exchange between adjacent reservoir intervals rather than a regional seal. However, this argillaceous lithological association provides the material basis for source-rock development. Recent wells, including BY1, BY5, and KT1(JN), reveal that the lower member contains thick (70–160 m) grayish-black argillaceous limestone and argillaceous dolostone with abundant black organic-rich laminae. TOC contents range from 0.10% to 9.68% (mean 1.55%), meeting the criteria for moderate-to-good source rocks [31]. This finding directly challenges the conventional interpretation described above. However, the kerogen type, maturity, depositional environment, and hydrocarbon contribution of the lower member have not been comprehensively evaluated. Whether it can act as an effective source rock to support hydrocarbon accumulation remains to be answered.

Controversy 3: Multiple interpretations of the gas origin and charge timing

Charge timing refers to the geological age at which hydrocarbons entered a trap and formed a commercial accumulation. Geochemical analyses show that the natural gas in the Keping area has dryness coefficients exceeding 0.9977, light methane carbon isotopes ($\delta^{13}\text{C}_1 = -37.6\text{‰}$ to -35.9‰), ethane carbon isotopes ($\delta^{13}\text{C}_2$) of -36.4‰ to -32.9‰ , and methane hydrogen isotopes (δD_1) of -176.2‰ to -175.7‰ . According to the genetic classification scheme for natural gas in the Tarim Basin, in which $\delta^{13}\text{C}_2 = -28.0\text{‰}$ separates oil-type gas from coal-type gas and δD_1 distinguishes sapropelic from humic parent material, the gas exhibits the characteristics of marine sapropelic oil-type gas [40–44]. However, opinions differ on the genetic mechanism, that is, whether the gas was generated by direct kerogen cracking or by secondary cracking of oil, and on its specific source, that is, the Yuertusi Formation or the lower member of the Xiaoerbulake Formation. Deep exploration studies of Wells Zhongshen-1 and Luntan-1 in the northern Tarim Basin support the presence of oil-cracking gas beneath the Cambrian salt [14,15], whereas studies of gas origin in the central Tarim Basin distinguish between kerogen-cracking gas and oil-cracking gas [40,41]. Homogenization temperatures of fluid inclusions are concentrated in two intervals, 100–130 °C and 140–150 °C. If interpreted by the conventional temperature-based method, these temperatures may indicate accumulation during the Late Caledonian–Hercynian (Silurian–Permian, ca. 443–252 Ma) or during the Himalayan period (Cenozoic, from 66 Ma onward). However, thermal-history modeling of the source rocks in this area shows that R_o values during the Late Caledonian–Hercynian were only 0.7–1.0%, corresponding to the oil-generation stage, and that large-scale gas generation had not yet occurred. The main gas-generation stage should postdate the middle-to-late Hercynian (Carboniferous–Permian, ca. 359–252 Ma). This mismatch between fluid-inclusion temperatures and the thermal history makes the determination of the accumulation stage a focus of controversy, and it is directly related to the evaluation of hydrocarbon trapping conditions and exploration risk.

1.3. Previous Work and Key Advances

With respect to source-rock evaluation, Zhu et al. [45] investigated the geochemical characteristics and depositional environment of the Lower Cambrian Yuertusi Formation source rocks and demonstrated that their high organic-matter abundance is closely related to upwelling and anoxic conditions. Through sedimentary facies analysis and geochemical prediction, Xiong et al. [30] proposed that high-quality source rocks of the Yuertusi Formation are developed in the middle–lower ramp zone. A ramp is a facies-belt division of carbonate depositional systems. The middle–lower ramp zone refers to the paleogeographic belt located between the normal wave base and the storm wave base during the Early Cambrian. It is a subdivision of the depositional environment and is unrelated to present-day topography. The water in this zone was deep, and reducing conditions were better developed, favoring organic-matter enrichment. This zone extends in an E–W direction and provides a basis for regional source-rock prediction. Gao et al. [31] analyzed the characteristics of the Xiaerbulake Formation source rocks at the northwestern margin of the Tarim Basin, proposed for the first time that the formation is a potential source rock, and preliminarily revealed its organic-matter abundance and distribution.

With respect to reservoirs and seals, Zheng et al. [35–37] established a reservoir geological model for the Xiaerbulake Formation in the Keping outcrop area, identified favorable reservoir facies such as microbial boundstone buildups and shoal grainstones, and indicated that dissolution pores, vugs, and fractures constitute the main reservoir space. Liu et al. [32,46] evaluated the influence of the Cambrian gypsum-salt seals on the subsalt dolostone reservoirs and pointed out that the plastic deformation and sealing capacity of the gypsum-salt rocks are the key to hydrocarbon trapping. Shen et al. [38] investigated the characteristics, origin, and distribution of the Lower–Middle Cambrian dolostone reservoirs in the Tarim Basin, providing a theoretical framework for reservoir prediction.

With respect to accumulation models, Yi et al. [47] proposed a “rift–uplift–depression” framework controlling large subsalt gas provinces in the Tarim Basin. In this framework, “rift” refers to the aulacogens developed during the breakup of the Rodinia supercontinent in the Neoproterozoic–Early Cambrian and under the subsequent Early Paleozoic extensional setting; “uplift” refers to the intra-cratonic paleo-uplifts; and “depression” refers to the depressions. The aulacogens controlled the development of high-quality source rocks, the paleo-uplifts controlled the distribution of large reservoirs and traps, and the depressions provided the hydrocarbon-generation centers. The coupling of the three elements governed hydrocarbon generation, migration, and accumulation. Zheng et al. [48] analyzed the accumulation process of deep Cambrian hydrocarbons in the Bachu–northern Tarim area and indicated that faults and unconformities are the main migration pathways. Lv et al. [34] re-evaluated the exploration potential of the Keping area and confirmed the prospectivity of the Cambrian subsalt play.

Several limitations nevertheless remain in existing studies. First, most results are based on blocks within the basin interior, such as the Tazhong and northern Tarim areas. Owing to data scarcity, the Keping fault-uplift is only briefly mentioned in most regional studies or lies at the edge of the study area. Detailed analysis of this unit is lacking, and its actual geological conditions as a first-order tectonic unit have not been fully documented. Second, an integrated source rock–reservoir–seal evaluation has not been carried out in the Keping area. In particular, the potential of the lower member of the Xiaerbulake Formation as a source rock has long been overlooked. Third, resource assessments have largely relied on static volumetric calculations, without quantitative analysis of the dynamic process of hydrocarbon generation, migration, and accumulation. They therefore cannot explain how accumulations can form in areas where effective source

rocks are absent, a mechanism referred to in this paper as “external-source accumulation;” that is, hydrocarbons migrate through fault- and unconformity-controlled carrier systems and accumulate beyond the distribution area of effective source rocks. Fourth, the analysis in this study (Section 4.3.2) shows that fluid-inclusion homogenization temperatures (100–150 °C) may indicate accumulation during the Late Caledonian–Hercynian according to the conventional temperature-based interpretation, whereas thermal-history modeling of the source rocks shows that R_o values during that period were only 0.7–1.0%, corresponding to the oil-generation stage. These two independent lines of evidence give conflicting accumulation ages, leaving the determination of the accumulation stage ambiguous and unresolved.

1.4. Research Objectives and Main Contents

Based on analytical and test data from 11 wells and 6 outcrop sections in the southern Keping area and its surroundings, this study addresses a central scientific question: can the hydrocarbon supply of the Lower Cambrian source rocks in the Keping area account for the gas accumulations that have been discovered? Four testable hypotheses are proposed and evaluated in turn.

(1) Dual source-rock hypothesis.

The effective source rocks of the Lower Cambrian in the Keping area are not limited to the Yuertusi Formation. The argillaceous carbonate rocks of the lower member of the Xiaerbulake Formation possess the organic-matter abundance, thickness, and distribution required to act as an independent effective source rock. The contradiction of “insufficient source rock” can be explained by joint hydrocarbon supply from the two source-rock intervals. This hypothesis is tested using the TOC contents, Rock-Eval pyrolysis parameters, and distributions of the two intervals (Section 4.1).

(2) Joint productivity–preservation hypothesis.

Organic-matter enrichment in the two source-rock intervals was jointly controlled by high productivity and anoxic preservation conditions, but the dominant factor differs with depositional setting. The Yuertusi Formation was controlled by upwelling-driven high productivity and strongly reducing (anoxic–euxinic) conditions, whereas the lower member of the Xiaerbulake Formation was controlled by moderately high productivity within restricted depressions and dysoxic–weakly anoxic conditions. This hypothesis is tested through provenance discrimination using trace elements (Fe/Ti ratios, correlations between trace elements and Al_2O_3 , and XRD-based petrographic analysis), productivity proxies (Ba and Zn), and redox proxies (U–Mo covariation, Ni/Co, U/Th, and V/Al ratios) (Section 4.2).

(3) Two-stage accumulation hypothesis.

The subsalt Cambrian gas in the Keping area is oil-cracking gas, and accumulation occurred in two stages: early oil charging during the Late Caledonian–Hercynian and late gas charging during the Himalayan. The mismatch between fluid-inclusion homogenization temperatures and the modeled thermal history does not record a contradiction within a single accumulation event but rather the superposition of two charging events. This hypothesis is tested by jointly applying natural gas compositional and carbon–hydrogen isotope analyses, fluid-inclusion thermometry, and thermal-history modeling (Section 4.3).

(4) Migration–accumulation model hypothesis.

The southern Keping area is the terminal zone of hydrocarbon migration, and its resource potential is governed by an accumulation model of “lower generation and upper storage, fault-dominated migration, and near-source accumulation.” The dynamic migrated

resource is expected to exceed the local static resource, and Trap 1-1 in the north is the most favorable exploration target. This hypothesis is tested by comparing the static resource estimated by the chloroform bitumen “A” method with the dynamic resource estimated by the migration-ratio method, together with an integrated analysis of accumulation elements and trap conditions (Section 4.4).

2. Geological Setting

2.1. Regional Tectonic Framework and Evolution

The Keping fault-uplift is situated along the northwestern margin of the Tarim Basin and constitutes a first-order tectonic element within the basin’s “five uplifts and five depressions” framework. It is bounded to the north by the Wuqia–Aheqi fault against the South Tianshan, to the south by the Kepingtage fault from the Bachu Uplift, to the east by the Awati sag, and to the west by the Kashgar sag (Figure 1). The southern Keping area lies on the Aheqi bulge in the central segment of the Keping fault-uplift, extending 96 km east–west and 46 km north–south, with a total area of 2560.65 km². The region remains largely underexplored.

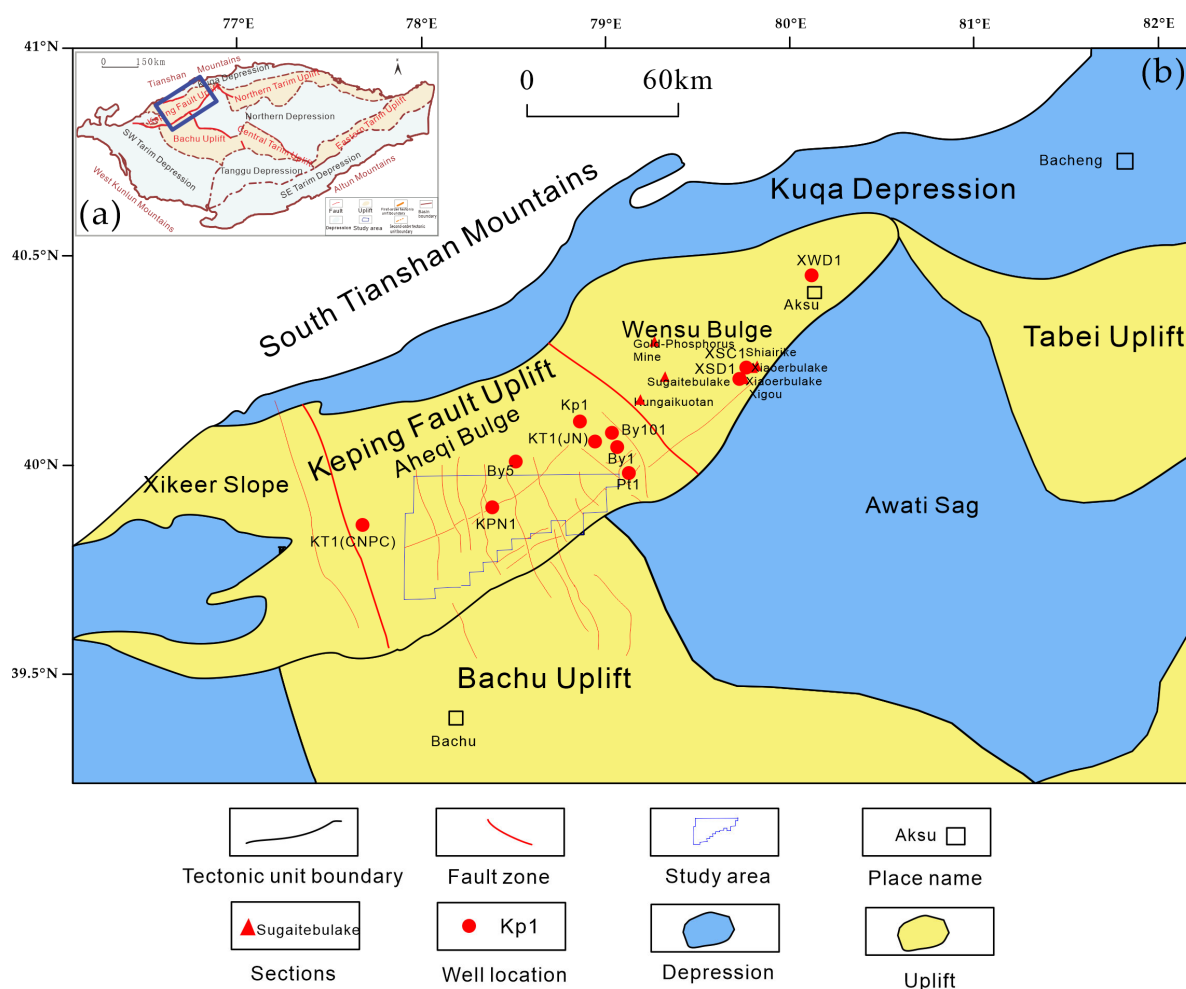


Figure 1. Tectonic location and data distribution of the southern Keping area. (a) Schematic tectonic map of the Tarim Basin, with the blue frame indicating the location of the Keping fault-uplift; (b) tectonic units of the Keping fault-uplift and adjacent areas, showing the distribution of wells and outcrop sections. Yellow denotes uplifts and blue denotes depressions and sags; solid red dots are the wells used in this study, red triangles are field outcrop sections, and the blue frame outlines the study area in southern Keping. The figure illustrates the tectonic position of the study area relative to the Bachu Uplift, Awati Sag, and South Tianshan Mountains.

The tectonic evolution of the Keping fault-uplift can be divided into four stages [49–55]. (1) Early–Late Paleozoic cratonic-margin stage (Cambrian–Permian, ca. 541–252 Ma; equivalent to the Caledonian–Hercynian in the Chinese tectonic-cycle scheme, as explained below). Cratonic-margin sedimentation prevailed, recording a transition from a passive continental margin to an active continental margin. (2) Late Hercynian continent–continent collisional orogeny (Late Permian, ca. 259–252 Ma). The South Tianshan remnant oceanic basin closed, north-to-south thrusting occurred, and the Keping thrust belt began to form. (3) Indosinian–Yanshanian stage (Mesozoic uplift stage; Triassic–Cretaceous, ca. 252–66 Ma). The Tarim plate collided with the Qiangtang block, the Keping area was uplifted, and Mesozoic strata are absent. (4) Middle–late Himalayan intracontinental compressional thrusting (middle–late Cenozoic, with the main deformation since the Neogene, ca. 23 Ma). The far-field effect of the India–Eurasia collision reactivated the South Tianshan. The Keping thrust system was emplaced over the Bachu Uplift along the Kepingtagh and other faults as thin-skinned thrust nappes, forming the present-day, nearly parallel rows of thrust-nappe mountains.

The tectonic-cycle terms “Caledonian,” “Hercynian,” “Indosinian–Yanshanian,” and “Himalayan” in this paper follow the conventional scheme used in the Chinese geological literature. In this scheme, the Caledonian covers the Cambrian–Silurian (ca. 541–419 Ma), and the Hercynian covers the Devonian–Permian (ca. 419–252 Ma). These time ranges are broader than the internationally accepted definition of the Caledonian orogeny (Silurian–Devonian, ca. 430–390 Ma). To avoid ambiguity, all specific tectonic events in this paper are labeled with absolute ages (Ma).

2.2. Lower Cambrian Stratigraphic Characteristics

The exposed strata in the Keping area are dominated by Paleozoic rocks. Mesozoic strata are absent, and the Cenozoic is represented by the Paleogene, Neogene, and Quaternary strata. The Cambrian strata are distributed in the Kalatieke Mountains and the Xiaerbulake area in the eastern part of the Keping area and along the southern slopes of the Kepingtagh and Yimgantawu mountains. They consist of marine carbonate rocks dominated by dolostone, with a phosphatic bed commonly present at the base. The Cambrian is approximately 1075 m thick and rests unconformably on the underlying Sinian Qigebak Formation [18–21]. Based on vertical lithological associations and paleontological characteristics, the Cambrian is divided into three series and six formations (Figure 2).

The Lower Cambrian includes three formations:

Yuertusi Formation (ϵ_1Y). The lithology consists of interbedded black shale and siliceous rocks. In the Xiaerbulake section, the lower part of the formation comprises interbedded light purple–red, medium- to thin-bedded mudstone and grayish-black, medium- to thin-bedded phosphatic siliceous rocks. The middle and upper parts comprise dark gray to gray, medium- to thick-bedded micritic limestone (equivalent to lime mudstone–wackestone of the Dunham classification) and dolostone, intercalated with black, yellowish-green, and purple–red shale. The formation yields abundant small shelly fossils (hyoliths, brachiopods, and gastropods) and acritarchs, and it is 26.4 m thick in this section. Drilling in the southern Keping area shows that the formation is only 4–5 m thick and consists of brown mudstone. Because this area lies closer to the platform interior (southeastward, toward the Bachu–Tazhong platform), the depositional water was shallower and more oxidizing, producing the oxidized color.

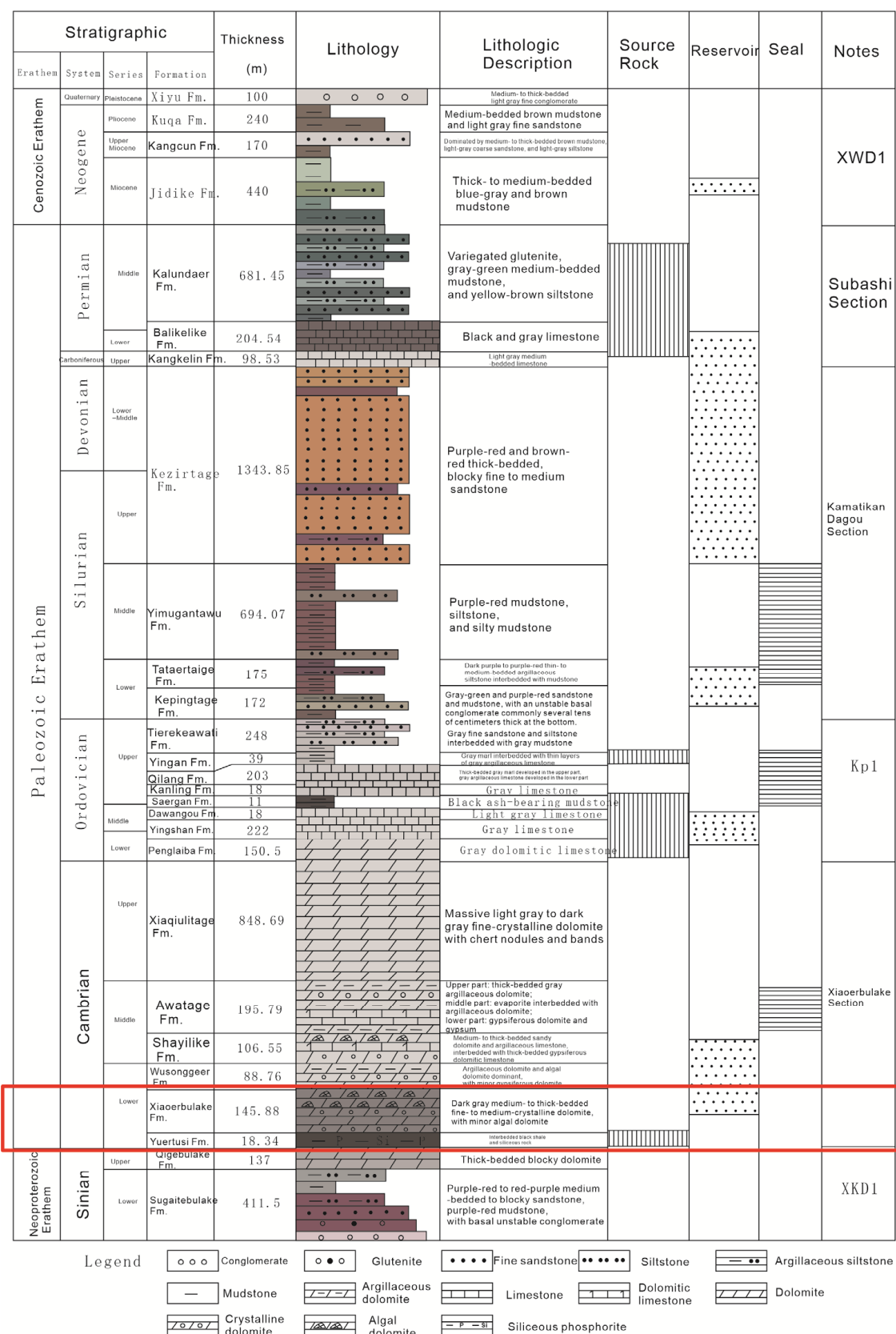


Figure 2. Integrated stratigraphic column in the Keping area, showing lithology and the vertical distribution of source rocks, reservoirs, and seals. The colors of the lithology column represent the actual colors of the corresponding strata. XWD1, KP1, and XKD1 are well names; Subashi, Kamatikan Dagou, and Xiaoerbulake are outcrop section names. The red frame highlights the target intervals of this study: the Yuertusi Formation and the Xiaoerbulake Formation.

Xiaoerbulake Formation (ϵ_1x). The formation consists of dark gray, medium- to thick-bedded dolostone with distinct vertical lithological variations. Rock types are classified following the Dunham (1962) textural classification of carbonate rocks, supplemented by the crystal-size classification of Sibley and Gregg (1987) [56] for rocks in which the original depositional texture has been altered. Based on lithological differences, the formation is divided into four members. Member 1 (ϵ_1x^1) consists of dolomitized lime mudstone with minor marlstone. In Well KPN1, the log-interpreted shale content averages 11.9% (locally reaching 64% in argillaceous interbeds), the gamma ray value ranges from 23 to 132 API (median 46 API), the deep laterolog resistivity ranges from 1998 to 10,540 $\Omega \cdot m$ (median 6207 $\Omega \cdot m$), and the interpreted porosity ranges from 0 to 1.4% (mean 0.37%). Member 2 (ϵ_1x^2) consists of dolomitized grainstone and dolomitized wackestone–grainstone, with grain contents of 10–80% (mean 50%). The shale content decreases to a mean of 4.5%, the gamma ray value ranges from 19 to 43 API (median 29 API), the resistivity ranges from 996 to 9220 $\Omega \cdot m$ (median 2578 $\Omega \cdot m$), and the interpreted porosity ranges from 0 to 1.9% (mean 0.95%), consistent with the published neutron porosity of 0.3–1.9% [32]. Member 3 (ϵ_1x^3) is fine- to medium-crystalline dolostone with well-developed dissolution pores, vugs, and fractures. The shale content averages 3.4%, the gamma ray value ranges from 12 to 24 API (median 20 API), the resistivity decreases to 12–114 $\Omega \cdot m$ (median 27 $\Omega \cdot m$), and the interpreted porosity ranges from 0 to 5.8% (mean 2.95%), making it the best reservoir interval of the formation. Member 4 (ϵ_1x^4) consists of calcimicrobial (cyanobacterial) intraclast grainstone with well-developed fractures. The gamma ray value ranges from 14 to 54 API (median 24 API), the resistivity varies over a wide range of 53–12,306 $\Omega \cdot m$, and the interpreted porosity ranges from 0 to 5.0% (mean 0.39%), reflecting the heterogeneity caused by alternating tight intervals and fractured intervals. The measured petrophysical data indicate that the upper member (Members 3 and 4) has a porosity of 0.87–22.49%, with a mean porosity of 3.18% and a mean permeability of $1.64 \times 10^{-3} \mu m^2$ in the grainstone; in the interval of very finely crystalline dolostone with relic grain texture, the mean porosity reaches 10.77% [33]. In contrast, the lower member (Members 1 and 2) is tight, with core-measured porosity of only 0.10–2.50% and no observed fractures [31].

Wusonggeer Formation (ϵ_1w). The lithology comprises argillaceous dolostone and stromatolitic bindstone (of microbial origin), with minor gypsiferous dolostone. The formation is one of the key producing intervals beneath the Cambrian salt, with dissolution pores, vugs, and fractures forming the reservoir space.

The Middle Cambrian includes the Shayilike Formation (ϵ_2s) and the Awatage Formation (ϵ_2a). These formations contain gypsum-salt rocks, drape over the Lower Cambrian gas-bearing intervals, and form a regional seal. The Shayilike Formation comprises medium- to very thick-bedded dolomitized intraclast grainstone and argillaceous limestone, intercalated with thick gypsiferous lime dolostone. The upper part of the Awatage Formation comprises thick-bedded gray argillaceous dolostone and stromatolitic bindstone interbedded with gypsiferous dolostone. The middle part comprises gypsum-salt rocks intercalated with argillaceous dolostone, and the lower part comprises gypsiferous dolostone, gypsum rock, and gypsum-salt rock. In the northern Keping block, the Middle Cambrian seal is 200–900 m thick and forms a high-quality reservoir–seal assemblage with the Lower Cambrian dolostone reservoirs.

The Upper Cambrian is represented by the Lower Qiulitage Formation (ϵ_3xq), which comprises grayish-white to dark gray, very finely to finely crystalline dolostone (Sibley and Gregg, 1987 [56]) with laminated fabric and common chert bands and nodules.

2.3. Sedimentary Evolution and Facies

During deposition of the Lower Cambrian, the Tarim Basin displayed a paleogeographic framework of uplift in the southwest and basin in the northeast. During deposition of the Yuertusi Formation (ca. 537–521 Ma), regional transgression occurred, and the Keping area showed a paleotopography that was high in the southwest and low in the northeast. The depositional system followed a ramp model, with platform, inner-ramp, mid-ramp, and outer-ramp to basinal facies developing in succession from south to north. Deposition of the Xiaoerbulake Formation (ca. 521–514 Ma) inherited this framework. As sea level fell, the basin evolved into a carbonate ramp environment, and from Member 2 onward, it transitioned into a rimmed carbonate platform. During deposition of the Wusonggeer Formation (ca. 514–509 Ma), sea level fell further, and a weakly rimmed carbonate platform developed, characterized by restricted-platform facies [33,57,58].

During deposition of the Yuertusi Formation, the southern Keping area occupied a shallow-water setting on the landward side of the carbonate platform, adjacent to the Bachu–Tazhong paleo-land. The water depth was less than 10 m. The formation is thin (only 4–5 m in wells) and has a limited hydrocarbon-generating potential. During deposition of the Xiaoerbulake Formation, syndepositional faulting uplifted the Wensu area to form the Wensu Bulge. A rimmed platform developed around the bulge. The baffling effect of microbial boundstone buildups along the platform margin created low-energy depressions within the platform interior, which favored the deposition of argillaceous limestone and the enrichment of organic matter [50,59].

3. Samples and Experimental Methods

3.1. Sample Collection and Sources

The samples in this study were collected from cores and cuttings of 11 wells and from outcrop samples of 6 field sections in the southern Keping area and its surroundings (Table 1). The wells include KPN1, BY1, BY5, KT1(JN), XSC1, KP1, KT1(CNPC), PT1, BY101, XSD1, and XWD1. The outcrop sections include the Kungaikuotan, Sugaitebulake, Gold-Phosphorus, Xiaoerbulake Xigou, Xiaoerbulake, and Shiairike sections. The sampling strategy followed four principles. (1) Well samples were taken from fresh cores and cuttings, avoiding weathered surfaces and contaminated intervals. (2) Outcrop samples were taken from fresh surfaces, avoiding weathering zones and fractured zones. (3) Sampling followed lithological variations, with denser sampling in source-rock intervals at spacings of 0.5–2 m. (4) Reservoir and seal samples were collected in coordination with the source-rock samples to establish a source–reservoir–seal stratigraphic framework.

Table 1. Basic information of wells and outcrop sections used in the evaluation of Lower Cambrian source rocks, southern Keping area.

No.	Well/Section	Type	Structural Position	Longitude (°E)	Latitude (°N)	Succession Involved	Number of Samples	Analyses Performed	Remarks
1	KPN1	Well	Aheqi Bulge	78.39	39.90	Є ₁ y, Є ₁ x	Yuertusi Fm.: 3; Lower Xiaoerbulake Fm.: 15	TOC; C–H isotopes of natural gas; well-log interpretation	Successful ignition in the Cambrian subsalt test; key well of the study area
2	BY1	Well	Aheqi Bulge	79.06	40.04	Є ₁ y, Є ₁ x	Yuertusi Fm.: 7; Lower Xiaoerbulake Fm.: 28; natural gas: 5	TOC; Rock-Eval pyrolysis; solid bitumen reflectance; ICP-MS major and trace elements; XRD; natural gas composition and C–H isotopes; fluid-inclusion microthermometry	Primary data well; tested gas production of 34.6×10^4 m ³ /d from the Wusongger Fm.
3	BY5	Well	Aheqi Bulge	78.51	40.01	Є ₁ y, Є ₁ x	Yuertusi Fm.: 4; Lower Xiaoerbulake Fm.: 10	Kerogen maceral identification; TOC	
4	KT1(JN)	Well	Aheqi Bulge	78.94	40.06	Є ₁ y, Є ₁ x, Є ₁ w	Yuertusi Fm.: 16; Lower Xiaoerbulake Fm.: 16; natural gas: 2	TOC; natural gas composition	Tested gas production of 104.03×10^4 m ³ /d from the Wusongger Fm.
5	XSC1	Well	Wensu Bulge	79.75	40.24	Є ₁ y, Є ₁ x	Yuertusi Fm.: 3; Lower Xiaoerbulake Fm.: 24	TOC; kerogen maceral identification	
6	KP1	Well	Aheqi Bulge	78.86	40.11	Є ₁ y, Є ₁ x	Yuertusi Fm.: 6; Lower Xiaoerbulake Fm.: 12	TOC; rock pyrolysis logging	Deepened well
7	KT1(CNPC)	Well	Western Aheqi Bulge	77.68	39.86	Є ₁ y	Yuertusi Fm.: 4	TOC	Drilling revealed that the Yuertusi Fm. is only 4–5 m thick
8	PT1	Well	Aheqi Bulge	79.12	39.98	Є ₁ y	Yuertusi Fm.: 3	TOC	Drilling revealed that the Yuertusi Fm. is only 4–5 m thick; the trap crest was not penetrated

Table 1. Cont.

No.	Well/Section	Type	Structural Position	Longitude (°E)	Latitude (°N)	Succession Involved	Number of Samples	Analyses Performed	Remarks
9	BY101	Well	Aheqi Bulge	79.03	40.08	Є ₁ y, Є ₁ x	Yuertusi Fm.: 5; Lower Xiaerbulake Fm.: 8	TOC; natural gas composition and C–H isotopes	Development well
10	XSD1	Well	Wensu Bulge	79.73	40.21	Є ₁ y, Є ₁ x	Yuertusi Fm.: 8; Lower Xiaerbulake Fm.: 15	TOC	
11	XWD1	Well	Northern margin of the Wensu Bulge	80.11	40.45	Є ₁ y, Є ₁ x	Yuertusi Fm.: 8; Lower Xiaerbulake Fm.: 15	TOC	
12	Kungaikuotan	Outcrop section	Keping fault-uplift	79.19	40.15	Є ₁ y	Yuertusi Fm.: 7	TOC; thin-section analysis	
13	Sugaitebulake	Outcrop section	Keping fault-uplift	79.32	40.21	Є ₁ x	Lower Xiaerbulake Fm.: 13	TOC	Mean TOC of the Lower Xiaerbulake Fm.: 2.00%
14	Gold-Phosphorus	Outcrop section	Keping fault-uplift	79.27	40.29	Є ₁ y	Yuertusi Fm.: 8	TOC; thin-section analysis	
15	Xiaoerbulake Xigou	Outcrop section	Keping fault-uplift	79.80	40.20	Є ₁ x	Lower Xiaerbulake Fm.: 23	TOC	Mean TOC of the Lower Xiaerbulake Fm.: 0.49%
16	Xiaoerbulake	Outcrop section	Keping fault-uplift	79.81	40.24	Є ₁ x	Lower Xiaerbulake Fm.: 6	TOC	Type section of the Xiaoerbulake Fm.
17	Shiairike	Outcrop section	Keping fault-uplift	79.81	40.27	Є ₁ y	Yuertusi Fm.: 7	TOC; thin-section analysis	

Є₁y, Yuertusi Formation; Є₁x, Xiaoerbulake Formation; Є₁w, Wusonggeer Formation. TOC, total organic carbon; XRD, X-ray diffraction; ICP-MS, inductively coupled plasma mass spectrometry; C–H isotopes, stable carbon and hydrogen isotopes. Coordinates are given in WGS-84 datum. “Lower Xiaerbulake Fm.” refers to the 1st and 2nd members of the Xiaoerbulake Formation. Wells are listed in order of data contribution to this study.

3.2. Analytical Methods

(1) Total organic carbon (TOC).

TOC contents were measured with a carbon–sulfur analyzer (Leco CS-230). In total, 32 analyses were performed. Samples were treated with dilute hydrochloric acid to remove inorganic carbon and were then combusted at high temperature to determine the organic carbon content.

(2) Rock-Eval pyrolysis.

Pyrolysis was conducted with a Rock-Eval 6 analyzer. In total, 36 analyses were performed. The measured parameters include free hydrocarbons (S1), hydrocarbons generated by kerogen cracking (S2), Tmax, and the hydrogen index (HI). These parameters were used to evaluate kerogen type and maturity.

(3) Vitrinite reflectance (Ro).

Reflectance was measured with a microphotometer. In total, 36 analyses were performed. Because vitrinite is scarce in marine carbonate rocks, equivalent vitrinite reflectance or bitumen-reflectance conversions were applied.

(4) Kerogen maceral identification.

Kerogen macerals were identified with a Leica microscope. Sapropelinite, exinite, vitrinite, and inertinite were distinguished, and the type index (TI) was calculated.

(5) Whole-rock X-ray diffraction (XRD).

Mineral compositions were analyzed by XRD. The analysis focused on the mineralogical characteristics of the Yuertusi and Xiaoerbulake formations, identifying barite, apatite, clay minerals, and siliceous minerals.

(6) Major and trace elements.

Trace elements were measured by inductively coupled plasma mass spectrometry (ICP-MS). In total, 33 analyses were performed. The analyzed elements include Ba, Zn, Cu, V, Ni, U, and Th, which were used to evaluate paleoproductivity and paleo-redox conditions.

(7) Natural gas composition and isotopes.

Gas compositions were analyzed by gas chromatography (GC). Stable-isotope mass spectrometry was used to measure the methane carbon isotope ($\delta^{13}\text{C}_1$), the ethane carbon isotope ($\delta^{13}\text{C}_2$), and the methane hydrogen isotope (δD_1).

(8) Fluid inclusions.

Calcite samples filling fractures were selected and prepared as thin sections. Inclusion morphology, color, and gas–liquid ratios were observed under the microscope, and homogenization temperatures were measured. In total, 25 analyses were performed.

3.3. Quality Control

The following quality-control measures were implemented during laboratory analysis: (1) National standard reference materials were inserted in each batch to monitor instrument stability. (2) Duplicate samples accounted for no less than 10% of the total to ensure data reproducibility. (3) Blank and parallel samples were used to calibrate TOC analyses. (4) Standard samples were run periodically to calibrate pyrolysis analyses. (5) International standard materials (NBS-19, VSMOW) were employed for isotopic calibration.

4. Results and Discussion

4.1. Characteristics of Source Rocks

4.1.1. Organic-Matter Abundance

Two potential source-rock intervals are developed in the Lower Cambrian of the study area: the Yuertusi Formation (ϵ_1y) and the lower member of the Xiaerbulake Formation (ϵ_1x^1). The Yuertusi Formation consists of grayish-black mudstone and siliceous mudstone and is a dark mudstone-type source rock. The lower member of the Xiaerbulake Formation consists of gray argillaceous limestone, grayish-black micritic limestone (lime mudstone), and gray very finely crystalline dolostone, and it is a carbonate source rock. The two intervals differ distinctly in lithology and therefore require different abundance criteria for evaluation. The classification criteria of organic-matter abundance adopted in this study (Table 2) are widely applied to the comparative evaluation of marine carbonate and mudstone source rocks (Gao et al., 2024) [31]. Table 3 summarizes the thickness and organic-matter abundance data of source rocks from typical wells and outcrop sections.

Table 2. Classification criteria of organic-matter abundance for source rocks.

Source-Rock Grade	Dark Mudstone/Shale TOC (%)	Carbonate Rock TOC (%)
Excellent	>2.0	>0.85
Good	1.5–2.0	0.65–0.85
Fair	1.0–1.5	0.45–0.65
Poor	0.5–1.0	0.25–0.45
Non-source rock	<0.5	<0.25

TOC, total organic carbon. The classification criteria are compiled from Gao et al. (2024) [31]. Separate thresholds are applied to mudstone/shale and carbonate source rocks; the lower TOC thresholds for carbonates account for the well-documented higher hydrocarbon-generating efficiency per unit TOC of marine carbonate source rocks.

Table 3. Thickness and TOC of source rocks from typical wells and outcrop sections along the northwestern margin of the Tarim Basin.

Well/Section	Interval	Top Depth (m)	Base Depth (m)	Thickness (m)	Lithology	TOC (%) (Min.–Max./Mean (n))
Well BY1	Lower Xiaerbulake Fm.	3869.00	3952.00	83.00	Gray argillaceous limestone	0.10–4.01/1.52 (28)
Well BY1	Yuertusi Fm.	3952.00	3956.00	4.00	Grayish-black mudstone	0.13–28.20/10.26 (7)
Well KT1(JN)	Lower Xiaerbulake Fm.	3843.00	3925.00	82.00	Grayish-black micritic limestone (lime mudstone)	0.60–5.00/2.39 (16)
Well KT1(JN)	Yuertusi Fm.	3925.00	3929.00	4.00	Grayish-black mudstone	0.60–5.00/4.30 (16)
Well KPN1	Lower Xiaerbulake Fm.	5245.00	5269.00	24.00	Gray argillaceous very finely crystalline dolostone	0.17–1.14/0.45 (15)
Well KPN1	Yuertusi Fm.	5269.00	5274.00	5.00	Brown dolomitic mudstone	0.26–2.02/0.85 (3)
Well XSC1	Lower Xiaerbulake Fm.	5013.00	5074.00	61.00	Gray dolomitic limestone	0.64–1.18/0.89 (24)

Table 3. Cont.

Well/Section	Interval	Top Depth (m)	Base Depth (m)	Thickness (m)	Lithology	TOC (%) (Min.–Max./ Mean (n))
Well XSC1	Yuertusi Fm.	5074.00	5110.00	36.00	Dark gray argillaceous limestone	2.10–2.40/2.20 (3)
Xiaoerbulake Xigou section	Lower Xiaoerbulake Fm.	—	—	—	Gray very finely crystalline dolostone	0.06–3.63/0.49 (23)
Sugaitebulake section	Lower Xiaoerbulake Fm.	—	—	—	Gray very finely crystalline dolostone	0.20–7.56/2.00 (13)
Xiaoerbulake section	Lower Xiaoerbulake Fm.	—	—	—	Gray very finely crystalline dolostone	0.19–3.69/1.47 (6)

TOC, total organic carbon. The “Lower Xiaoerbulake Fm.” refers to the lower member (1st and 2nd members) of the Xiaoerbulake Formation. TOC values are given as (minimum–maximum)/mean (number of samples, n). “—” indicates no data available (outcrop sections without well-depth information).

The source rocks of the Yuertusi Formation consist of grayish-black mudstone and siliceous mudstone and are evaluated against the criteria for dark mudstone (shale). The TOC contents of the formation range from 0.13% to 28.20%. In Well BY1, the TOC values of seven samples range from 0.13% to 28.20% (mean 10.26%). Two samples have TOC < 0.5% (28.6%) and are classified as non-source rocks. One sample has a TOC of 1.17% (14.3%) and is classified as a fair source rock. The remaining four samples have TOC > 2.0% (57.1%) and reach the excellent grade. In Well KT1(JN), the TOC values of 16 samples range from 0.60% to 5.00% (mean 4.30%). One sample has a TOC of 0.60% (6.3%) and is classified as a poor source rock. The other 15 samples have TOC > 2.0% (93.8%) and reach the excellent grade. In Well XSC1, the three samples have TOC values of 2.10–2.40% (mean 2.20%) and are also of excellent grade. The formation thins rapidly toward the southern Keping area and the platform interior, however. In Well KPN1, the TOC values of three samples range from 0.26% to 2.02% (mean 0.85%). Two of them have TOC < 0.5% (66.7%) and are non-source rocks, and the lithology consists of brown mudstone.

The source rocks of the lower member of the Xiaoerbulake Formation consist of gray argillaceous limestone, grayish-black micritic limestone (lime mudstone), and gray very finely crystalline dolostone, and they are evaluated against the criteria for carbonate rocks. In Well BY1, the TOC values of 28 samples range from 0.10% to 4.01% (mean 1.52%). Three samples have TOC < 0.25% (10.7%) and are non-source rocks. One sample has a TOC of 0.62% (3.6%) and is a fair source rock. Four samples have TOC values of 0.65–0.85% (14.3%) and are good source rocks. The remaining 20 samples have TOC > 0.85% (71.4%) and reach the excellent grade. In Well KT1(JN), the TOC values of 16 samples range from 0.60% to 5.00% (mean 2.39%). One sample has a TOC of 0.60% (6.3%) and is a fair source rock. The other 15 samples all have TOC > 0.85% and reach the excellent grade. In Well XSC1, the TOC values of 24 samples range from 0.64% to 1.18% (mean 0.89%). One sample has a TOC of 0.64% (4.2%) and is a fair source rock, and the rest are good-to-excellent source rocks. In Well KPN1, the TOC values of 15 samples range from 0.17% to 1.14% (mean 0.45%). Four samples have TOC < 0.25% (26.7%) and are non-source rocks, and the rest are poor-to-fair source rocks. Among the outcrop sections, the 13 samples from the Sugaitebulake section have a mean TOC of 2.00%, and all but one sample (0.20%) reach the excellent grade. The six samples from the Xiaoerbulake section have a mean TOC of 1.47%

and are also dominated by excellent source rocks. The 23 samples from the Xiaerbulake Xigou section have a mean TOC of 0.49% and are dominated by fair source rocks.

The TOC frequency distributions of the two source-rock intervals are shown in Figure 3. The TOC distribution of the Yuertusi Formation is right-skewed, with a large proportion of high-TOC samples (>2%). The TOC values of the lower member of the Xiaerbulake Formation are concentrated in the 0.5–2.0% interval, indicating a predominance of moderate-to-high abundance.

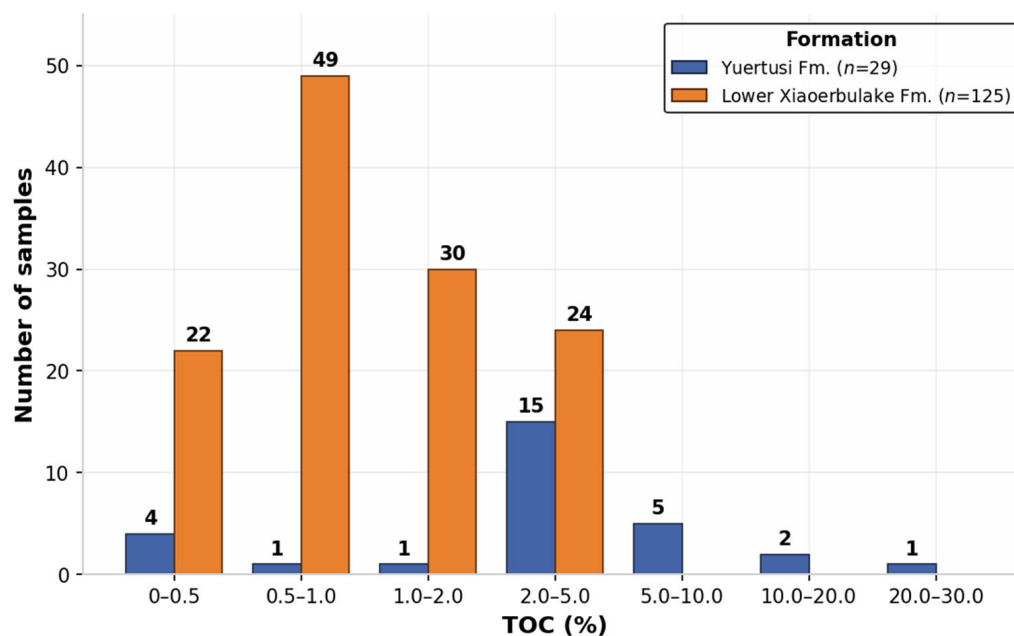


Figure 3. Histogram of TOC distribution in the Lower Cambrian source rocks from recently drilled wells along the northwestern margin of the Tarim Basin. Blue bars, Yuertusi Formation ($n = 29$); orange bars, Lower Xiaerbulake Formation ($n = 125$). Numbers above the bars indicate the sample count in each TOC interval.

Taken together, the two Lower Cambrian source-rock intervals in the study area differ in organic-matter abundance both vertically and laterally. The Yuertusi Formation shows high-to-very high abundance in the northern Keping area and the depression to the north. It thins and deteriorates toward the southern Keping area and the platform interior because of the more oxidizing environment and shallower water, displaying a pattern of higher abundance and greater thickness in the north than in the south. The lower member of the Xiaerbulake Formation is dominated by moderate-to-high abundance, but it is thick (70–160 m) and widely distributed (approximately 20,000–30,000 km²). Its cumulative organic-matter inventory may therefore exceed that of the thin but enriched Yuertusi Formation, making it the more practically significant effective source rock in the Keping area. This finding revises the conventional view that the Yuertusi Formation is the only Cambrian source rock in the northwestern Tarim Basin.

The petroleum generation potential ($S_1 + S_2$) is a supplementary indicator of organic-matter abundance. Two classification schemes, each with its own source and purpose, are used in this study. The classification in Table 2 is based solely on TOC and is used for rapid assessment of organic-matter abundance and well-to-well correlation; it follows Gao et al. (2024) [31], who apply lowered TOC thresholds for highly mature marine source rocks, particularly carbonates. Figure 4 employs the TOC versus ($S_1 + S_2$) diagram of Peters (1986) [60] for an integrated evaluation of the generation potential, and its grades (Poor/Fair/Good/Very good/Excellent) account for both organic-matter quantity and

pyrolysis-derived generative potential. The two schemes differ in the number and naming of grades. For example, “Very good” in the Peters scheme has no counterpart in Table 2. The schemes serve different purposes and are not used interchangeably, and the scheme underlying each classification statement is explicitly indicated in this paper. In Well BY1, the $S_1 + S_2$ values of the Lower Xiaerbulake samples range from 0.10 to 7.39 mg/g (mean 2.82 mg/g, $n = 28$), and those of the Yuertusi samples range from 2.25 to 2.94 mg/g (mean 2.58 mg/g, $n = 7$). Most samples plot in the poor-to-good range, indicating a moderate-to-good generation potential. TOC content alone, however, is not the only diagnostic indicator of source-rock potential. The hydrocarbon-generating capacity of organic matter also depends on its hydrogen content and thermal maturity. Table 4 lists the Rock-Eval pyrolysis results of the Lower Cambrian source rocks in Well BY1.

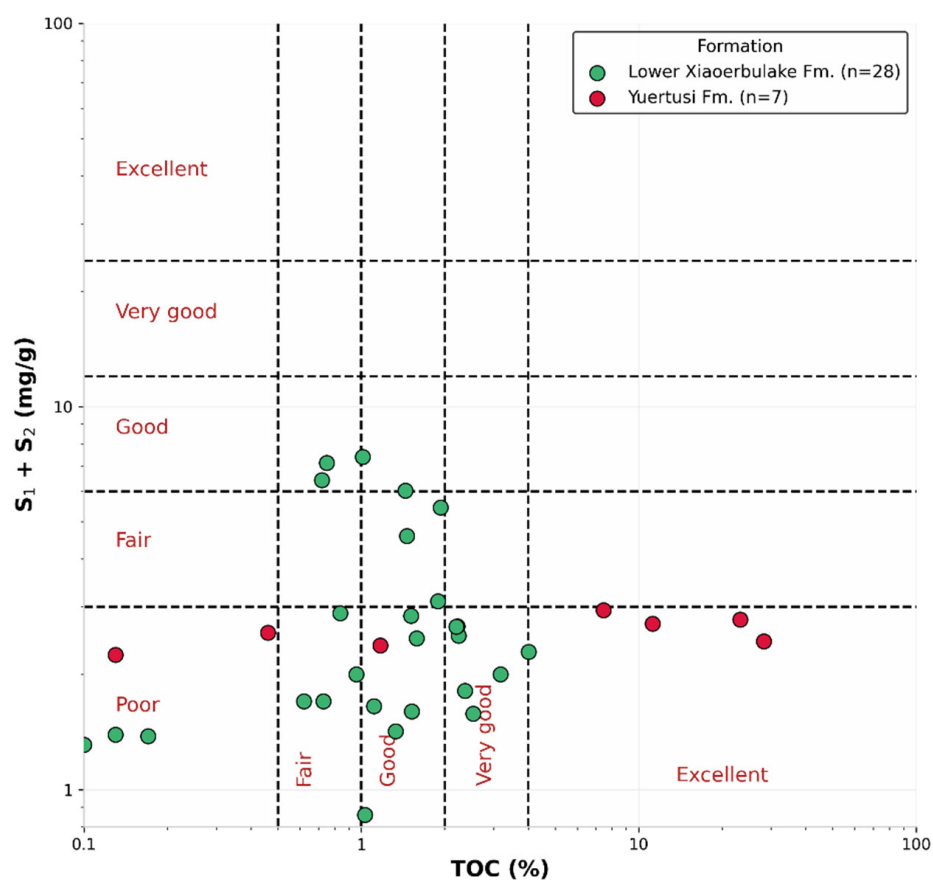


Figure 4. Cross-plot of total organic carbon (TOC) versus petroleum generation potential ($S_1 + S_2$) for the Lower Cambrian source rocks in Well BY1, with classification fields after Peters (1986) [60]. Green dots, Lower Xiaerbulake Formation ($n = 28$); red dots, Yuertusi Formation ($n = 7$).

Table 4. Rock-Eval pyrolysis results of the Lower Cambrian source rocks in Well BY1, northwestern margin of the Tarim Basin.

No.	Depth (m)	S_0 (mg/g)	S_1 (mg/g)	S_2 (mg/g)	T_{max} (°C)	$S_1 + S_2$ (mg/g)	PI	HI (mg HC/g TOC)	TOC (%)
ϵ_1x-1	3879.1	0.0227	3.9126	1.5405	468	5.45	0.72	79.82	1.93
ϵ_1x-2	3879.5	0.0235	3.1567	1.4358	548	4.59	0.69	98.34	1.46
ϵ_1x-3	3880	0.0186	5.9134	1.4742	473	7.39	0.80	145.96	1.01
ϵ_1x-4	3880.8	0.0165	4.9432	1.4765	493	6.42	0.77	205.07	0.72
ϵ_1x-5	3881.3	0.0233	0.7168	0.9860	484	1.70	0.42	159.03	0.62
ϵ_1x-6	3881.8	0.0258	0.6984	0.9530	474	1.65	0.42	85.86	1.11

Table 4. Cont.

No.	Depth (m)	S ₀ (mg/g)	S ₁ (mg/g)	S ₂ (mg/g)	T _{max} (°C)	S ₁ + S ₂ (mg/g)	PI	HI (mg HC/g TOC)	TOC (%)
Є ₁ x-7	3882	0.0253	3.8879	3.2404	481	7.13	0.55	432.05	0.75
Є ₁ x-8	3882.5	0.0211	3.1564	2.8764	473	6.03	0.52	199.75	1.44
Є ₁ x-9	3884.7	0.0172	0.0300	0.0677	465	0.10	0.31	2.33	2.91
Є ₁ x-10	3885.8	0.0239	0.7009	0.7171	473	1.42	0.49	53.92	1.33
Є ₁ x-11	3886	0.0252	0.7761	0.9217	485	1.70	0.46	126.26	0.73
Є ₁ x-12	3887	0.0174	0.8083	0.7893	482	1.60	0.51	51.93	1.52
Є ₁ x-13	3888	0.0179	0.0300	0.8334	471	0.86	0.03	80.91	1.03
Є ₁ x-14	3889	0.0171	0.7582	0.8259	472	1.58	0.48	32.64	2.53
Є ₁ x-15	3890	0.0193	0.9708	1.0321	470	2.00	0.48	107.51	0.96
Є ₁ x-16	3891	0.0249	1.5977	1.5046	483	3.10	0.52	79.61	1.89
Є ₁ x-17	3891.5	0.0346	1.3526	1.1246	474	2.48	0.55	71.18	1.58
Є ₁ x-18	3891.8	0.0375	1.4213	1.4213	474	2.84	0.50	94.13	1.51
Є ₁ x-19	3892.1	0.0256	0.6572	1.1554	475	1.81	0.36	48.96	2.36
Є ₁ x-20	3892.8	0.0245	0.7321	1.2634	548	2.00	0.37	39.85	3.17
Є ₁ x-21	3893.5	0.0197	0.7975	1.4947	458	2.29	0.35	37.27	4.01
Є ₁ x-22	3894	0.0235	0.9726	1.6996	549	2.67	0.36	76.56	2.22
Є ₁ x-23	3894.8	0.0253	0.9735	1.5435	462	2.52	0.39	68.91	2.24
Є ₁ x-24	3896.6	0.0232	1.1934	1.4616	460	2.66	0.45	66.44	2.20
Є ₁ x-25	3896.8	0.0324	1.6749	1.2176	482	2.89	0.58	144.95	0.84
Є ₁ x-26	3940.4	0.0232	0.6243	0.6866	486	1.31	0.48	686.60	0.10
Є ₁ x-27	3944.4	0.0225	0.7302	0.6494	451	1.38	0.53	382.00	0.17
Є ₁ x-28	3945.2	0.0242	0.6437	0.7434	448	1.39	0.46	571.85	0.13
Є ₁ y-1	3953.4	0.0196	0.2754	2.1643	548	2.44	0.11	7.67	28.20
Є ₁ y-2	3953.5	0.0186	0.2543	2.5214	549	2.78	0.09	10.87	23.20
Є ₁ y-3	3953.7	0.0285	0.2965	2.6436	548	2.94	0.10	35.39	7.47
Є ₁ y-4	3954	0.0275	0.2853	2.4286	466	2.71	0.11	21.68	11.20
Є ₁ y-5	3954.3	0.0180	0.2474	2.1375	455	2.38	0.10	182.69	1.17
Є ₁ y-6	3954.8	0.0140	0.2965	2.2742	458	2.57	0.12	494.39	0.46
Є ₁ y-7	3955.3	0.0200	0.4811	1.7700	458	2.25	0.21	1361.54	0.13

TOC, total organic carbon; S₀, thermally extracted gaseous hydrocarbons; S₁, free hydrocarbons; S₂, hydrocarbons generated by kerogen cracking; T_{max}, temperature at the maximum of the S₂ peak; PI, production index, S₁/(S₁ + S₂); HI, hydrogen index, S₂/TOC × 100. Sample numbers prefixed with Є₁x and Є₁y denote the Xiaerbulake and Yuertusi formations, respectively.

4.1.2. Kerogen Type

The type of organic matter determines the products of a source rock and is a key parameter in source-rock evaluation. The kerogen type of the Lower Cambrian source rocks in the study area was determined by combining Rock-Eval pyrolysis parameters (S₁, S₂, and HI) with kerogen maceral identification. Rock-Eval analysis of 35 samples from Well BY1 (Table 4) shows that S₂ ranges from 0.0677 to 3.2404 mg/g. Most samples ($n = 20$) have S₂ values below 1.5 mg/g, and the remaining 15 samples have S₂ values of 1.5–3.24 mg/g. The S₂ values of the Yuertusi Formation (Є₁y) samples range from 1.7700 to 2.6436 mg/g (mean 2.28 mg/g, $n = 7$), and those of the lower member of the Xiaerbulake Formation (Є₁x) range from 0.0677 to 3.2404 mg/g (mean 1.25 mg/g, $n = 28$). S₁ ranges from 0.0300 to 5.9134 mg/g. Most samples ($n = 22$) have S₁ values below 1.0 mg/g, and the remaining 13 samples have S₁ values of 1.0–5.91 mg/g, indicating higher free-hydrocarbon contents. The S₁ values of the Yuertusi Formation samples range from 0.2474 to 0.4811 mg/g (mean 0.31 mg/g, $n = 7$), and those of the Lower Xiaerbulake samples range from 0.0300 to 5.9134 mg/g (mean 1.57 mg/g, $n = 28$).

The S₁–TOC cross-plot (Figure 5) was used to determine the origin of the free hydrocarbons. Following the classical studies of Smith (1994, in Hunt, 1996) [61] and Peters (1986) [60], S₁/TOC values of 0.1 and 0.2 are the empirical thresholds for free-hydrocarbon

occurrence in mudstone and shale, and $S_1/TOC = 1.5$ is the threshold for identifying non-indigenous hydrocarbons. This standard was originally established for mudstone–shale systems and can be applied to low-TOC carbonate samples after lithological correction [62]. Most Yuertusi Formation samples (dark mudstone) plot in the indigenous-hydrocarbon field. Only sample ϵ_{1y-7} , with a low TOC of 0.13%, has a high S_1/TOC ratio of 3.70, which may reflect the influence of light oil or soluble organic matter. Its generation potential ($S_1 + S_2 = 2.25$ mg/g) and PI value (0.21), however, do not show the typical features of migrated-hydrocarbon contamination, and S_2 remains the main component. For the lower member of the Xiaerbulake Formation (carbonate rocks), calcite and dolomite have small specific surface areas, and their adsorption capacity for organic matter is far lower than that of clay minerals. The S_1/TOC ratios of this interval are therefore inherently high, and the mudstone thresholds of 0.1 and 0.2 are not applicable. Ten samples have $S_1/TOC > 1.5$, which may reflect lithology-related differences in free-hydrocarbon release or hydrocarbons filling microfractures. The other samples with moderate-to-high TOC are dominated by indigenous hydrocarbons. Two carbonate samples have very low S_1 values, reflecting extensive hydrocarbon expulsion and the loss of indigenous free hydrocarbons. From the perspective of Rock-Eval pyrolysis mechanisms, all samples exceeding $S_1/TOC = 1.5$ have S_2 values and total generation potentials within the normal range, with no anomalous trends. Light migrated hydrocarbons are completely released during the 300 °C isothermal S_1 stage and do not enter the kerogen-cracking stage. The samples show neither the concurrent increase in S_2 nor the depression of T_{max} that would result from solid bitumen contamination. The S_2 and HI values of all samples are therefore unaffected by external hydrocarbons and can serve as key parameters for kerogen-type evaluation.

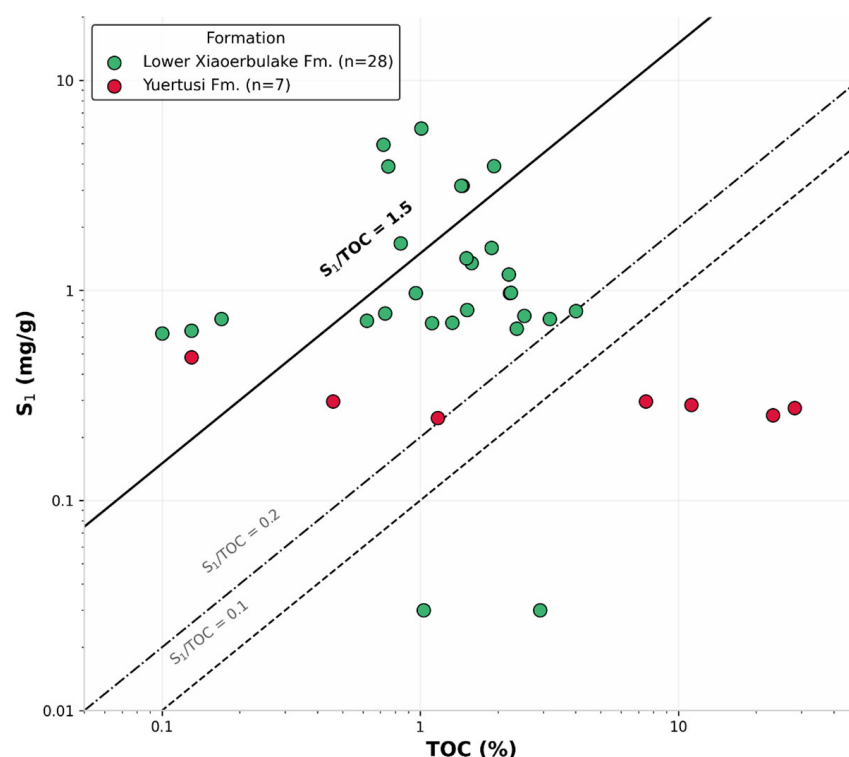


Figure 5. Cross-plot of free hydrocarbons (S_1) versus total organic carbon (TOC) for the Lower Cambrian source rocks in Well BY1. Green dots, Lower Xiaerbulake Formation ($n = 28$); red dots, Yuertusi Formation ($n = 7$). The dashed ($S_1/TOC = 0.1$) and dash-dotted ($S_1/TOC = 0.2$) lines denote the empirical thresholds of free-hydrocarbon enrichment for mudstone/shale; the solid line ($S_1/TOC = 1.5$) is the threshold for identifying non-indigenous (migrated) hydrocarbons.

The hydrogen index ($HI = S_2 \times 100/TOC$) is a key parameter for kerogen-type discrimination. The HI values of the samples from Well BY1 range from 2.33 to 1361.54 mg HC/g TOC. The HI values of the Yuertusi Formation samples range from 7.67 to 1361.54 mg HC/g TOC (mean 302.03 mg HC/g TOC), and those of the Lower Xiaoerbulake samples range from 2.33 to 686.60 mg HC/g TOC (mean 151.06 mg HC/g TOC). Four samples have TOC contents below 0.2% and anomalously high HI values, and they were excluded from kerogen-type discrimination. The S_2 –TOC cross-plot (Figure 6) and the HI–TOC cross-plot (Figure 7) show that most samples plot in the Type II/III transitional and Type III–IV fields. This pattern may be an artifact caused by maturity interference. Kerogen-type discrimination based solely on pyrolysis diagrams therefore has clear limitations. Previous studies have shown that the organic matter of Cambrian source rocks is highly mature, and the algae (including cyanobacteria and other microbes) have lost their fluorescence, making it difficult to identify the kerogen type by fluorescence microscopy [63]. Kerogen maceral composition is the key evidence that is unaffected by thermal maturity and directly reflects the kerogen type. The kerogen of the Lower Cambrian source rocks in Wells XSC1 (Figure 8) and BY5 (Figure 9) is dominated by sapropelinite, with contents exceeding 80%. Vitrinite and inertinite together account for less than 20%, and no exinite enrichment is observed. Sapropelinite is derived from lower aquatic organisms such as algae (including cyanobacteria and other microbes) and plankton, and it is a typical indicator of Type I–II kerogen. Vitrinite, in contrast, is derived from the lignin of higher plants and is the main component of Type III kerogen. During the Early Cambrian (ca. 541–485 Ma), land plants had not yet appeared, and higher plants flourished only from the Devonian onward [64]. There was therefore no material basis for large inputs of terrigenous organic matter during deposition, which rules out the development of primary Type III kerogen. Microscopic observations show abundant bioclasts in the dolostone of the Xiaoerbulake Formation, including trilobites, sponge spicules, ostracods, brachiopod fragments, and calcimicrobial (cyanobacterial) fragments. The abundant aquatic bioclasts are consistent with an aquatic origin of the organic matter in this interval. In addition, the ethane carbon isotope values of the natural gas are light, ranging from -36.4‰ to -32.9‰ (Table 5), which indirectly indicates a Type I–II parent material [65]. Integrating the Rock-Eval pyrolysis parameters, kerogen maceral composition, sedimentary lithofacies, and biological evolution, the primary kerogen type of the Lower Cambrian source rocks in the Keping area is Type I–II. The low HI values and Type II/III distribution shown by the pyrolysis diagrams are secondary features produced by high thermal maturity.

Table 5. Carbon and hydrogen isotope compositions of natural gases from wells in the Keping fault-uplift.

Sample	Formation	$\delta^{13}\text{C}$ (‰, VPDB)						δD (‰, VSMOW)		
		C ₁	C ₂	C ₃	iC ₄	nC ₄	CO ₂	δD_1	δD_2	δD_3
KPN1	Xiaoerbulake	−37.6	−34.7	−28.1	−25.9	−25.7	−0.3	—	—	—
KPN1	Wusonggeer	−35.2	—	—	—	—	−2.7	—	—	—
BY1-9	—	−36.3	−36.4	—	—	—	−3.3	−175.7	—	—
BY1-5	—	−35.9	−32.9	—	—	—	—	−176.2	—	—

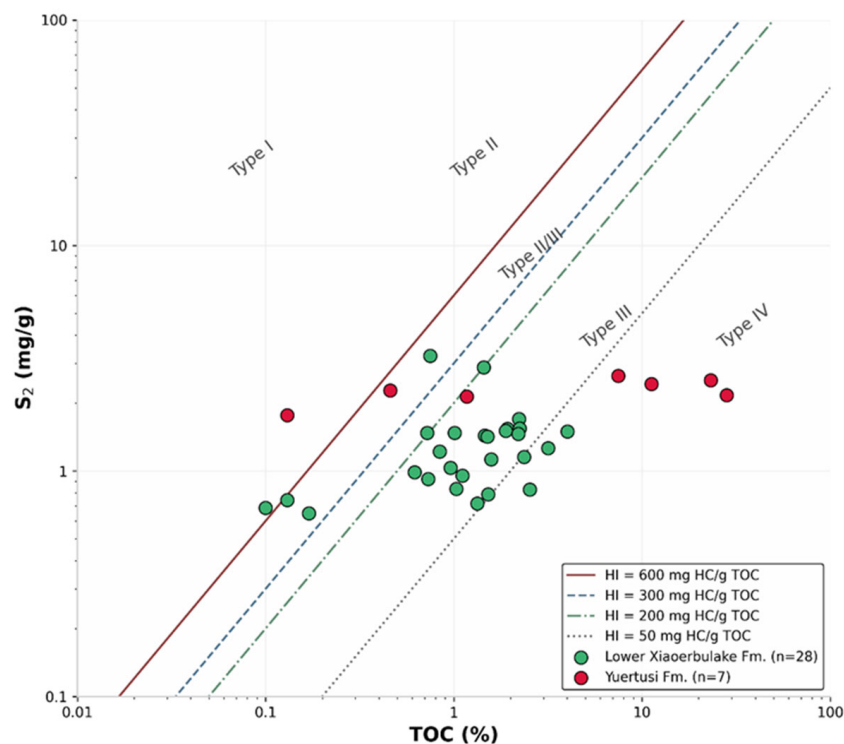


Figure 6. Cross-plot of S_2 versus total organic carbon (TOC) for the Lower Cambrian source rocks in Well BY1, with hydrogen index (HI) isolines of 600, 300, 200, and 50 mg HC/g TOC separating the kerogen-type fields (Type I to Type IV). Green dots, Lower Xiaerbulake Formation ($n = 28$); red dots, Yuertusi Formation ($n = 7$).

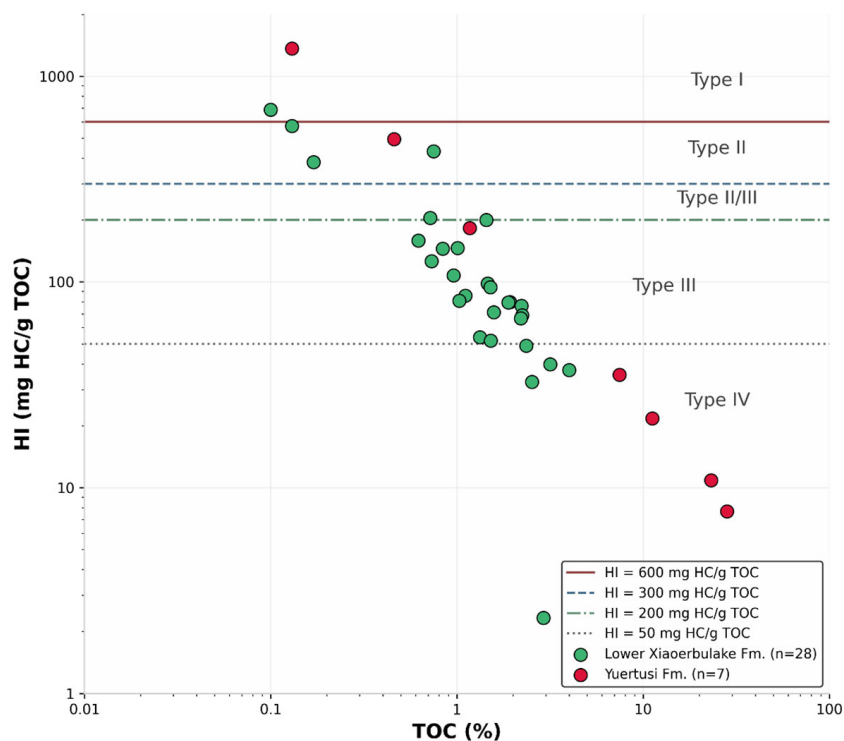


Figure 7. Cross-plot of hydrogen index (HI) versus total organic carbon (TOC) for the Lower Cambrian source rocks in Well BY1, with HI thresholds of 600, 300, 200, and 50 mg HC/g TOC separating the kerogen-type fields (Type I to Type IV). Green dots, Lower Xiaerbulake Formation ($n = 28$); red dots, Yuertusi Formation ($n = 7$).

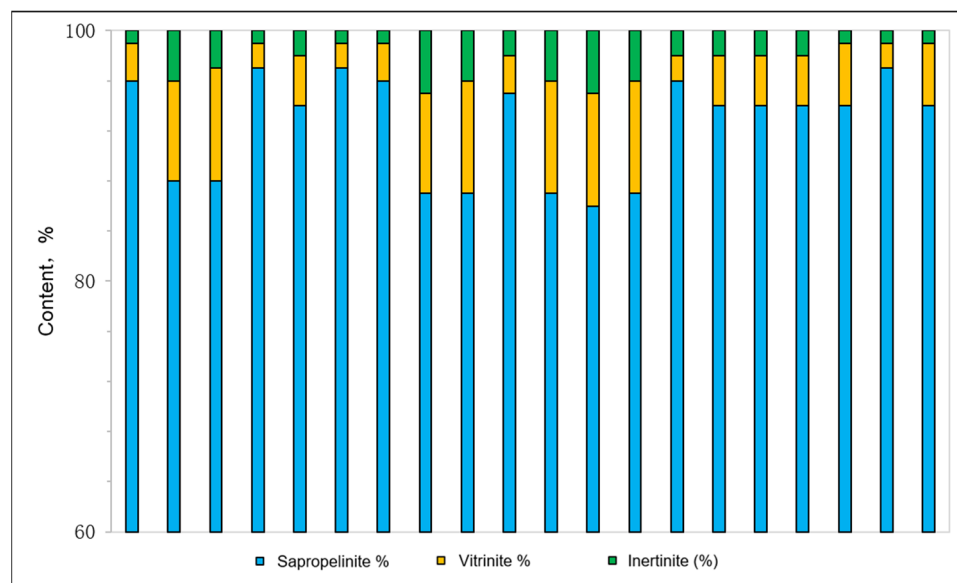


Figure 8. Maceral composition of kerogen from the Lower Cambrian source rocks in Well XSC1, determined by transmitted-light microscopy. Note the dominance of sappropelinite (>80% in all samples), consistent with a Type I–II kerogen assemblage.

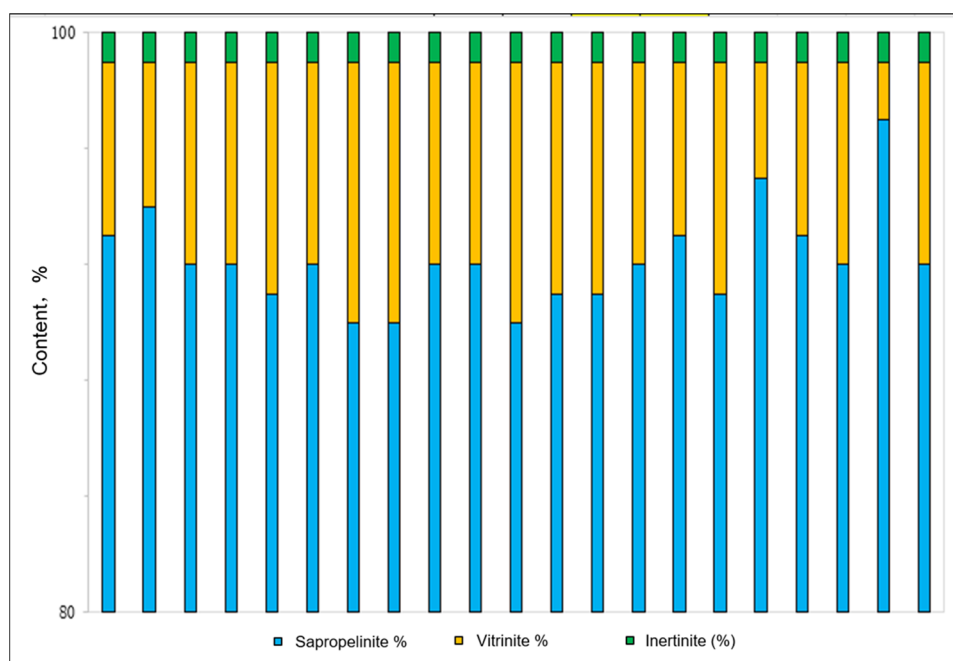


Figure 9. Maceral composition of kerogen from the Lower Cambrian source rocks in Well BY5, determined by transmitted-light microscopy. Sappropelinite dominates all samples (>80%), with subordinate vitrinite-like macerals and minor inertinite; liptinite (exinite) is absent, consistent with a Type I–II kerogen assemblage.

4.1.3. Organic-Matter Maturity

Thermal maturity constrains the stage of hydrocarbon generation and the type of products, and it is a key parameter in source-rock evaluation. The maturity of the Lower Cambrian source rocks in the study area was determined by combining Tmax, the production index (PI), and solid bitumen reflectance (BRb). Because vitrinite is scarce in marine carbonate rocks, equivalent vitrinite reflectance (EqVRO) converted from BRb was used for maturity evaluation.

Rock-Eval analysis of Well BY1 (Table 4) shows that the 28 samples from the lower member of the Xiaerbulake Formation have T_{max} values of 448–549 °C (mean 481 °C) and PI values of 0.03–0.80 (mean 0.48). Two samples have $T_{max} < 455$ °C, five have T_{max} of 455–470 °C, and 21 have $T_{max} > 470$ °C. One sample (ϵ_1 x-13) has PI < 0.1, six have PI of 0.1–0.4, and 21 have PI > 0.4. The seven Yuertusi Formation samples have T_{max} values of 455–549 °C (mean 483 °C) and PI values of 0.09–0.21 (mean 0.12). Four of them have T_{max} of 455–470 °C, three have $T_{max} > 470$ °C, and all have PI < 0.22. On the PI– T_{max} cross-plot (Figure 10), most samples plot in the high-maturity to overmature field, but the pyrolysis responses of the two intervals differ. Most samples from the lower member of the Xiaerbulake Formation plot in the wet gas-to-dry gas window, following the normal thermal evolution trajectory of Type I–II kerogen. Some samples with $T_{max} < 470$ °C and PI > 0.4 deviate from the normal trend, suggesting contamination by early migrated hydrocarbons or the influence of redeposited high-maturity organic debris. The Yuertusi Formation shares a similar maturity background with the Lower Xiaerbulake member, but its PI values are low throughout. This pattern may reflect the loss of hydrocarbons after extensive generation during the high-to-overmature stages.

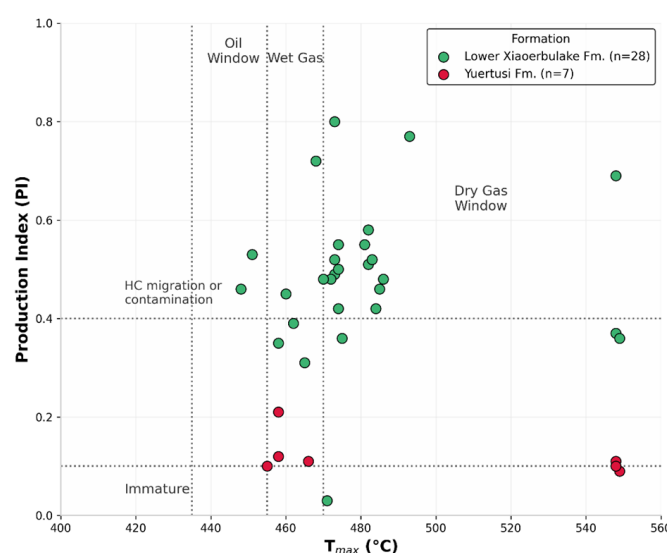


Figure 10. Cross-plot of production index (PI) versus T_{max} for the Lower Cambrian source rocks in Well BY1, showing the maturity zones (oil window, wet gas, and dry gas window), the immature field (PI < 0.1), and the field suggestive of hydrocarbon migration or contamination (PI > 0.4). The vertical dotted lines at $T_{max} = 435$, 455, and 470 °C indicate the boundaries of the oil window, the wet-gas window, and the dry-gas window. The horizontal dotted lines at PI = 0.1 and 0.4 indicate the upper limit of the immature field and the lower limit of the hydrocarbon migration or contamination field. Green dots, Lower Xiaerbulake Formation ($n = 28$); red dots, Yuertusi Formation ($n = 7$).

Solid bitumen reflectance provides an independent constraint on maturity. Various workers have established relationships between BRb and EqVRo for different regions and sample types [66,67] (Table 6). The EqVRo values calculated by the method of Liu, D. [66] range from 2.28% to 2.62% (mean 2.38%), and those calculated by the method of Schmidt [67] range from 3.03% to 3.50% (mean 3.18%) (Table 7). The EqVRo values of the two source-rock intervals exceed 2.0%, indicating the overmature gas-generation stage. The multi-parameter analysis therefore shows that the source rocks of both the Xiaerbulake and Yuertusi Formations in the study area have reached the high-to-overmature stage. Such high maturity implies that the source rocks have generated large quantities of gaseous hydrocarbons, which is consistent with the gas-dominated exploration results in this area.

Table 6. Conversion relationships between solid bitumen reflectance (BRb) and equivalent vitrinite reflectance (EqVRo).

Conversion Formula	Reference
$\text{EqVR}_o = 0.668\text{R}_b + 0.346$	Liu, D. [66]
$\text{EqVR}_o = 0.938\text{BR}_b + 0.3145$	Schmidt [67]

BRb, solid bitumen reflectance; Rb, bitumen reflectance; EqVRo, equivalent vitrinite reflectance converted from BRb or Rb.

Table 7. Solid bitumen reflectance (BRb) and converted equivalent vitrinite reflectance (EqVRo) of the Lower Cambrian source rocks in Well BY1.

No.	Depth (m)	Mean BRb (%)	BRb, Min (%)	BRb, Max (%)	n	Std. Dev.	EqVRo (%) [53]	EqVRo (%) [54]	Remarks
€ ₁ x-1	3879.1	2.94	2.76	3.12	20	0.10	2.31	3.07	Solid bitumen
€ ₁ x-2	3879.5	2.89	2.70	3.08	22	0.10	2.28	3.03	Solid bitumen
€ ₁ x-3	3880	2.90	2.81	3.00	8	0.05	2.28	3.03	Solid bitumen
€ ₁ x-6	3881.8	2.94	2.80	3.08	12	0.07	2.31	3.07	Solid bitumen
€ ₁ x-7	3882	2.92	2.70	3.14	14	0.11	2.30	3.05	Solid bitumen
€ ₁ x-8	3882.5	2.95	2.80	3.10	28	0.08	2.32	3.08	Solid bitumen
€ ₁ x-9	3884.7	2.90	2.71	3.10	20	0.10	2.28	3.03	Solid bitumen
€ ₁ x-10	3885.8	2.92	2.76	3.08	11	0.09	2.30	3.05	Solid bitumen
€ ₁ x-12	3887	2.96	2.76	3.15	8	0.10	2.32	3.09	Solid bitumen
€ ₁ x-13	3888	2.90	2.72	3.08	6	0.09	2.28	3.03	Solid bitumen
€ ₁ x-14	3889	2.92	2.71	3.10	30	0.10	2.30	3.05	Solid bitumen
€ ₁ x-15	3890	2.99	2.81	3.19	26	0.10	2.34	3.12	Solid bitumen
€ ₁ x-16	3891	3.02	2.86	3.18	4	0.09	2.36	3.15	Solid bitumen
€ ₁ x-17	3891.5	2.95	2.72	3.18	14	0.12	2.32	3.08	Solid bitumen
€ ₁ x-18	3891.8	3.03	2.80	3.26	11	0.12	2.37	3.16	Solid bitumen
€ ₁ x-19	3892.1	3.05	2.82	3.28	30	0.12	2.38	3.18	Solid bitumen
€ ₁ x-20	3892.8	3.06	2.85	3.25	30	0.10	2.39	3.18	Solid bitumen
€ ₁ x-21	3893.5	2.95	2.70	3.24	30	0.15	2.32	3.08	Solid bitumen
€ ₁ x-22	3894	3.05	2.85	3.25	23	0.12	2.38	3.18	Solid bitumen
€ ₁ x-23	3894.8	2.91	2.62	3.20	30	0.16	2.29	3.04	Solid bitumen
€ ₁ x-24	3896.6	2.95	2.75	3.15	7	0.11	2.32	3.08	Solid bitumen
€ ₁ x-25	3896.8	3.04	2.85	3.25	15	0.11	2.38	3.17	Solid bitumen
€ ₁ x-27	3944.4	3.40	3.22	3.58	4	0.15	2.62	3.50	Solid bitumen
€ ₁ x-28	3945.2	3.32	3.01	3.64	22	0.15	2.56	3.43	Solid bitumen
€ ₁ y-1	3953.4	3.34	3.24	3.44	30	0.06	2.58	3.45	Vitrinite-like maceral
€ ₁ y-2	3953.5	3.32	3.20	3.44	30	0.07	2.56	3.43	Vitrinite-like maceral
€ ₁ y-3	3953.7	3.40	3.21	3.60	30	0.10	2.62	3.50	Solid bitumen
€ ₁ y-4	3954	3.30	3.14	3.46	30	0.09	2.55	3.41	Vitrinite-like maceral
Min.	—	2.89	2.62	3.00	4	0.05	2.28	3.03	—
Max.	—	3.40	3.24	3.64	30	0.16	2.62	3.50	—
Mean	—	3.05	2.86	3.24	19	0.10	2.38	3.18	—

BRb, solid bitumen reflectance; BRb, min and BRb, max, minimum and maximum measured BRb values; n, number of measurement points; Std. dev., standard deviation; EqVRo, equivalent vitrinite reflectance converted from BRb using the equations of [53] and [54], respectively. Sample numbers prefixed with €₁x and €₁y denote the Xiaerbulake and Yuertusi Formations, respectively. The “Remarks” column indicates the measurement target (solid bitumen or vitrinite-like maceral). “—” indicates not applicable.

4.1.4. Distribution Characteristics of Source Rocks

Based on well data, outcrop section analysis, and regional seismic calibration, the thickness of argillaceous limestone in the lower member of the Xiaerbulake Formation

from individual wells was used to construct an isopach map of the source rocks (Figure 11). The results are as follows.

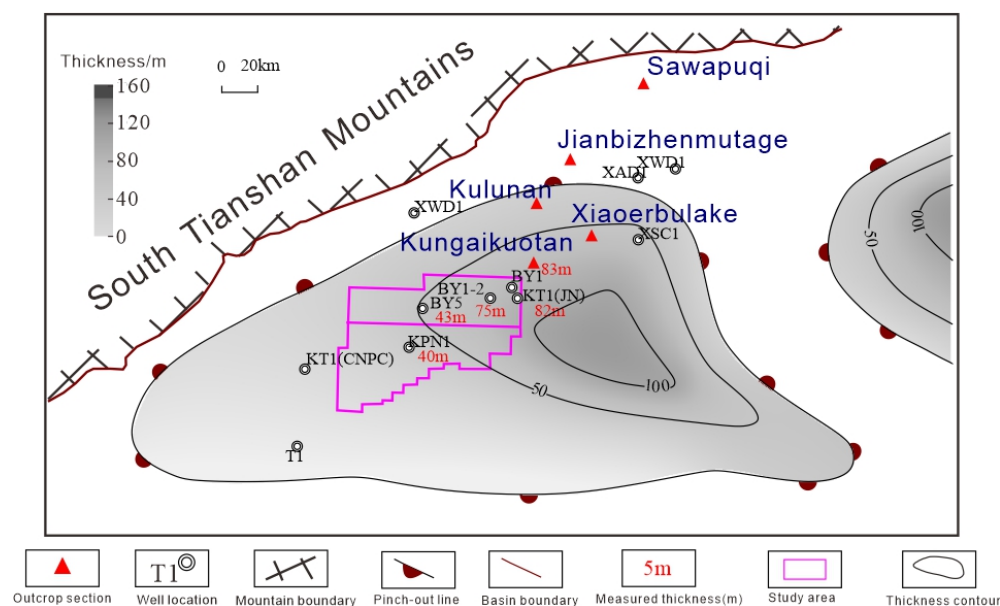


Figure 11. Thickness distribution of source rocks in the Lower Xiaerbulake Formation in the southern Keping area. Red triangles, outcrop sections; circled dots, wells with measured source-rock thicknesses (red labels, in meters); gray shading and contour lines (in meters) show the interpolated thickness distribution. The magenta outline denotes the study area.

(1) Lower member of the Xiaerbulake Formation.

The source rocks are thickest in Wells BY1 and KT1(JN), where local depressions may have developed. The thickness ranges from 70 to 160 m, and the distribution area is approximately 20,000–30,000 km². The mean TOC content is 1.55%, corresponding to a fair-to-good source rock. This result revises the conventional view that only the Yuertusi Formation source rock is developed in the Cambrian of the northwestern Tarim Basin.

(2) Yuertusi Formation.

The facies belt hosting high-quality source rocks extends in an E–W direction, and the middle–lower ramp zone is the favorable depositional area. The formation averages 22.45 m thick in the Keping outcrop area and reaches 33 m in Well Xinghuo-1 to the north, where argillaceous limestone is developed. The depositional water deepens from south to north, with platform, inner-ramp, mid-ramp, and outer-ramp to basinal facies developing in succession. Because the southern Keping area occupied a shallow-water intra-platform setting, the formation there is thin and of poor quality (Figure 12).

4.2. Depositional Environment and Organic-Matter Enrichment Mechanisms

The development of high-quality source rocks in the Lower Cambrian was governed by the depositional environment. Paleoproductivity determined the input flux of organic matter, and paleo-redox conditions controlled the preservation efficiency of organic matter during deposition and diagenesis. Major elements (Al, Fe, Ti) record the intensity of terrigenous clastic input and the sedimentation rate, and trace elements (V, U, Mo, Ni, Co, Ba) respond sensitively to the redox state of the water column, serving as indicators for reconstructing paleo-redox conditions and paleoproductivity. However, the enrichment of trace elements in sediments is controlled not only by the redox conditions of the depositional water column but may also be disturbed by hydrothermal activity, detrital input, and diagenetic alteration. The provenance of these elements must therefore be identified

before they are used for paleoenvironmental reconstruction. In this study, major- and trace-element analyses were performed on 21 source-rock samples from the lower member of the Xiaerbulak Formation (ϵ_{1x}) and the Yuertusi Formation (ϵ_{1y}) in Well BY1 (Table 8), and whole-rock XRD mineral analysis was conducted on representative samples (Table 9). Through combined lithofacies and geochemical constraints, this study reconstructs the paleoproductivity and paleo-redox characteristics during deposition of the Lower Cambrian source rocks in the study area and investigates the controlling factors of organic-matter enrichment.

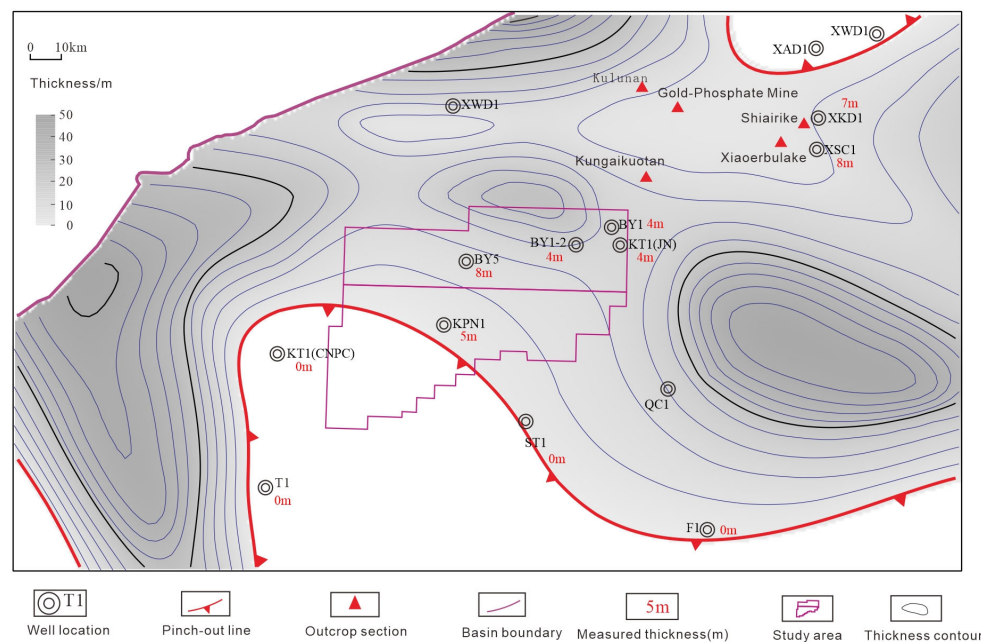


Figure 12. Thickness distribution of source rocks in the Yuertusi Formation in the southern Keping area. Red triangles, outcrop sections; circled dots, wells with measured source-rock thicknesses (red labels, in meters; “0 m” indicates wells where the formation was penetrated but source rocks are absent, i.e., pinch-out points); gray shading and contour lines (in meters) show the interpolated thickness distribution. The magenta outline denotes the study area.

4.2.1. Source Discrimination of Trace Elements

Before redox-sensitive trace elements (V, U, Mo, Ni, Co) can be used to reconstruct paleoproductivity and paleo-redox conditions, their sources must be identified to exclude misleading paleoenvironmental interpretations caused by hydrothermal activity and detrital input [68,69]. In this study, the detrital, hydrothermal, and authigenic sources of trace elements in the BY1 samples were evaluated using the Fe/Ti–Al/(Al + Fe) diagram, correlation analysis between trace elements and Al_2O_3 , and XRD-based lithofacies analysis.

Hydrothermal activity can alter the relative abundances of Fe, Ti, Al, and trace elements in sediments. According to the review of Maravelis et al. (2026) [68], the combination of $\text{Fe}/\text{Ti} > 20$ and $\text{Al}/(\text{Al} + \text{Fe}) < 0.4$ indicates a hydrothermal origin. In the BY1 samples, Fe/Ti ranges from 5.67 to 11.27 (mean 7.84) and Al/(Al + Fe) from 0.55 to 0.74 (mean 0.67) in the lower member of the Xiaerbulak Formation ($n = 17$), and Fe/Ti ranges from 5.13 to 16.97 (mean 9.0) and Al/(Al + Fe) from 0.62 to 0.76 (mean 0.71) in the Yuertusi Formation ($n = 4$). On the Fe/Ti–Al/(Al + Fe) discrimination diagram (Figure 13), all 21 samples fall within the non-hydrothermal field.

Table 8. Major- and trace-element contents and provenance discrimination indices of the Lower Cambrian source rocks in Well BY1.

No.	Fm.	Al ₂ O ₃ (%)	TFe ₂ O ₃ (%)	TiO ₂ (%)	Fe/Ti	Al/(Al + Fe)	Ba	Zn	Cu	V	Ni	Co	U	Th	Mo
X-1	Є ₁ x	8.84	3.41	0.56	6.07	0.72	294.10	30.90	26.00	93.20	47.70	10.60	6.23	10.81	5.92
X-2	Є ₁ x	7.31	2.54	0.40	6.30	0.74	208.10	26.40	22.30	74.90	44.70	8.00	6.98	9.36	1.23
X-3	Є ₁ x	2.53	0.99	0.16	6.07	0.72	88.00	16.90	8.20	28.40	13.40	3.60	3.05	3.08	0.80
X-4	Є ₁ x	3.42	1.30	0.23	5.67	0.72	148.90	20.90	11.00	37.00	21.40	4.10	4.76	4.65	0.61
X-5	Є ₁ x	1.02	0.70	0.08	8.84	0.60	65.40	11.50	5.40	13.80	9.80	1.40	1.85	1.40	0.32
X-6	Є ₁ x	9.98	3.54	0.52	6.86	0.74	409.30	1517.00	41.60	101.20	78.70	10.40	12.30	12.57	3.14
X-7	Є ₁ x	0.59	0.33	0.04	7.76	0.65	3104.00	10.10	4.40	13.40	7.80	1.00	0.81	0.84	0.79
X-8	Є ₁ x	3.89	1.64	0.22	7.63	0.70	295.80	20.30	18.20	55.20	39.30	4.80	7.44	6.18	1.60
X-9	Є ₁ x	2.95	1.16	0.17	6.96	0.72	273.80	18.50	15.30	58.10	22.30	4.70	7.44	3.86	9.24
X-10	Є ₁ x	2.36	1.10	0.13	8.19	0.68	346.90	25.20	22.90	171.90	57.20	3.80	9.77	3.14	17.50
X-11	Є ₁ x	6.34	2.62	0.35	7.41	0.71	316.40	230.30	59.40	615.90	151.90	9.20	17.98	8.41	58.32
X-12	Є ₁ x	2.09	0.91	0.12	7.37	0.70	997.70	27.90	14.80	40.20	22.10	3.50	3.71	2.73	7.57
X-13	Є ₁ x	1.77	0.81	0.11	7.63	0.69	72.80	11.70	11.70	39.90	13.50	3.70	7.62	2.26	8.45
X-14	Є ₁ x	0.99	0.72	0.07	10.73	0.58	87.50	9.40	4.50	11.70	5.80	1.50	0.26	1.30	0.22
X-15	Є ₁ x	0.75	0.39	0.05	7.88	0.65	1105.60	6.50	3.30	10.70	8.30	3.30	0.45	0.92	0.89
X-16	Є ₁ x	0.84	0.62	0.06	11.27	0.58	83.90	10.00	4.50	10.00	8.80	1.40	0.49	1.34	0.23
X-17	Є ₁ x	0.66	0.54	0.05	10.70	0.55	49.00	8.50	3.10	9.40	7.00	1.80	0.41	1.05	0.62
Min.	Є ₁ x	0.59	0.33	0.04	5.67	0.55	49.00	6.50	3.10	9.40	5.80	1.00	0.26	0.84	0.22
Max.	Є ₁ x	9.98	3.54	0.56	11.27	0.74	3104.00	1517.00	59.40	615.90	151.90	10.60	17.98	12.57	58.32
Mean	Є ₁ x	3.31	1.37	0.20	7.84	0.67	467.48	117.76	16.27	81.46	32.92	4.52	5.39	4.35	6.91
Y-1	Є ₁ y	10.78	4.15	0.58	7.10	0.72	19,206.60	627.30	266.10	5459.30	249.30	30.10	174.54	6.92	183.31
Y-2	Є ₁ y	9.64	3.29	0.64	5.13	0.75	1696.50	18.10	79.20	2290.60	190.10	26.70	317.21	7.09	241.52
Y-3	Є ₁ y	9.79	3.11	0.46	6.81	0.76	11,115.10	131.80	367.80	2253.80	208.90	12.40	73.34	6.72	43.45
Y-4	Є ₁ y	1.66	1.02	0.06	16.97	0.62	41,259.80	58.50	97.00	503.20	27.50	5.40	129.29	1.83	11.84
Min.	Є ₁ y	1.66	1.02	0.06	5.13	0.62	1696.50	18.10	79.20	503.20	27.50	5.40	73.34	1.83	11.84
Max.	Є ₁ y	10.78	4.15	0.64	16.97	0.76	41,259.80	627.30	367.80	5459.30	249.30	30.10	317.21	7.09	241.52
Mean	Є ₁ y	7.97	2.89	0.43	9.00	0.71	18,319.50	208.93	202.53	2626.73	168.95	18.65	173.59	5.64	120.03

Fm., formation; Є₁x, Xiaerbulake Formation; Є₁y, Yuertusi Formation. Trace-element (Ba, Zn, Cu, V, Ni, Co, U, Th, Mo) contents are in µg/g. The Fe/Ti and Al/(Al + Fe) ratios were calculated from oxide weight percentages. TFe₂O₃, total iron expressed as Fe₂O₃.

Table 9. Whole-rock XRD mineral compositions (%) of the Lower Cambrian source rocks in Well BY1.

Sample	Depth (m)	Quartz	K-Feldspar	Plagioclase	Calcite	Dolomite	Pyrite	Ankerite	Clay	Siderite	Barite	Fluorapatite
X-1	3879.1	22.9	6.9	0	0	0	5.5	50.3	14.3	0	0	0
X-2	3879.5	13.5	4.6	0	0	0	3.5	68.6	9.8	0	0	0
X-3	3880.0	4.8	1.2	0	85.0	0	1.5	4.0	3.5	0	0	0
X-4	3881.3	8.3	2.0	0	66.4	0	1.7	17.5	4.1	0	0	0
X-5	3881.8	2.6	0	0	94.6	0	0.9	1.3	0.6	0	0	0
X-6	3884.7	33.2	8.5	0	17.8	0	7.0	17.1	13.8	2.6	0	0
X-7	3887.0	1.0	0	0	88.3	0	0	10.3	0.4	0	0	0
X-8	3890.0	7.8	2.7	0	52.1	0	3.4	27.9	6.1	0	0	0
X-9	3891.5	6.8	1.8	0	18.7	0	2.6	65.0	5.1	0	0	0
X-10	3892.1	10.7	1.4	0	61.8	0	2.5	18.6	5.0	0	0	0
X-11	3893.5	21.7	5.1	0.2	27.7	0	4.9	33.9	6.5	0	0	0
X-12	3894.8	6.8	1.7	0	59.2	0	1.4	30.8	0.1	0	0	0
X-13	3896.6	6.2	1.5	0	18.3	69.1	1.7	0	3.2	0	0	0
X-14	3940.4	1.3	1.3	0	96.0	0	0	0	1.4	0	0	0
X-15	3942.0	0.8	2.5	0	93.6	0	0	2.6	0.5	0	0	0
X-16	3943.0	0.7	1.4	0	96.8	0	0	0.9	0.2	0	0	0
X-17	3945.2	0.8	0.8	0	97.1	0	0	0	1.3	0	0	0
Min.	∈ _{1x}	0.7	0	0	0	0	0	0	0.1	0	0	0
Max.	∈ _{1x}	33.2	8.5	0.2	97.1	69.1	7.0	68.6	14.3	2.6	0	0
Mean	∈ _{1x}	8.8	2.6	0	57.3	4.1	2.2	20.5	4.5	0.2	0	0
Y-1	3953.5	45.4	8.0	0	0	4.5	11.5	0	25.6	0	5.0	0
Y-2	3953.7	45.6	15.0	0	0	0	9.1	7.7	19.7	0	2.9	0
Y-3	3954.0	21.5	5.9	0	0	0	0	0	20.2	0	5.9	46.5
Y-4	3954.3	6.3	0	0	0	0	0	0	1.3	21.3	6.7	64.4
Min.	∈ _{1y}	6.3	0	0	0	0	0	0	1.3	0	2.9	0
Max.	∈ _{1y}	45.6	15.0	0	0	4.5	11.5	7.7	25.6	21.3	6.7	64.4
Mean	∈ _{1y}	29.7	7.2	0	0	1.1	5.2	1.9	16.7	5.3	5.1	27.7

X-1 to X-17, Lower Xiaerbulake Formation (∈_{1x}); Y-1 to Y-4, Yuertusi Formation (∈_{1y}). Mineral contents are in wt% determined by whole-rock X-ray diffraction (XRD).

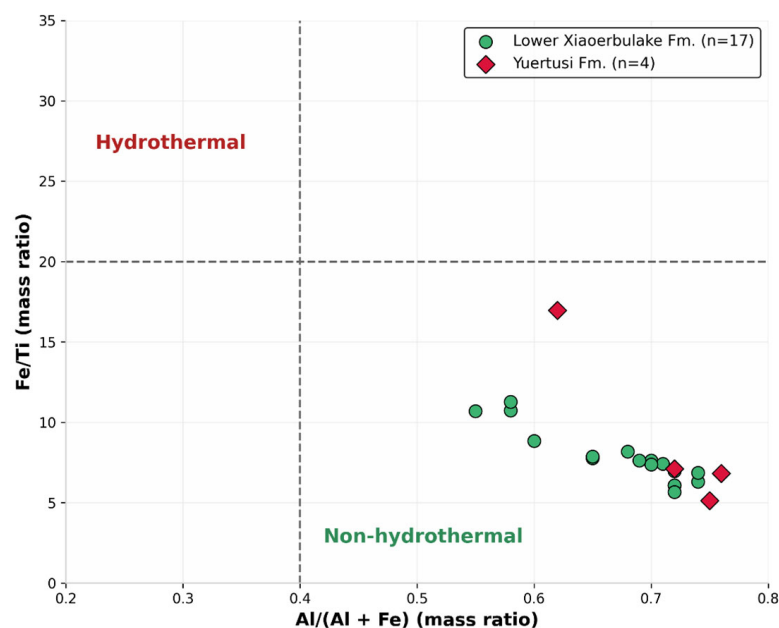


Figure 13. Fe/Ti versus Al/(Al + Fe) discrimination diagram for the Lower Cambrian source rocks in Well BY1. The dashed lines ($\text{Al}/(\text{Al} + \text{Fe}) = 0.4$ and $\text{Fe}/\text{Ti} = 20$) separate hydrothermal from non-hydrothermal deposits [68]. Green dots, Lower Xiaerbulake Formation ($n = 17$); red diamonds, Yuertusi Formation ($n = 4$). All samples plot in the non-hydrothermal field, indicating a normal marine sedimentary origin without significant hydrothermal input.

After excluding a hydrothermal origin, detrital and authigenic sources must be further distinguished. In this study, Al_2O_3 was used as a proxy for the terrigenous detrital background, and correlation analyses between key trace elements and Al_2O_3 were performed (Figure 14). In the samples from the lower member of the Xiaerbulak Formation ($n = 17$), Co and Cu show strong positive correlations with Al_2O_3 ($R^2 = 0.94$ and 0.61); Ni, U, and Zn show moderate positive correlations ($R^2 = 0.46$, 0.48 , and 0.39); V shows a weak positive correlation ($R^2 = 0.18$, statistically insignificant); and Mo and Ba show no correlation ($R^2 = 0.08$ and 0.04). In the Yuertusi Formation samples ($n = 4$), Ni shows a strong positive correlation with Al_2O_3 ($R^2 = 0.98$); Ba shows a negative correlation trend ($R^2 = 0.73$, $r = -0.85$); Co, V, and Mo show moderate positive correlations ($R^2 = 0.63$, 0.59 , and 0.44); and Zn, Cu, and U show weak correlations ($R^2 = 0.07$ – 0.28). However, with only four Yuertusi samples, none of these trends except that of Ni pass significance testing, so their statistical meaning is limited and they must be evaluated together with the lithofacies differences revealed by XRD (Table 9).

The Yuertusi Formation contains a siliceous mudstone–barite–apatite assemblage, with quartz 45.4–45.6%, clay minerals 19.7–25.6%, pyrite 9.1–11.5%, and barite 2.9–5.0% in samples Y-1 and Y-2, and fluorapatite 46.5–64.4% and siderite 21.3% in samples Y-3 and Y-4. This association is indicative of upwelling deposition. The lower member of the Xiaerbulak Formation consists of calcite, ankerite, and clay minerals (calcite 0–97.1%, ankerite 0–68.6%, and clay minerals 0.1–14.3%), with pyrite contents of 0–7% (mean 2.2%) and no barite or fluorapatite, representing a carbonate–mudstone succession deposited under normal marine conditions.

On this basis, Co and Cu in the lower member of the Xiaerbulak Formation are hosted in detrital components such as clay minerals; Ni, U, and Zn have mixed detrital–authigenic sources; and V, Mo, and Ba are authigenic in origin. In the Yuertusi Formation, the strong Ni– Al_2O_3 correlation may reflect a lithofacies coupling in which clay detritus and authigenic sulfides in the siliceous mudstone were enriched together, rather than control by terrigenous input alone. The negative Ba– Al_2O_3 correlation indicates that Ba

contents are not governed by detrital dilution and may instead be controlled by lithofacies differentiation between the phosphorite–barite and siliceous mudstone facies, with Ba being of authigenic origin. The positive correlation trends of Co, V, and Mo may likewise reflect the coupled occurrence of these elements across different lithofacies. Taken together, the anomalous enrichment of trace elements in the Yuertusi Formation is closely associated with the authigenic apatite–barite–pyrite mineral assemblage.

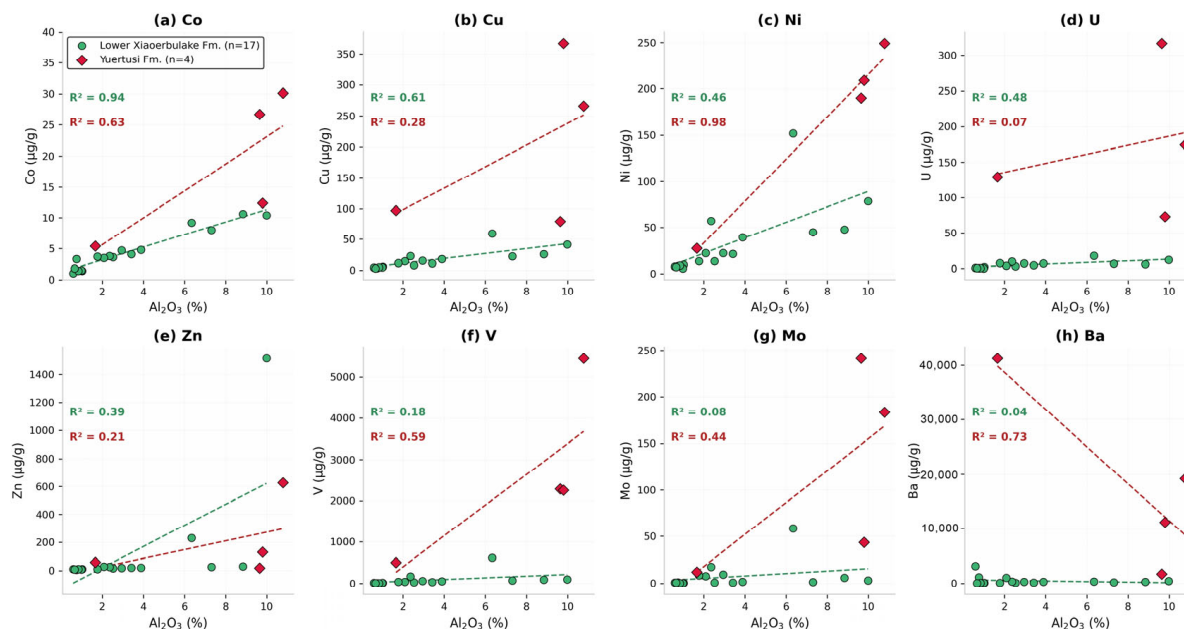


Figure 14. Correlations of trace elements with Al_2O_3 for the Lower Cambrian source-rock samples in Well BY1. (a) Co; (b) Cu; (c) Ni; (d) U; (e) Zn; (f) V; (g) Mo; (h) Ba. Green circles, Lower Xiaerbulake Formation ($n = 17$); red diamonds, Yuertusi Formation ($n = 4$); dashed lines denote linear trends for each formation, with the corresponding coefficients of determination (R^2) shown in matching colors. Given the small sample size of the Yuertusi Formation ($n = 4$), its trend lines and R^2 values are indicative only.

Based on these constraints, redox-sensitive trace elements such as V, U, and Mo require Al normalization or enrichment factor (EF) correction in paleo-redox reconstruction to remove the dilution effect of terrigenous detrital input. For productivity evaluation, because Ba enrichment is authigenic, its concentrations can be used directly. In contrast, Cu in the lower member of the Xiaerbulak Formation is controlled by detrital input and is therefore unsuitable for productivity evaluation, and Zn in this interval has mixed detrital–authigenic sources and can be used only after Al normalization. In the Yuertusi Formation, Zn enrichment is authigenic and can be used directly for productivity analysis.

4.2.2. Paleoproductivity Characteristics

Paleoproductivity provides the material basis for organic-matter enrichment. Ba is a micronutrient required by marine organisms, and its long residence time and high preservation rate in seawater make it a proxy for the evolution of primary productivity in the upper ocean. Cu and Zn enrichment records the transport of these metals into sediments by organic matter and their subsequent preservation under reducing conditions. P is a key nutrient limiting marine primary productivity, and its enrichment indicates the intensity of nutrient supply by upwelling [70–73]. Based on the source discrimination above, these proxies are applied differently. Ba concentrations are used directly. Zn enrichment in the Yuertusi Formation is authigenic, so its concentrations are used directly, whereas Zn in the lower member of the Xiaerbulak Formation is used after Al normalization (Zn/Al_2O_3 , in

($\mu\text{g g}^{-1}/\%$) to remove the detrital background. Cu is controlled by detrital input and is excluded from productivity evaluation. P is represented qualitatively by the fluorapatite content revealed by XRD.

Two reference standards were selected according to the lithological differences between the two intervals. The Yuertusi Formation, composed of siliceous mudstone and mudstone, is evaluated against the Post-Archaean Australian Shale (PAAS: $\text{Al}_2\text{O}_3 = 18.9\%$, $\text{Ba} = 650 \mu\text{g/g}$, $\text{Zn} = 85 \mu\text{g/g}$ [74]) as the detrital background. The lower member of the Xiaerbulak Formation, composed of carbonate rocks, is not directly comparable with shale standards and is referenced to the upper continental crust (UCC: $\text{Al}_2\text{O}_3 = 15.4\%$, $\text{Ba} = 628 \mu\text{g/g}$, $\text{Zn} = 67 \mu\text{g/g}$ [75]).

In the Yuertusi Formation, Ba ranges from 1696.5 to 41,259.8 $\mu\text{g/g}$ (mean 18,319.5 $\mu\text{g/g}$), about 28 times the PAAS value, and Zn ranges from 18.1 to 627.3 $\mu\text{g/g}$ (mean 208.9 $\mu\text{g/g}$), about 2.5 times the PAAS value (Table 8). XRD results show increased contents of barite, apatite, clay minerals, and silica in the Yuertusi Formation (Table 9). Barite and apatite are markers of nutrient-rich deposition supplied by upwelling, and together they indicate a nutrient-rich, high-productivity depositional environment. In the lower member of the Xiaerbulak Formation, Ba ranges from 49.0 to 3104.0 $\mu\text{g/g}$ (mean 467.5 $\mu\text{g/g}$), below the UCC value (628 $\mu\text{g/g}$), and $\text{Zn}/\text{Al}_2\text{O}_3$ ranges from 3.50 to 152.00 ($\mu\text{g g}^{-1}/\%$) (mean 18.92), about 4.3 times the UCC background ($\text{Zn}/\text{Al}_2\text{O}_3 = 4.35$).

Integrating the lithofacies and geochemical evidence, the Yuertusi Formation is characterized by high Ba and Zn contents and a phosphorite–barite–siliceous rock assemblage, indicating high primary productivity in the paleo-ocean. The Xiaerbulak source rocks show Zn enrichment comparable to that of the Yuertusi Formation, and Zn correlates positively with TOC in both intervals (Figure 15), indicating a link between high productivity and high TOC. The Sinian Qigebulak Formation (Z₂q), immediately adjacent to the Yuertusi Formation, shows low Ba and Zn contents, indicating that a productivity bloom event occurred during Yuertusi deposition. Post-glacial warming during deposition of the Yuertusi Formation (537–521 Ma) released glacial meltwater that carried nutrients into the ocean, which may have been a key climatic trigger for the upwelling and high productivity of this interval.

4.2.3. Paleo-Redox Conditions

Paleo-redox conditions determine the preservation efficiency of organic matter. In this study, the paleo-redox conditions of the Lower Cambrian source rocks in Well BY1 were evaluated using the $\text{U}_{\text{EF}}\text{--}\text{Mo}_{\text{EF}}$ covariation diagram [76], the Ni/Co ratio [77], the U/Th ratio [78], and the quantitative V/Al , U/Al , and Mo/Al thresholds proposed by Bennett and Canfield (2020) [69]. U_{EF} and Mo_{EF} are Al-normalized enrichment factors relative to PAAS [74], and V/Al , U/Al , and Mo/Al are the ratios of trace-element concentrations to Al_2O_3 content (%), in ($\mu\text{g g}^{-1}/\%$). Because the lower member of the Xiaerbulak Formation consists of carbonate rocks, its X/Al ratios were additionally evaluated against the upper continental crust (UCC [75]).

On the $\text{U}_{\text{EF}}\text{--}\text{Mo}_{\text{EF}}$ covariation diagram (Figure 16a), all four Yuertusi samples have U_{EF} and Mo_{EF} values well above 3 and plot in the strongly reducing enrichment field. The $\text{Mo}_{\text{EF}}/\text{U}_{\text{EF}}$ ratios of samples Y-1, Y-2, and Y-3 (2.17, 1.57, and 1.22) fall close to the $0.3 \times \text{SW} \text{--} 0.1 \times \text{SW}$ trend, indicating a restricted, euxinic basin. Sample Y-4 is enriched in U and depleted in Mo relative to the other samples ($\text{U}_{\text{EF}} = 474.85$, $\text{Mo}_{\text{EF}} = 89.87$) and plots below the $0.1 \times \text{SW}$ line, reflecting additional U enrichment hosted in fluorapatite (64.4%). The Xiaerbulak samples plot along the $0.1 \times \text{SW} \text{--} 1 \times \text{SW}$ trend, with enrichment factors far lower than those of the Yuertusi Formation. Referenced to the UCC ($\text{V}/\text{Al} = 6.30$, $\text{U}/\text{Al} = 0.175$, $\text{Mo}/\text{Al} = 0.071$ ($\mu\text{g g}^{-1}/\%$) [75]), the mean V/Al , U/Al , and Mo/Al ratios

of this interval are 3.6, 9.5, and 28.4 times the UCC background, respectively. Given the amplifying effect of carbonate dilution on Al-normalized ratios, the actual degree of enrichment is limited.

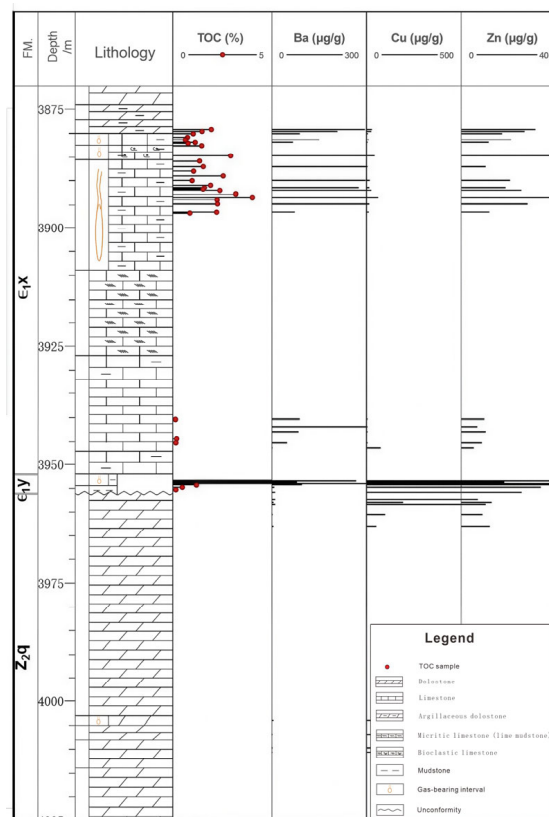


Figure 15. Stratigraphic column of Well BY1 showing the vertical distribution of TOC and redox-sensitive trace elements across the Lower Cambrian source-rock interval. Tracks from left to right: lithology, TOC (%), Ba ($\mu\text{g/g}$), Cu ($\mu\text{g/g}$), and Zn ($\mu\text{g/g}$). Red dots in the TOC track denote analyzed sample points. ϵ_1x , Xiaoerbulake Formation; ϵ_1y , Yuertusi Formation; Z_2q , Qigebulake Formation. Note the sharp enrichment of Ba and Cu at the base of the Yuertusi Formation, coincident with the phosphatic, organic-rich black shale.

On the Ni/Co–U/Th cross-plot (Figure 16b), three of the four Yuertusi samples have Ni/Co > 7 and U/Th > 1.25 and plot in the anoxic field. Sample Y-4 has Ni/Co of 5.09 (between 5 and 7) and U/Th of 70.61 (well above 1.25), placing it in the dysoxic–anoxic transition. Thirteen of the 17 Xiaoerbulak samples have Ni/Co < 7 or U/Th < 1.25 and plot in the oxic–dysoxic field. Samples X-5 and X-12 have Ni/Co between 5 and 7 and U/Th > 1.25, in the dysoxic–anoxic transition. Samples X-10 (Ni/Co = 15.06, U/Th = 3.11) and X-11 (Ni/Co = 16.49, U/Th = 2.14) plot in the anoxic field.

On the V/Al–U/Al cross-plot (Figure 16c), all Yuertusi samples have V/Al > 46 and U/Al > 5 and plot in the core of the perennial OMZ (Within P-OMZ). Fifteen of the 17 Xiaoerbulak samples have V/Al < 23. Nine of these have U/Al > 1 and plot in the Beneath P-OMZ field, whereas samples X-10 (V/Al = 72.8) and X-11 (V/Al = 97.2) have V/Al > 46 and approach the Within P-OMZ field. On the V/Al–Mo/Al cross-plot (Figure 16d), three of the four Yuertusi samples have Mo/Al > 5 and V/Al > 46, supporting the Within P-OMZ interpretation, whereas sample Y-3 has Mo/Al of 4.44, just below the threshold of 5, near the field boundary. Fifteen of the 17 Xiaoerbulak samples have V/Al < 23 and plot in the Beneath P-OMZ field. Samples X-10 and X-11 have Mo/Al of 7.42 and 9.20 (>5) and V/Al > 46, indicating local strongly reducing conditions.

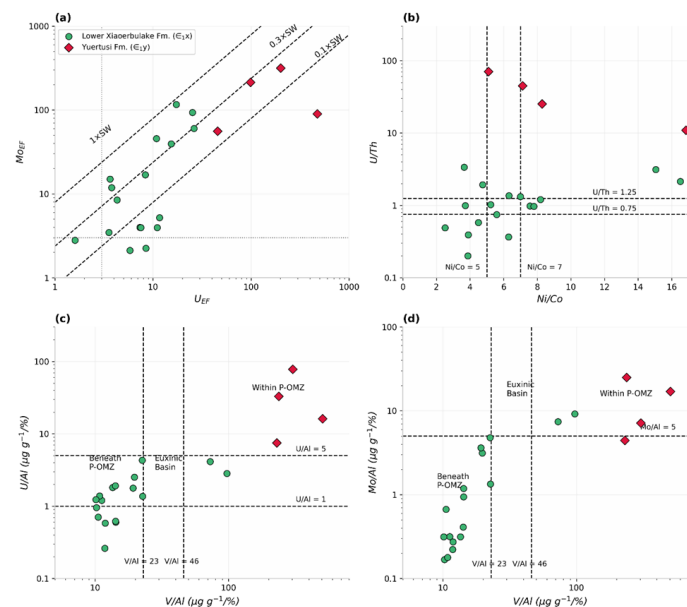


Figure 16. Paleo-redox proxies for the Lower Cambrian source rocks in Well BY1. (a) U_{EF} versus Mo_{EF} covariation diagram (SW = seawater Mo/U ratio, after Algeo and Tribouillard (2009) [76]; enrichment factors (EFs) normalized to PAAS, after McLennan (1993)) [74]; (b) Ni/Co versus U/Th (thresholds after Jones and Manning (1994) [77] and Wignall and Twitchett (1996)) [78]; (c) V/Al versus U/Al; (d) V/Al versus Mo/Al (thresholds after Bennett and Canfield (2020) [69]). Green circles, Lower Xiaerbulake Formation (E_{1x} , $n = 17$); red diamonds, Yuertusi Formation (E_{1y} , $n = 4$).

Integrating these proxies, the water column during Yuertusi deposition was strongly reducing (anoxic to euxinic), corresponding to the core of a perennial OMZ or a euxinic basin. During deposition of the lower member of the Xiaerbulak Formation, the water column was dysoxic to weakly anoxic, corresponding to a setting beneath the P-OMZ or a dysoxic environment, with local anoxia.

4.2.4. Controlling Factors on Organic-Matter Enrichment

The enrichment of organic matter in the Lower Cambrian source rocks of northwestern Tarim resulted from the combined effects of paleoclimate, the paleo-marine environment, and the tectonic setting.

(1) Climatic control: productivity release during post-glacial warming

Deposition of the Yuertusi Formation (537–521 Ma) occurred within a post-glacial warming interval following the retreat of the late Ediacaran glaciation. Warming released glacial meltwater that carried nutrients (P, N, and Fe) into the ocean, promoting phytoplankton blooms and raising marine primary productivity. At the same time, the reduced temperature contrast between surface and deep waters under a warm climate weakened vertical mixing of the water column, facilitating the formation and maintenance of bottom-water anoxia. These climatic conditions provided the setting for the development of the high-quality Yuertusi source rocks.

(2) Depositional control: upwelling and anoxia

During Yuertusi deposition, strong upwelling brought nutrient-rich deep water into the photic zone, stimulating high primary productivity, and the resulting organic matter was preserved under euxinic conditions. The deep-water, restricted settings of the lower-to-outer ramp facilitated the development of a perennial OMZ, favoring organic-matter enrichment and preservation. In contrast, the thick source rocks of the lower member of

the Xiaerbulak Formation were controlled by local depocenters, where the water column was dysoxic to weakly anoxic and organic-matter preservation was moderate.

(3) Tectonic control: rift-trough-controlled deposition

During the Early Cambrian, the northwestern margin of the Tarim Basin was in the rifting stage of a passive continental margin, and NE-trending rift troughs developed in the Keping–Bachu area, controlling the distribution of the Yuertusi source rocks. Deep-water settings within the rift troughs were favorable for source-rock development. Drilling at Wells BY1 and KT1(JN) confirms that the thickness center of the Yuertusi source rocks lies in the Aksu–Wushi area and thins toward the margins.

4.3. Natural Gas Origin and Charge Timing

4.3.1. Natural Gas Origin Analysis

(1) Composition and Dryness Coefficient

Natural gas from the Cambrian reservoirs in the northern Keping block has high methane contents, with dryness coefficients above 0.9977, indicating cracked gas of high-to-overmature levels. The combination of high N_2 (>8%) and low CO_2 (<2%) is characteristic of gas derived from the cracking of sapropelic kerogen (Table 10).

Table 10. Natural gas compositions of wells in the Keping fault-uplift, northwestern Tarim Basin.

Sample	Dryness Coefficient	CH ₄ (%)	C ₂ H ₆ (%)	C ₂ H ₄ (%)	C ₃ H ₈ (%)	iC ₄ H ₁₀ (%)	nC ₄ H ₁₀ (%)	Neo-C ₅ (%)	iC ₅ H ₁₂ (%)	nC ₅ H ₁₂ (%)	N ₂ (%)	CO ₂ (%)
BY1-A	0.997849	89.15	0.18	0	0.0060	0.0004	0.0006	0.0001	0.0002	0.0002	10.0	0.18
BY1-B	0.997848	89.14	0.18	0	0.0060	0.0004	0.0006	0.0001	0.0002	0.0002	10.0	0.19
BY1-2	0.997846	89.89	0.16	0	0.0060	0.0006	0.0012	0.0001	0.0013	0.0002	9.3	0.19
KT1(JN)-A	0.997745	88.80	0.16	0	0.0060	0.0007	0.0014	0.0001	0.0015	0.0003	10.5	0.031
KT1(JN)-B	0.997743	88.82	0.16	0	0.0060	0.0007	0.0015	0.0001	0.0016	0.0003	10.4	0.031
BY1-9	0.998231	85.96	0.15	0	0.0050	0.0004	0.0006	0	0.0002	0	13.0	0.092
BY1-5	0.998071	86.35	0.16	0	0.0050	0.0007	0.0006	0	0.0002	0	9.3	0.031
Min.	0.997743	85.96	0.15	0	0.0050	0.0004	0.0006	0	0.0002	0	9.3	0.031
Max.	0.998231	89.89	0.18	0	0.0063	0.0007	0.0015	0.0001	0.0016	0.0003	13.0	0.19
Mean	0.997970	88.30	0.16	0	0.0059	0.0006	0.0009	0.0001	0.0007	0.0002	10.9	0.106

The dryness coefficient is defined as $CH_4 / \Sigma(CH_4 - C_5H_{12})$ by volume. neo-C₅, neo-pentane; iC₄H₁₀ and iC₅H₁₂, iso-butane and iso-pentane; nC₄H₁₀ and nC₅H₁₂, normal butane and normal pentane. Gas components are reported in volume percent.

(2) Carbon Isotope Discrimination

The carbon isotopic composition of ethane is only weakly affected by maturity and inherits the signature of the source organic matter, making $\delta^{13}C_2$ a robust indicator for the genetic typing of natural gas. A threshold of $\delta^{13}C_2 = -28\text{‰}$ is widely used to distinguish oil-type gas (<−28‰) from coal-type gas (>−28‰) [79,80]. In the Keping area, $\delta^{13}C_2$ values are −36.4‰ in Well BY1-9, −32.9‰ in Well BY1-5, and −34.7‰ in Well KPN1, all below −28.0‰ (Table 5), identifying the gas as oil-type (sapropelic). In contrast, seven gas samples from the Wensu Bulge have $\delta^{13}C_2$ values above −28.0‰ and are derived from Jurassic humic source rocks in the Baicheng Sag to the north, a different source from the Cambrian subsalt gas in the Keping area (Figure 17).

(3) Hydrogen Isotope Discrimination

The δD_1 values of sapropelic organic matter (marine origin) range from −300‰ to −180‰, and those of humic organic matter (terrestrial higher plants) range from −250‰ to −100‰ [69–71]. The δD_1 values of Well BY1-9 and Well BY1-5 are −175.7‰ and −176.2‰, respectively (Table 5). Both values lie near the upper limit of the sapropelic range and, together with the $\delta^{13}C_2$ evidence, indicate sapropelic organic matter of marine origin.

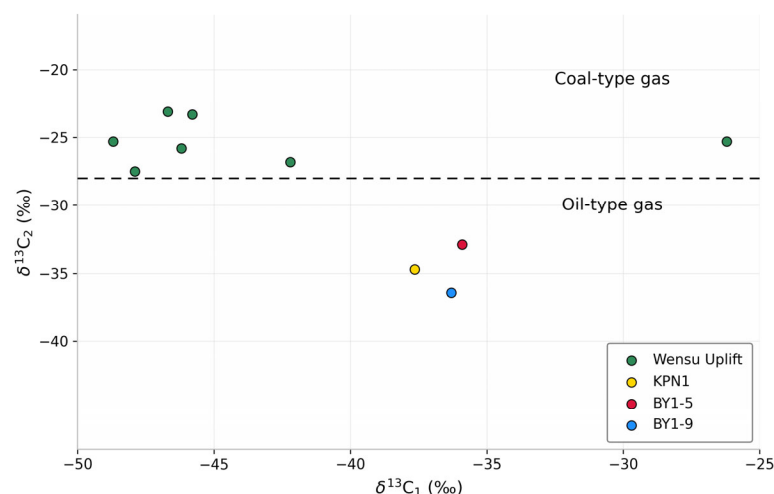


Figure 17. Cross-plot of $\delta^{13}\text{C}_1$ versus $\delta^{13}\text{C}_2$ for natural gases from the Tarim Basin. The dashed line ($\delta^{13}\text{C}_2 = -28\text{‰}$) separates coal-type gas from oil-type gas [79,80]. Gases from the Keping area (KPN1, BY1-5, and BY1-9) plot in the oil-type gas field, distinctly different from the coal-type gases of the Wensu Uplift.

(4) Integrated Interpretation

The Cambrian subsalt gas in the Keping area is oil-cracked gas, sourced from the marine sapropelic source rocks of the Yuertusi Formation or the Xiaerbulak Formation. The combination of light $\delta^{13}\text{C}_1$ ($< -35\text{‰}$), $\delta^{13}\text{C}_2 < -28\text{‰}$, and light δD_1 ($\sim -175\text{‰}$), together with high dryness coefficients (> 0.9977), indicates dry gas generated by the secondary cracking of oil at high-to-overmature stages.

4.3.2. Charge Timing

(1) Fluid-Inclusion Evidence

In Well BY1, fluid inclusions occur in fracture-fill calcite. The aqueous inclusions coexisting with hydrocarbon inclusions are elliptical to irregular in shape. Homogenization temperatures cluster in two intervals, 100–130 °C and 140–150 °C (Figure 18).

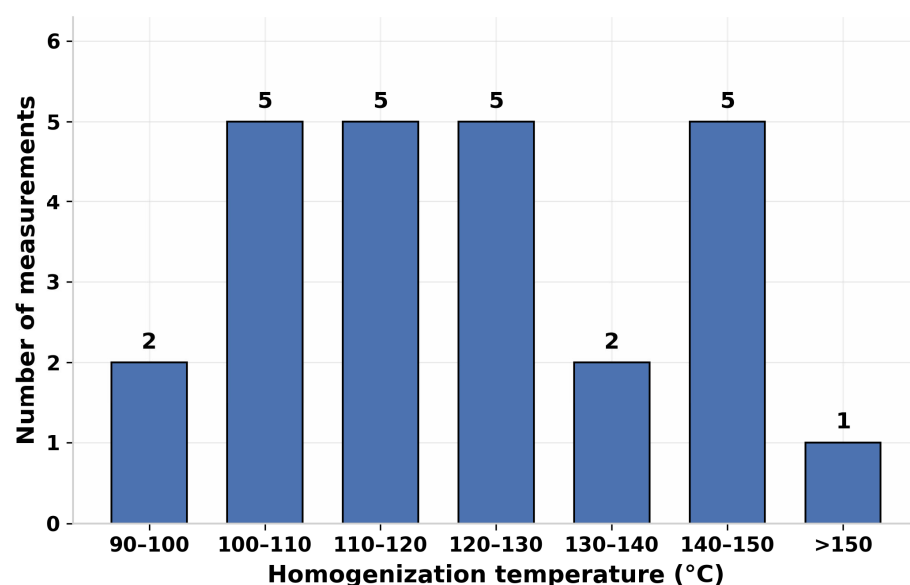


Figure 18. Histogram of homogenization temperatures of fluid inclusions from the Lower Cambrian reservoirs in Well BY1 ($n = 25$). Numbers above the bars indicate the measurement count in each temperature interval.

(2) Constraints from the thermal evolution history

Thermal evolution modeling of the Lower Cambrian source rocks in northwestern Tarim shows the following burial and maturation history (Figure 19). From the Late Caledonian to the Hercynian (Silurian–Permian, ca. 443–252 Ma), Ro reached 0.7–1.0%, and the organic matter was in the oil-generation stage. During the middle–late Hercynian (Carboniferous–Permian, ca. 359–252 Ma), Ro began to exceed 1.3%, marking the onset of the gas-generation stage. In the Himalayan orogeny (Cenozoic, since 66 Ma), Ro exceeded 2.0%, with extensive generation of dry gas.

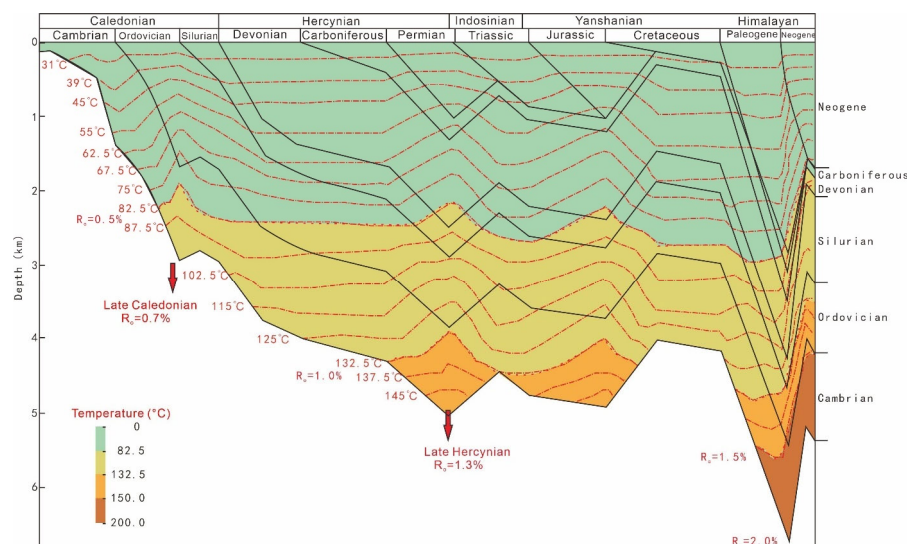


Figure 19. Modeled burial and thermal history of the Lower Cambrian source rocks in the northwestern Tarim Basin, showing the burial curves, isotherms (dashed lines), and the evolution of vitrinite reflectance (Ro) through time. Key maturity milestones are marked by red arrows: Ro = 0.7% in the Late Caledonian, Ro = 1.0–1.3% during the Hercynian, and Ro = 1.5–2.0% in the Neogene (Himalayan), indicating that the main maturation of the source rocks occurred in the Neogene.

(3) Integrated determination of the accumulation timing

Taken at face value, homogenization temperatures of 100–150 °C would indicate hydrocarbon accumulation during the Late Caledonian–Hercynian (ca. 443–252 Ma) or the Himalayan orogeny (since 66 Ma). However, the thermal evolution history shows that the source rocks had not yet generated large volumes of gas during the Late Caledonian–Hercynian and could not have formed large gas accumulations at that time. The inclusions therefore probably record the superposition of two charging events: early oil charging (Late Caledonian–Hercynian) and late gas charging (Himalayan). Alternatively, the inclusion temperatures may have been influenced by later tectono-thermal events. Integrating these constraints, large-scale gas accumulation in this area occurred during the Himalayan orogeny (Cenozoic, since 66 Ma, with the main phase in the Neogene). This timing matches the main gas-generation stage of the source rocks and coincides with the formation of migration pathways and traps during strong Himalayan compression and faulting.

4.4. Resource Evaluation and Exploration Potential

4.4.1. Method for Resource Calculation

Static resources were estimated using the chloroform bitumen “A” method. In this method, the measured chloroform bitumen “A” content of a source rock represents the residual hydrocarbons; the total hydrocarbon generation is back-calculated from the expul-

sion efficiency; and the resources are then obtained by applying a migration–accumulation coefficient. The calculation is

$$Q_g = [1/(1 - K_{exp})] \times (S \cdots H \cdots A \cdots \rho) \times K_{acc} \quad (1)$$

where Q_g is the total resources, t; K_{exp} is the expulsion efficiency, taken as 80% for carbonate rocks; S is the net source-rock area, km^2 ; H is the net source-rock thickness, m; A is the chloroform bitumen “A” content, %; ρ is the source-rock density, taken as 2.58 t/m^3 ($25.8 \times 10^8 \text{ t/km}^3$); and K_{acc} is the migration–accumulation coefficient, taken as 3%.

4.4.2. Results of the Static Resource Estimation

- (1) Yuertusi Formation: geological resources are $990.3 \times 10^9 \text{ m}^3$ in the Keping area and $13.1 \times 10^9 \text{ m}^3$ in the southern Keping area.
- (2) Lower member of the Xiaerbulak Formation: geological resources are $131.1 \times 10^9 \text{ m}^3$ in the Keping area and $7.0 \times 10^9 \text{ m}^3$ in the southern Keping area.

The total resources are $1121.4 \times 10^9 \text{ m}^3$ in the Keping area and $20.1 \times 10^9 \text{ m}^3$ in the southern Keping area.

4.4.3. Dynamic Migration–Accumulation Potential

The source rocks in the southern Keping area have poor hydrocarbon-generating conditions, but the area lies at the terminal end of regional migration pathways. It borders the hydrocarbon-generating sag of northern Keping to the north, and deep-seated faults (such as the Aqia and Ying'an faults) connect it to regional oil sources, so its dynamic resource potential may exceed the static estimate. The total resources of the entire Keping area reach $1121.4 \times 10^9 \text{ m}^3$, and the fault system is well developed, allowing hydrocarbons to migrate vertically along faults and laterally along unconformities [81,82] and fractures, accumulating at structural highs from the generating sag. Under a conservative assumption that 10% of the hydrocarbons generated in the Keping area migrated into the southern Keping area and accumulated with the same migration–accumulation coefficient (3%), the migrated contribution to the resources of the southern Keping area would reach $112.1 \times 10^9 \text{ m}^3$, far higher than its static estimate ($20.1 \times 10^9 \text{ m}^3$), indicating high exploration potential. The 10% migration ratio is an assumption, and the actual migration efficiency may be higher. However, migration efficiency is controlled by the timing of fault activity, the continuity of carrier beds, and the integrity of seals.

4.4.4. Accumulation Model and Key Controlling Factors

The southern Keping area is characterized by an accumulation model of “lower generation and upper storage, fault control, and near-source accumulation” (Table 11, Figure 20).

Table 11. Hydrocarbon accumulation elements of the Keping area.

Accumulation Element	Characteristics
Source rocks	Marine sapropelic source rocks of the Lower Cambrian Yuertusi Formation and the lower member of the Xiaerbulake Formation; oil generation began in the Late Caledonian–Hercynian, and gas generation began in the Late Hercynian
Reservoirs	Dissolution pore-, vug-, and fracture-type dolostone reservoirs of the Wusonggeer Formation; fracture-developed reservoirs in the upper member of the Xiaerbulake Formation
Seals	Thick gypsum-salt rocks of the Middle Cambrian Shayilike–Awatage formations, forming a high-quality regional seal

Table 11. Cont.

Accumulation Element	Characteristics
Migration	Deep-seated faults (e.g., the Ying'an and Aqia faults), unconformities, and fractures constitute vertical and lateral migration pathways
Traps	NW–SE-trending faulted anticlines formed during the Late Caledonian–Hercynian and finalized by Himalayan reworking
Accumulation period	Large-scale hydrocarbon accumulation during the Himalayan period

The tectonic-cycle terms (Caledonian, Hercynian, Himalayan) follow the conventional Chinese tectonic-cycle scheme; absolute ages are given in the text where specific events are discussed.

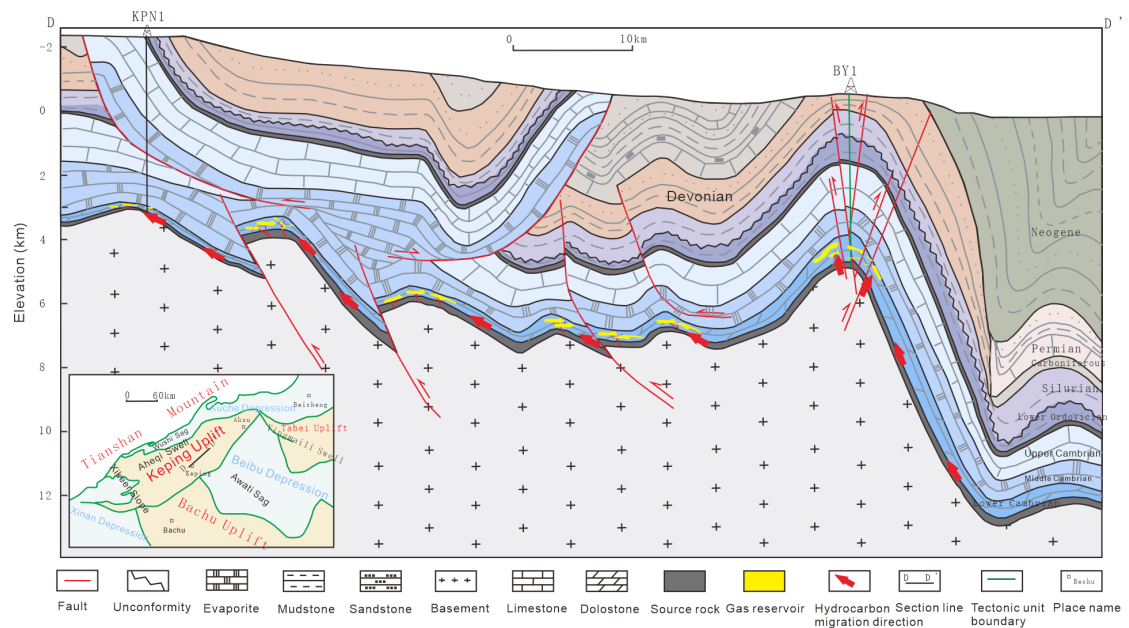


Figure 20. Hydrocarbon accumulation model of the southern Keping area (cross-section D–D' through Wells KPN1 and BY1). Red arrows indicate hydrocarbon migration directions; yellow intervals denote gas reservoirs; dark gray intervals denote source rocks. The inset shows the location of the section line. The model illustrates vertical migration through deep-seated faults and lateral migration along unconformities from the kitchen areas toward the faulted anticline traps beneath the Middle Cambrian gypsum-salt regional seal.

- The main factors controlling hydrocarbon accumulation include:
- (1) Sealing capacity of the gypsum-salt caprock.
At burial depths greater than 3500 m, gypsum-salt rocks behave plastically and provide the best sealing capacity, which is the key to hydrocarbon trapping.
 - (2) Reservoir quality of the Wusongger Formation.
Dissolution vugs and fractures determine well productivity: the vugs provide storage space, and the fractures provide flow pathways.
 - (3) Dual role of faults in migration and sealing.
Early faults (Caledonian) served as migration pathways for early oil charging, whereas late faults (Himalayan) favor hydrocarbon trapping if they did not cut through the gypsum-salt caprock.
 - (4) Penetration of trap crests by wells.
The failures of wells such as KPN1 and PT1 may be related to missing the trap crest and encountering positions below the gas–water contact.

4.4.5. Favorable Exploration Targets

Trap interpretation on the top surfaces of the Lower Cambrian Wusongger Formation, the Xiaoerbulak Formation, and the Sinian Qigebulak Formation in the southern Keping area delineated nine traps covering 247 km², nine traps covering 244 km², and eight traps covering 217 km², respectively (Figure 21).

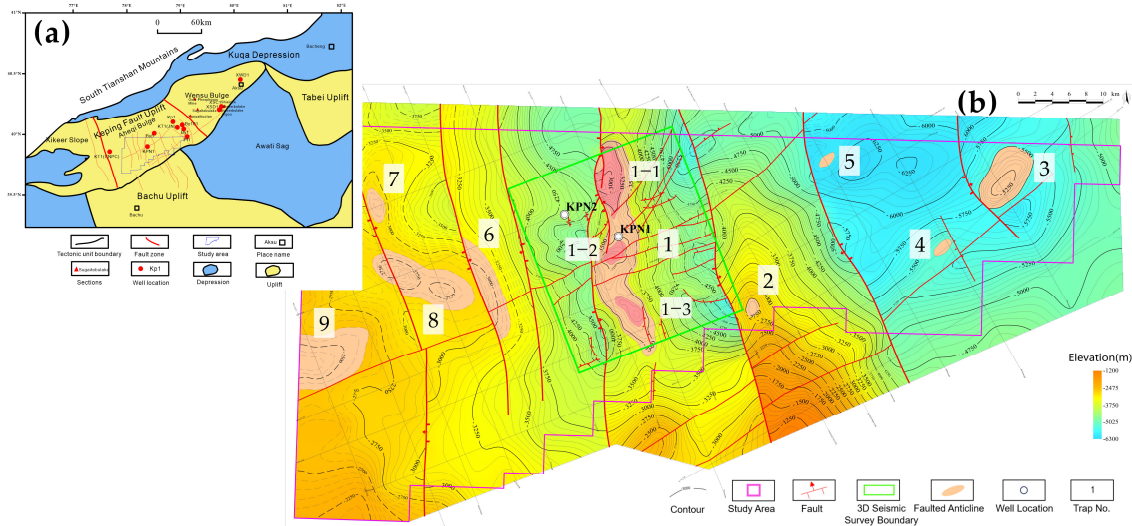


Figure 21. Structure map of the top surface of the Lower Cambrian in the southern Keping block. (a) Regional tectonic map of the Keping fault-uplift, with the blue frame indicating the study area; (b) enlarged view of the study area, where warm colors denote shallow burial and cool colors denote deep burial of the top surface (elevation in meters). Numbers (1–9) are trap numbers; traps 1-1 to 1-3 are subdivisions of Trap 1 adjacent to Wells KPN1 and KPN2. The green outline denotes the 3D seismic survey boundary.

The first-priority target is the trap crest in the northern part of the 3D seismic survey area (Trap 1-1). This trap is controlled by NW-trending faults formed during the Late Caledonian–Hercynian, and its geometry is stable. The subsalt trap was little affected by the Himalayan north-to-south thrusting. It lies close to the BY1 hydrocarbon-generating sag, a position favorable for hydrocarbon migration and charging.

The second-priority target is the trap crest in the southern part of the 3D seismic survey area (Trap 1-3). Its closure integrity is poor, and hydrocarbon sealing depends solely on the lateral fault, so the risk to trapping is higher. It lies close to the Bachu Uplift, where reservoir quality is better, but it is far from the main hydrocarbon-generating sag.

5. Conclusions

- (1) Two source-rock intervals, the Yuertusi Formation and the lower member of the Xiaoerbulak Formation, are developed in the Lower Cambrian of the southern Keping area. The Yuertusi Formation has TOC contents of 0.13–28.20% and is a high-quality source rock. In the southern Keping area, however, proximity to the paleo-land and a shallow, oxygenated water column restricted its thickness to 4–5 m and lowered the mean TOC to 0.85%, giving a pattern of thicker and richer source rocks in the north and thinner, leaner ones in the south. The lower member of the Xiaoerbulak Formation has TOC contents of 0.10–9.68% (mean 1.55%), a thickness of 70–160 m, and a distribution area of 20,000–30,000 km², rating as a moderate-to-good source rock. Its cumulative organic-matter inventory may far exceed that of the thin but enriched Yuertusi Formation, making it a newly recognized source rock in the Keping area and

changing the conventional view that the Yuertusi Formation is the only Cambrian source rock in northwestern Tarim.

- (2) In both intervals, sapropel-group macerals account for more than 80% of the kerogen, and the parent organic matter consists of algae (including cyanobacteria and other microbes) and planktonic lower aquatic organisms, corresponding to original Type I–II kerogen. The low HI and Type II/III signatures shown on pyrolysis diagrams are artifacts of secondary thermal alteration at high-to-overmature levels, not the original kerogen type. EqVRo values of 2.28–3.50% (>2.0%) indicate that both intervals have entered the high-to-overmature gas-generation stage, consistent with the gas-dominated exploration results in this area.
- (3) The Yuertusi Formation was deposited in a high-productivity setting controlled by upwelling (mean Ba of 18,319.5 µg/g, about 28 times PAAS; mean Zn of 208.9 µg/g, about 2.5 times PAAS; barite–apatite–siliceous rock assemblage) under a strongly reducing (anoxic–euxinic) water column corresponding to the core of a perennial OMZ. The lower member of the Xiaoerbulak Formation shows no anomalous Ba enrichment, but its Al-normalized Zn/Al₂O₃ ratio is about 4.3 times the UCC background, indicating elevated productivity, and its depositional water column was dysoxic to weakly anoxic with local anoxia. Post-glacial warming, upwelling, and rift-trough-controlled deposition jointly governed organic-matter enrichment in the two intervals.
- (4) Geochemical analyses confirm that the Cambrian subsalt gas in the Keping area is oil-cracked gas, sourced from the marine sapropelic source rocks of the Yuertusi or Xiaoerbulak formations. The mismatch between fluid-inclusion homogenization temperatures (100–130 °C and 140–150 °C) and the thermal evolution history (main gas generation after the middle–late Hercynian) indicates two charging events: early oil charging (Late Caledonian–Hercynian) and late gas charging (Himalayan), with the main accumulation stage in the Himalayan orogeny.
- (5) Based on the chloroform bitumen “A” method, the static geological gas resources of the Lower Cambrian in the Keping area reach $1121.4 \times 10^9 \text{ m}^3$ ($990.3 \times 10^9 \text{ m}^3$ in the Yuertusi Formation and $131.1 \times 10^9 \text{ m}^3$ in the lower member of the Xiaoerbulak Formation), and those of the southern Keping area total $20.1 \times 10^9 \text{ m}^3$. Its dynamic resource potential, however, may be far higher than the static estimate and requires further quantification through basin modeling.
- (6) The southern Keping area follows an accumulation model of “lower generation and upper storage, fault control, and near-source accumulation”. Trap 1-1 in the northern part of the 3D survey area, with a stable geometry and proximity to the generating sag, is the most favorable drilling target. Trap 1-3 in the south is the second-priority target, but it is far from the main hydrocarbon-generating sag and carries higher risks to trapping and hydrocarbon migration.

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