

Evaluation of the oil and gas preservation conditions, source rocks, and hydrocarbon-generating potential of the Qiangtang Basin: New evidence from the scientific drilling project

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ABSTRACT

The Qiangtang Basin of the Tibetan Plateau, located in the eastern Tethys tectonic domain, is the largest new marine petroliferous region for exploration in China. The scientific drilling project consisting primarily of well QK-1 and its supporting shallow boreholes for geological surveys (also referred to as the Project) completed in recent years contributes to a series of new discoveries and insights into the oil and gas preservation conditions and source rock evaluation of the Qiangtang Basin. These findings differ from previous views that the Qiangtang Basin has poor oil and gas preservation conditions and lacks high-quality source rocks. As revealed by well QK-1 and its supporting shallow boreholes in the Project, the Qiangtang Basin hosts two sets of high-quality regional seals, namely an anhydrite layer in the Quemo Co Formation and the gypsum-bearing mudstones in the Xiali Formation. Moreover, the Qiangtang Basin has favorable oil and gas preservation conditions, as verified by the comprehensive study of the sealing capacity of seals, basin structure, tectonic uplift, magmatic activity, and groundwater motion. Furthermore, the shallow boreholes have also revealed that the Qiangtang Basin has high-quality hydrocarbon source rocks in the Upper Triassic Bagong Formation, which are thick and widely distributed according to the geological and geophysical data. In addition, the petroleum geological conditions, such as the type, abundance, and thermal evolution of organic matter, indicate that the Qiangtang Basin has great hydrocarbon-generating potential.

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1. Introduction

The Qiangtang Basin is located in the eastern portion of the Tethys tectonic domain, which boasts the most abundant hydrocarbons in the world. This basin is the last large-scale marine petroliferous basin with the absence of breakthroughs in offshore hydrocarbon exploration in China (Wang J et al., 2009). It has the same tectonic setting and similar petroleum geological conditions as the oil and gas regions in Middle

East, and its oil and gas resource potential has thus attracted wide attention (Zhao ZZ et al., 1997; Liu CY et al., 2001; Xu ZQ et al., 2011; Wang J et al., 2022b). Many researchers believe that the Qiangtang Basin has great resource potential and is the target with the strongest possibility that breakthroughs can be achieved in onshore hydrocarbon exploration in China (Wang CS and Zhang SN 1996; Wang CS et al., 2001; Wang J et al., 2004, 2009; Liu JD et al., 2007; Qiao DW et al., 2011; Wu ZH et al., 2019).

Since the beginning of the 21st century, the Ministry of Land and Resources of P.R.C., China Petroleum & Chemical Corporation (Sinopec), and PetroChina have organized multiple rounds of strategic area selection, investigation, and evaluation of oil and gas resources. Based on the 1 : 250000 regional geological surveys, these organizations have made

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great efforts in the fields of basic geology, petroleum geology, geophysics, hydrocarbon geochemistry, shallow boreholes, and the drilling of scientific exploration wells in the Qiangtang Basin, obtaining a series of new understandings: (1) The Qiangtang Basin has rigid Precambrian basements, a framework consisting of large-scale uplifts and depressions, and Mesozoic strata with a sedimentary thickness of 1.3–5.9 km (Wang J et al., 2004; Tan FW et al., 2009; Gao R et al., 2013; Fu XG et al., 2020a; Xiong SQ et al., 2020; Wang et al., 2022a); (2) This basin possesses the petroleum geological conditions necessary for the formation of large oil and gas fields, as shown by the studies of the sedimentary filling successions, stratigraphic-tectonic framework, lithofacies paleogeographic characteristics, and source-reservoir-caprock assemblages of the basin (Wang CS et al., 2001; Wang J and Fu XG, 2018; Wang J et al., 2022a); (3) More than 250 oil and gas shows have been identified in the basin, including six liquid oil seepages, one paleo-reservoir zone, two oil shale zones, and several exhalative mud volcanic clusters, reflecting that large-scale hydrocarbon generation, migration, and accumulation once occurred in the Qiangtang Basin (Wang J et al., 2020a; Fu XG et al., 2020a); (4) Significant progress has been made in seismic exploration techniques. As a result, 2D seismic data with high signal-to-noise ratios have been obtained from local areas of the North Qiangtang depression, revealing that the Qiangtang Basin hosts stably distributed sedimentary successions and intact trap structures (Li ZX et al., 2013, 2019; Lu ZW et al., 2006, 2013; Wang J et al., 2020b, 2022a).

However, the understandings mentioned above are still controversial in terms of the oil and gas preservation conditions and source rocks. Regarding the oil and gas preservation conditions, Zhao ZZ et al. (2001b) and Xu ZQ et al. (2011) consider that the Qiangtang Basin hosts well-developed faults and accordingly poor oil and gas preservation conditions due to the strong transformation caused by the plateau uplift, which, together with subsequent tectonic movements, severely destroyed the oil reservoirs, leading to poor oil and gas preservation conditions. With regard to the source rocks, PetroChina analyzed more than 2400 source rock samples in the 1990s during its reconnaissance survey and evaluation of petroleum geology in the Qiangtang Basin, obtaining total organic carbon (TOC) content values of less than 0.5% overall. Accordingly, many scholars argue that the Qiangtang Basin lacks high-quality source rocks or contains only poor-quality ones, or it may even be devoid of source rocks (Zhao ZZ et al., 2001a; Fan XJ et al., 2020).

Targeting the key petroleum geological problems mentioned above, the China Geological Survey has organized and implemented the Project in the Qiangtang Basin in recent years. This has led to the establishment of stratigraphic sedimentary successions of the sedimentary basin and several new findings. Among these are the discovery of an extremely thick anhydrite layer in the Quemo Co Formation and the gypsum-bearing mudstones in the Xiali formations, as well as

high-quality source rocks and hydrocarbon anomaly shows occurring in multiple beds in the Bagong Formation. Drawing from the recent project data and two decades of petroleum geological surveys over the past 20 years, this study primarily explores the oil and gas preservation conditions and source rocks in the Qiangtang Basin and, accordingly, analyzes the basin's resource potential, aiming to promote the hydrocarbon exploration and achieve early breakthroughs in the basin.

2. The scientific drilling project

The Project mainly includes the drilling of well QK-1 (depth: 4696.18 m), 17 supporting shallow boreholes (depths: hundreds of meters to about 2000 m) for geological surveys, the 2D seismic survey over a length of 1160 km, and related surface geological surveys and comprehensive research (Figs. 1, 2, 3). This section focuses on the new data obtained by the Project, including the first established stratigraphic sedimentary successions of the basin, the newly discovered caprocks (the extremely thick anhydrite layer of the Quemo Co Formation and the gypsum-bearing mudstones of the Xiali Formation), the high-quality source rocks and multiple hydrocarbon anomaly shows in the Bagong Formation, and 2D seismic data.

2.1. Well QK-1

Well QK-1 is located in the Bandaohu area in the northern Qiangtang Basin of the northern Tibetan Plateau, with an open hole in the Upper Jurassic Suowa Formation, a wellhead elevation of 5030 m, and a final hole depth of 4696.18 m. Five formations were encountered in this well QK-1 (Fig. 4), namely the carbonate rocks in the Upper Jurassic Suowa Formation, the terrigenous clastic rocks interbedded with carbonate rocks in the Middle Jurassic Xiali Formation, the carbonate rocks in the Middle Jurassic Buqu Formation, the anhydrite and the carbonate rocks interbedded with clastic rocks in the Middle-Lower Jurassic Quemo Co Formation, and the volcanoclastic rocks in the Upper Triassic Nadi Kangri Formation from top to bottom.

The scientific drilling of well QK-1 allows for roughly establishing the profiles of the lithology (lithofacies), electrical properties, physical properties, formation pressure, and hydrocarbon-bearing properties of strata in the Bandaohu area of the Qiangtang Basin. Consequently, a series of geophysical parameters were obtained, and the reliability of geophysical data and hinterland structures was verified. In particular, a series of new discoveries regarding regional caprocks, oil and gas shows, and basin sedimentary successions were made based on the drilling of well QK-1. Specifically, two sets of seals have been identified, namely the extremely thick anhydrite layer of the Quemo Co Formation and the gypsum-bearing mudstones of the Xiali Formation, with gas logging anomalies having been found in 13 beds in total. Furthermore, complete and continuous sedimentary successions of Jurassic strata were encountered in this well. In addition, many new understandings have been

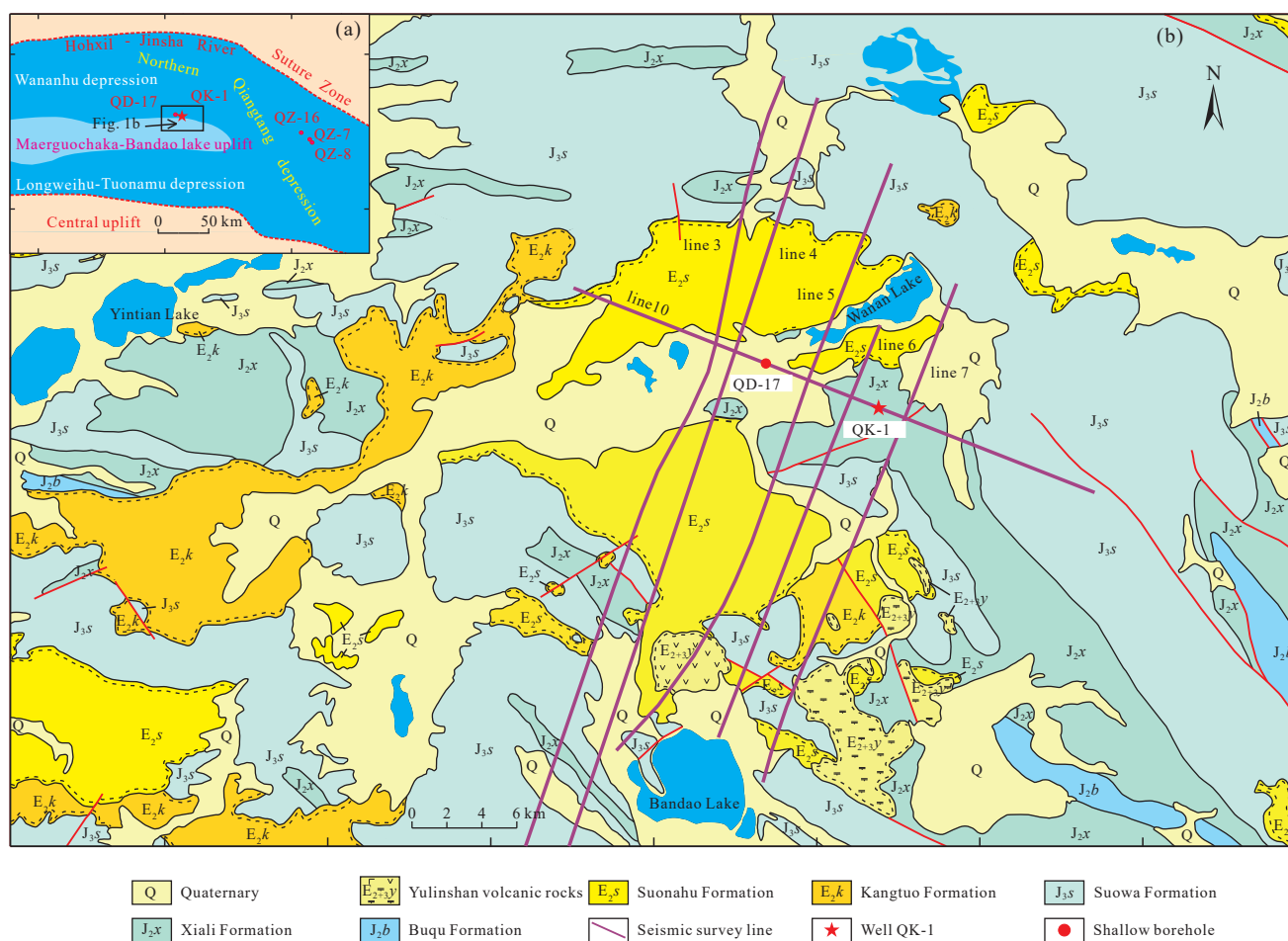


Fig. 1. Map showing the locations of well QK-1 and shallow borehole QD-17 (modified from Wang J et al., 2022a).

gained in the exploration of the drilling, logging, well completion, and test techniques for the permafrost in the Qiangtang Plateau.

(i) Stratigraphic successions

Complete, continuous sedimentary successions of the Upper Triassic–Jurassic strata were encountered in well QK-1. As shown by the log curves and cutting logs, as well as the shallow boreholes and outcrop profiles, the Upper Triassic – Jurassic strata exhibit a transgression-retrogradation-overlap process overall, during which the continental facies gradually transitioned to the marine facies. These strata gradually transitioned from terrigenous clastic rocks and volcanoclastic rocks to carbonate rocks, and from a restricted basin to open-sea and mixed carbonate platforms. Moreover, these strata are generally composed of four sedimentary successions, namely the volcanic rock–volcanoclastic rock, fluvial-lacustrine-delta, tidal flat–lagoon, and restricted carbonate platform (shoal)–open carbonate platform (tidal flat) sedimentary successions.

Volcanic rock–volcanoclastic rock sedimentary succession in the Nadi Kangri Formation (T_{3nd}): This sedimentary succession has a thickness of 639.2 m at a well depth of 4057–4696.2 m. The Nadi Kangri Formation is composed primarily of grayish-green tuffites and tuffs interbedded with small amounts of diabases and basalts. This formation is in conformable contact with the purplish-red

fluvial-lacustrine-delta facies glutenites at the bottom of the overlying Quemo Co Formation. Its bottom is not yet controlled.

Fluvial–lacustrine–delta and tidal flat–lagoon sedimentary successions in the Quemo Co Formation (J_{1-2q}):

Both sedimentary successions have thicknesses of 1561 m at a well depth of 2496–4057 m. The Quemo Co Formation is composed primarily of limestones, anhydrite, calcareous siltstones, calcareous argillaceous siltstones, calcareous mudstones, and mudstones, interbedded with small amounts of argillaceous siltstones, conglomerates, and conglomeratic sandstones. It is in conformable contact with the overlying Buqu Formation.

Tidal flat–carbonate platform (shoal) sedimentary succession in the Buqu Formation (J_{2b}):

This sedimentary succession has a thickness of 1446 m at a well depth of 1050–2496 m. The Buqu Formation is composed primarily of algal calcarenites, oolitic limestones, chalky limestones, calcareous siltstones, calcareous silty mudstones, calcareous mudstones, and mudstones. It is in comfortable contact with the overlying Xiali Formation.

Tidal flat – lagoon sedimentary succession in the Xiali Formation (J_{2x}):

This sedimentary succession has a thickness of 991 m at a well depth of 59–1050 m. The Xiali Formation is composed primarily of mudstones, calcareous mudstones, and micritic limestones, interbedded with gypsum

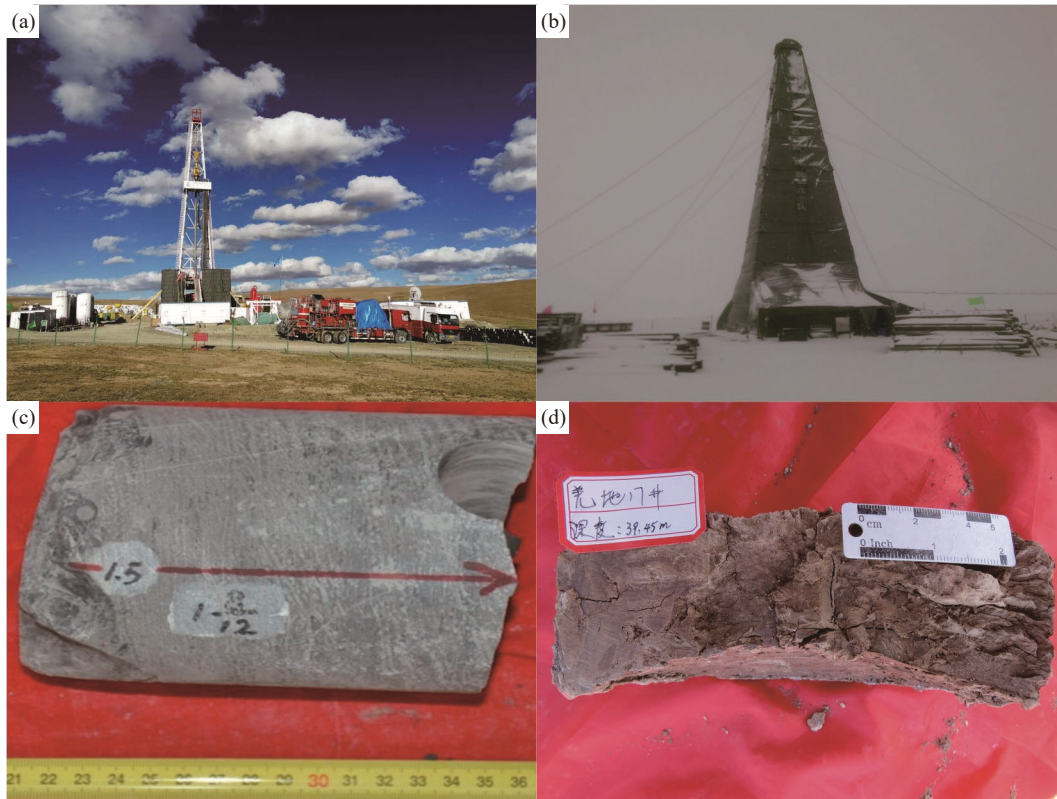


Fig. 2. Some photos of scientific drilling project. a–Photo of well QK-1; b–photo of well QD-17; c–micrite limestone at 1057.41 m in QK-1; d–mudstone at 39.45 m in QD-17.

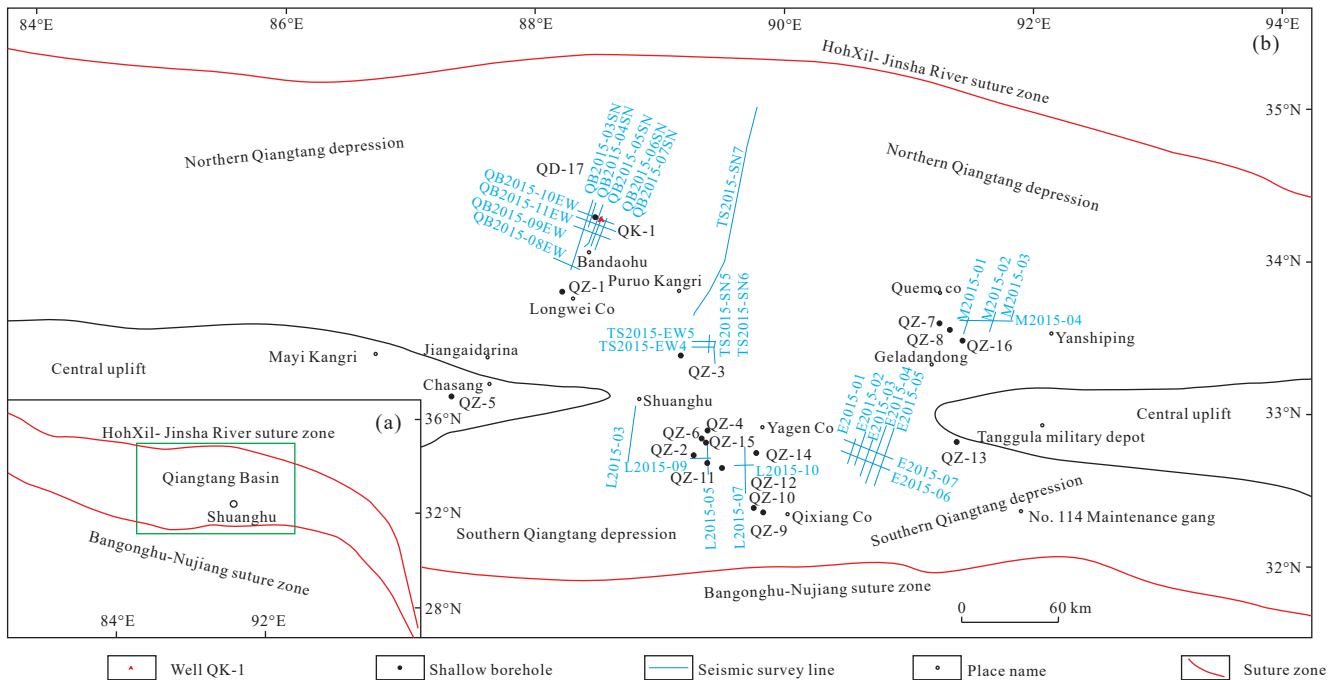


Fig. 3. Map showing the regional tectonic setting and scientific drilling project arrangement in the Qiangtang Basin (modified from Wang J et al., 2022a).

and sandstones. It is in comfortable contact with the overlying Suowa Formation.

Carbonate platform sedimentary succession in the Suowa Formation (J₃s): This sedimentary succession has a thickness of 59 m at a well depth of 0–59 m. The Suowa

Formation is composed primarily of open-platform carbonate rocks. Its top is not yet controlled.

(ii) Anhydrite layer in the Quemo Co Formation

The anhydrite layer in the middle member of the Quemo Co Formation in well QK-1 has a continuous thickness of 365

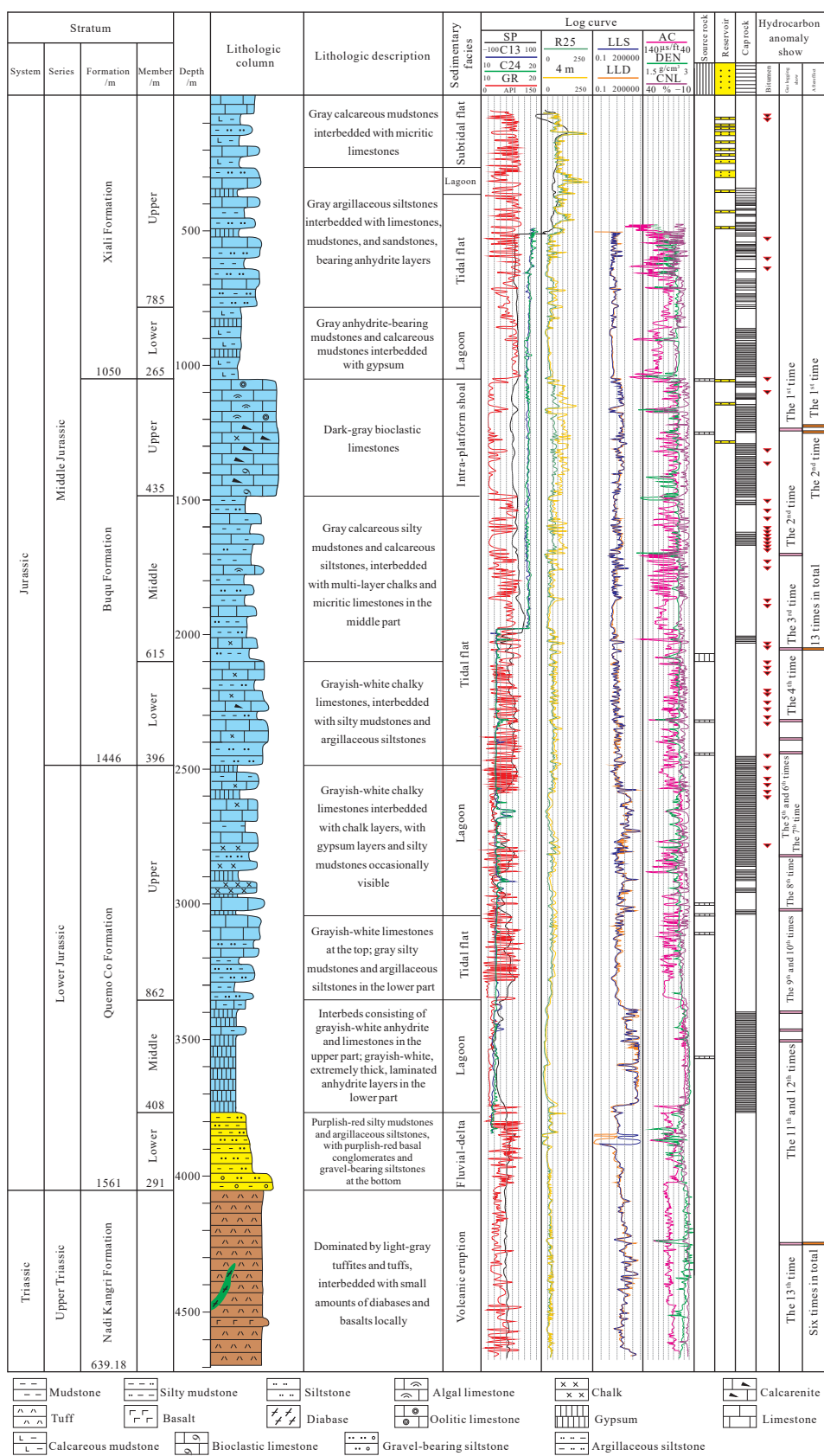


Fig. 4. Comprehensive stratigraphic column of the drilling and logs of well QK-1 (modified from Wang J et al., 2020a, 2022b).

m at a well depth of 3358–3766 m (Fig. 4). As revealed by core samples and cutting log data, the anhydrite occurs in a laminated or stratoid form and is occasionally mixed with small amounts of carbonates (dolomites), argillaceous clays,

ferric oxides and pyrites.

The log curves of the anhydrite layer are stated as follows:
 (1) The gamma-ray (GR) log exhibits low to extremely low GR values, with GR spectrometry data presenting significant

low radioactivity; (2) the density (DEN) log curve shows a formation density of about 2.91 g/cm³; (3) The laterolog shallow (LLS) and laterolog deep (LLD) log curves show extremely high resistivity; (4) The spontaneous potential (SP) log curve is flat; (5) The formation micro-imaging (FMI) logging yielded bright orange images, which exhibit higher resistivity than limestones, as well as blocky textures and occasionally visible argillaceous bands or filled (semi-filled) fractures; (6) The cross-dipole acoustic (AC) log curve shows clear compressional, shear, and Stoneley wave trains. As indicated by the physical property analysis, the anhydrite samples had porosities of 0.6%–2.1% and permeabilities of 0.0342×10^{-3} – 0.161×10^{-3} μm².

(iii) Gypsum-bearing mudstones in the Xiali Formation

The gypsum-bearing mudstones of the Xiali Formation in well QK-1 have a thickness of 230 m at a well depth of 820–1050 m (Fig. 4). As revealed by core samples and cutting log data, this layer is composed primarily of mudstones and calcareous mudstones, interbedded with gypsum.

The log curves of mudstones and calcareous mudstones exhibit high GR values, high interval transit time (ITT), high neutron values, low resistivity, low density, and flat and straight SP log curves. The GR spectrometry data of conventional logging show relatively high radioactivity (i.e., high thorium and potassium concentrations), and the DEN log curve shows a density of 1.82–2.48 g/cm³ (Fig. 4). In addition, the FMI logging yielded dark brown static images, which reveal the occurrence of beddings. The cross-dipole AC log curve shows lags of compressional, shear, and Stoneley waves.

The anhydrite in the Xiali Formation exhibits very similar log curves to that in the Quemo Co Formation, showing low to extremely low GR values, extremely high resistivity in LLD and LLS log curves, and a density of close to 2.98 g/cm³. Moreover, various porosity logs show apparent porosity values of nearly 0.

In terms of physical properties, the anhydrite samples from the Xiali Formation had an average porosity of 1.42%, a permeability of 0.0012 Md, and a saturated water breakthrough pressure of 18.37 MPa, suggesting high sealing performance.

As shown in the seismic profile (Fig. 5), the gypsum-bearing mudstones and the calcareous mudstones interbedded with anhydrite in the lower member of the Xiali Formation are present as snowflake-like weak reflections with discontinuous seismic events, which can be traced and compared regionally.

(iv) Gas logging anomalies of hydrocarbons

Significant gas logging anomalies were discovered in 13 beds in well QK-1 in total. These anomalies occur at well depths of 1237–4254 m, involving three strata, namely the Middle Jurassic Buqu Formation, the Lower Jurassic Quemo Co Formation, and the Upper Triassic Nadi Kangri Formation.

In the Buqu Formation, hydrocarbon anomalies occur in six beds, with a total thickness of 22.7 m (15.7 m in three

limestone beds, 5 m in two argillaceous siltstone beds, and 2 m in one mudstone bed). Notably, the most significant hydrocarbon anomalies in this formation occur at well depths of 1237.0–1249.3 m (apparent thickness: 12.3 m), with a gas logging-derived total hydrocarbon (methane) value of 4.459%, including 3.577% of methane (C₁) and 0.002% of ethane (C₂), and a hydrogen sulfide concentration of up to 210 ppm.

The hydrocarbon anomalies in the Quemo Co Formation occur in six beds, with a total thickness of 21 m (17 m in four limestone beds, 2 m in one calcareous dolomite bed, and 2 m in one mudstone bed). The hydrocarbon anomalies in this formation that are the most active and have the most significant aftereffects occur at well depths of 3401.0–3407.0 m (apparent thickness: 6 m).

Regarding the Nadi Kangri Formation, hydrocarbon anomalies are present in one bed (calcareous tuffs) at well depths of 4246.0–4253.7 m (apparent thickness: 7.7 m) below the anhydrite layer of the Quemo Co Formation. Intriguingly, their gas logging-derived total hydrocarbon (methane) value increases rapidly by 80.5 times from 0.044% to 3.544% (C₁: 3.359%; C₃: 0.048%; C₄: 0.002%; iC₄: 0.005%). During the drilling of this bed, the drilling time shortened from 27.42 min/m to 15.20 min/m and the mud density decreased from 1.25 g/cm³ to 1.23 g/cm³. Moreover, about 5% of pinhole-shaped bubbles appeared on the trough surface. This is the first time that gas-bearing zones are discovered in pyroclastic rocks in the Upper Triassic Nadi Kangri Formation of the Qiangtang Basin.

It is noteworthy that significant hydrocarbon anomalies, accompanied by the escape of high-concentration hydrogen sulfide, were discovered after two sets of seals (the gypsum-bearing mudstones in the Xiali Formation and the anhydrite layer in the Quemo Co Formation) were drilled through.

2.2. Shallow boreholes

To obtain the required core logs, 17 fully cored shallow boreholes were drilled in the basin in the Project, ensuring that there are intact physical cores from all formations in the Upper Triassic, Jurassic, Cretaceous, and Cenozoic strata. High-quality source rocks in the Upper Triassic Bagong and Bolila formations were discovered in these boreholes. Similar to well QK-1, the shallow boreholes also encountered two sets of seals, namely the extremely thick anhydrite and gypsum-bearing mudstones in the Quemo Co and Xiali formations. In addition, oil and gas shows were identified in multiple beds in these shallow boreholes. The basic conditions of boreholes QD-17, QZ-16, QZ-7, and QZ-8 are introduced as follows:

(i) Borehole QD-17

Borehole QD-17 is located 6.25 km west of well QK-1 and has a depth of 2001.8 m. This borehole was drilled to obtain cores of the Xiali and Buqu formations at the same horizon as the upper part of well QK-1 and to acquire information about the Upper Cretaceous-Cenozoic strata above the Jurassic-Late Yanshanian (Early Cretaceous) fold

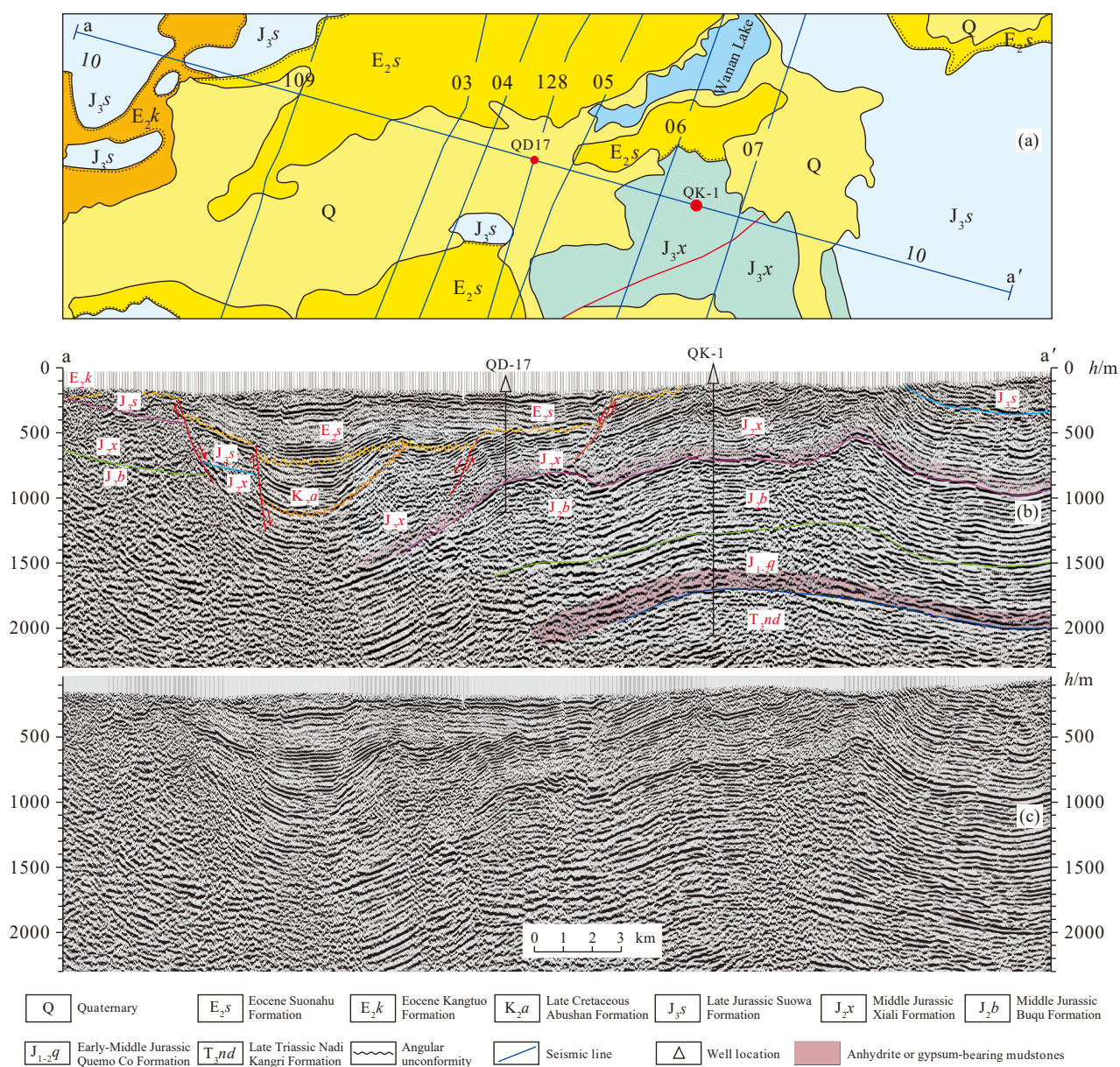


Fig. 5. Locations of wells and boreholes in the Bandaohu area of the North Qiangtang depression and the stratigraphic -structural interpretation of the 2D reflection seismic profile QB2015-10EW. a–Relative positions of some seismic survey lines; b–structural interpretation of the seismic profile (QB2015-10EW) across well QK-1 and borehole QD-17; c–seismic profile QB2015-10EW (uninterpreted; for comparison with Fig. 5b).

system (Fig. 6).

The strata encountered in Borehole QD-17 consist of the Quaternary (Q) with a thickness of 4.4 m, the Eocene Suonahu Formation (E_{2s}) with a thickness of 466.5 m, the Middle Jurassic Xiali Formation (J_{2x}) with a thickness of 673.3 m, and the middle and upper parts of the Buqu Formation (J_{2b}) with a total thickness of 857.6 m. The gypsum-bearing mudstones with a thickness of 252 m in the Xiali Formation were discovered during the drilling of this borehole. These caprocks have similar log characteristics to well QK-1, with an average porosity of 1.42%, a permeability of 0.0012 Md, and a saturated water breakthrough pressure of 18.37 MPa. This borehole reveals very similar gas anomalies to well QK-1. In particular, after drilling through the gypsum-bearing mudstones of the Xiali Formation, gas shows were

discovered at depths of 1484–1485 m in the upper member of the Buqu Formation, i.e., at the same horizon where gas shows were found in well QK-1. As shown by the real-time logging during the drilling of this borehole, the gas logging-derived total hydrocarbon value of the mud increased from 0.186% to 3.901%, with an aftereffect value of 10.587%, which included 10.197% of C₁ (dominant), 0.001% of C₂, and 0.003% of C₃.

In addition, borehole QD-17 revealed hydrocarbon anomalies in the Eocene Suonahu Formation at a depth of 147.9 m. The anhydrite in the cores of the anhydrite-bearing calcareous mudstones was oil immersed and black in color, and it has a fluorescence-detection contrast level of 5.2 and an oil-bearing property index of 0.8, suggesting light oil.

(ii) Boreholes QZ-7 and QZ-8

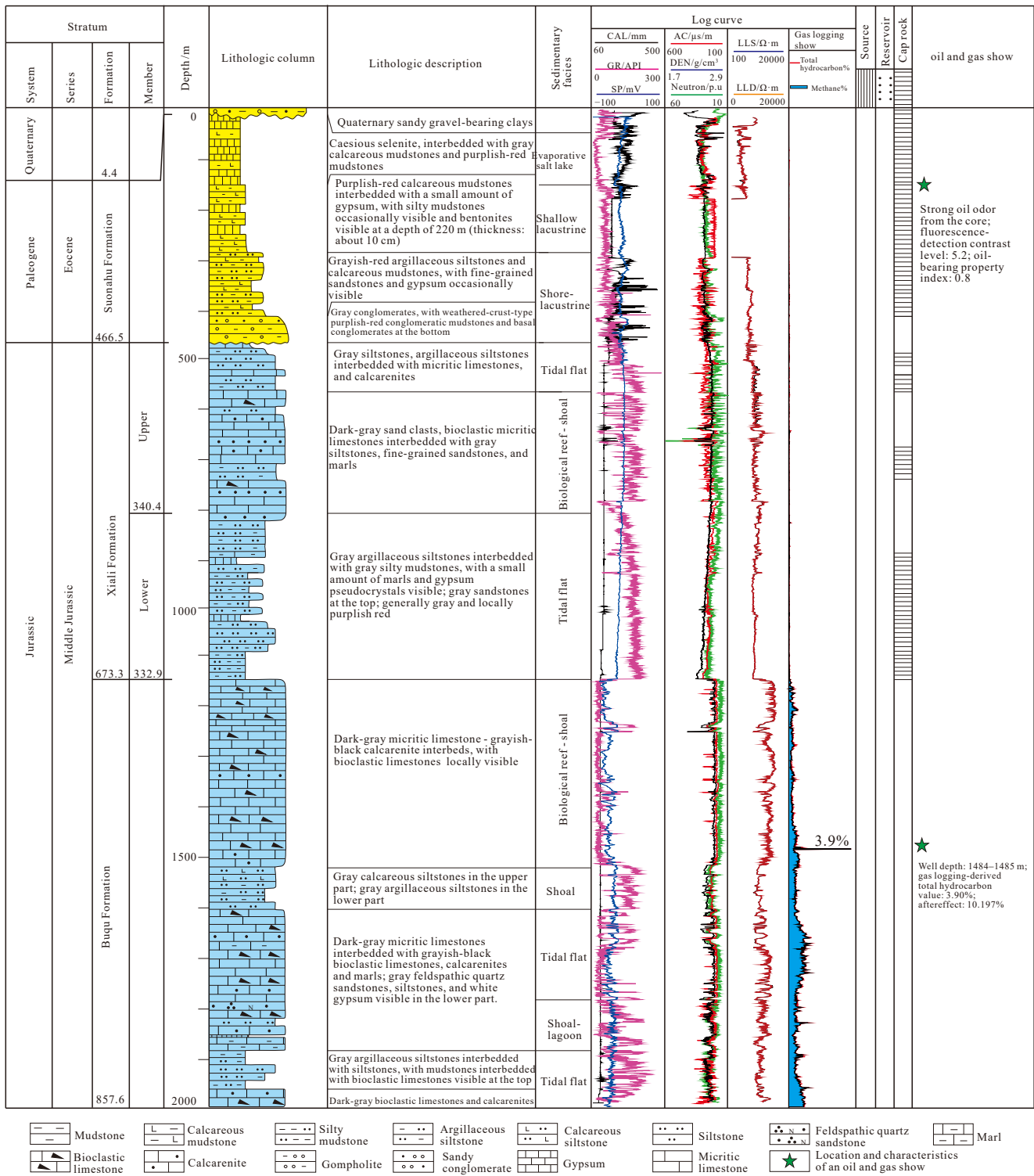


Fig. 6. Comprehensive stratigraphic column revealed by shallow borehole QD-17.

Boreholes QZ-7 and QZ-8, only a few hundred meters apart, are both located in the Qumo Co area in northern Geladandong in the eastern part of the North Qiangtang depression. They have depths of 402.5 m and 501.7 m, respectively, and both revealed the dark argillaceous Upper Triassic source rocks (Figs. 7, 8).

In borehole QZ-7, the fully cored horizons include the Quaternary (Q) with a thickness of 3.7 m, the Upper Triassic Bagong Formation (T_3bg) with a thickness of 241.2 m, and

the top part of the Upper Triassic Bolila Formation (T_3b) with a thickness of 157.6 m (Fig. 7). Notably, the Upper Triassic Bagong Formation (together with the top part of the Bolila Formation) is composed of black carbonaceous and argillaceous rocks and carbonate rocks. The black carbonaceous and argillaceous rocks have a TOC content of up to 3.56%. Among them, source rocks with TOC contents of above 2% and above 1% have thicknesses of 36 m and 61 m, respectively. Fourteen core samples of source rocks

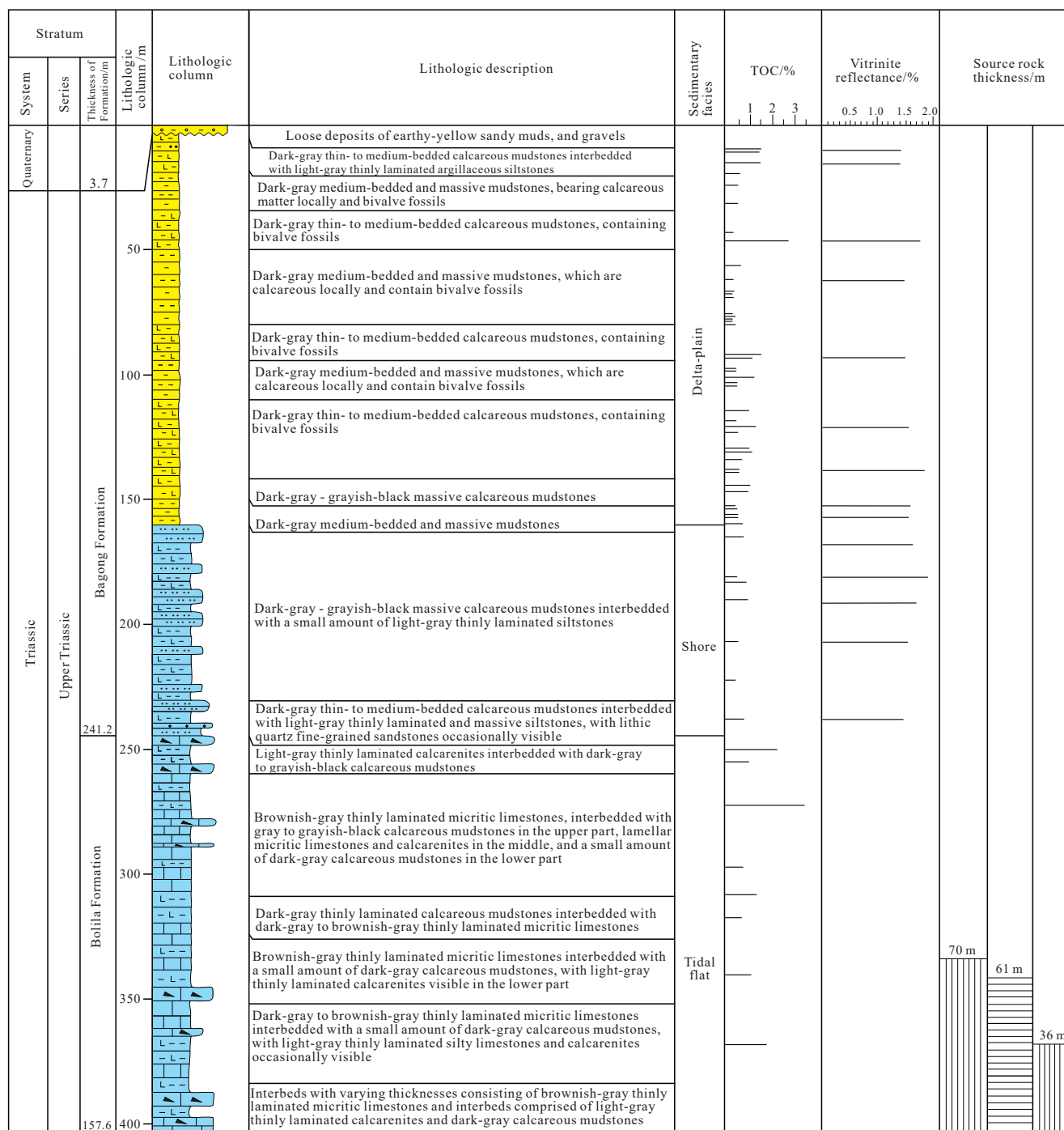


Fig. 7. Comprehensive stratigraphic column revealed by shallow borehole QZ-7.

collected at well depths of 9–250 m showed type II₂ and type III kerogens and vitrinite reflectance (R_0) values (2%–1.3%). Moreover, a large amount of hydrocarbon gas was observed leaking at a well depth of 250 m, accompanied by a large amount of gas emitted at the wellhead and a strong odor of oil and gas. Oil sands in the form of thin slabs were found at a depth of 360 m. The logs show that two major gas-bearing zones occur at depths of 249.1–251.2 m and 278.5–281.6 m, with gas saturation and oil saturation of 10.08% and 28.41%, respectively.

The fully cored horizons in borehole QZ-8 include the Quaternary (Q) with a thickness of 3.2 m, the Upper Triassic

Bagong Formation (T_3bg) with a thickness of 166.4 m, and the middle and upper parts of the Upper Triassic Bolila Formation (T_3b) with a total thickness of 332.1 m (Fig. 8). The black carbonaceous and argillaceous rocks in the Upper Triassic Bagong Formation exhibit very similar characteristics to those encountered in borehole QZ-7. Specifically, twenty-seven samples of these rocks had TOC contents of 0.30%–3.37% (average: 1.10%), with source rocks with a TOC content of above 1% accounting for 56%.

(iii) QZ-16

Borehole QZ-16, with a depth of 1592.7 m, is located near borehole QZ-7 and at a distance of about 200 km from well

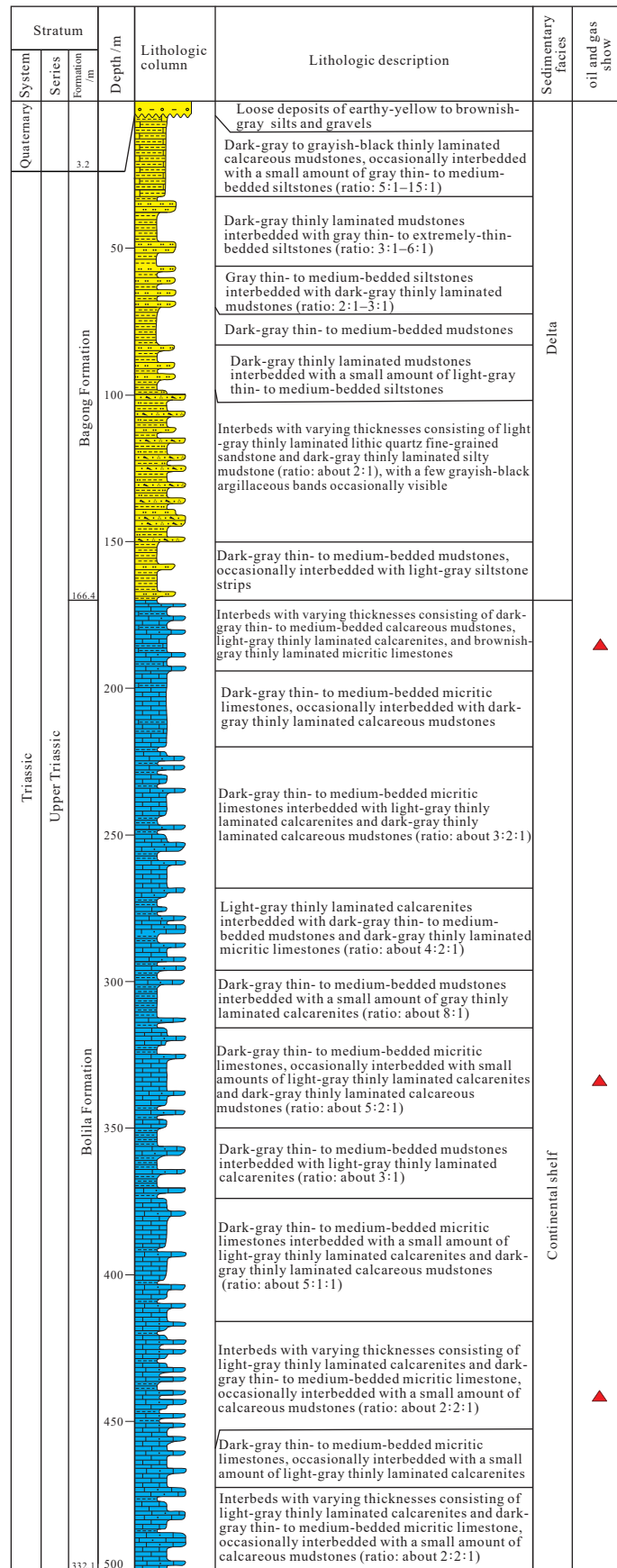


Fig. 8. Comprehensive stratigraphic column revealed by shallow borehole QZ-8.

QK-1 (Fig. 9). This borehole was drilled to collect the core samples of the Quemo Co, Nadi Kangri, Bagong and Bolilia

formations at the same horizons as those in the middle to lower part of well QK-1. The strata encountered in borehole

QZ-16 include the Middle-Lower Jurassic Quemo Co Formation (J_{1-2q}) with a thickness of 855.7 m, the Upper Triassic Nadi Kangri Formation (T_{3nd}) with a thickness of 22.6 m, the Upper Triassic Bagong Formation (T_{3bg}) with a thickness of 445.3 m, the Upper Triassic Bolila Formation (T_{3b}) with a thickness of 185.0 m, and the top part of the Upper Triassic Jiapila Formation (T_{3j}) with a thickness of 84.1 m. The 382.9-m-thick anhydrite layer in the Quemo Co Formation was discovered during the drilling of borehole QZ-16, showing highly similar log characteristics to that in well QK-1. This anhydrite layer has an extremely low porosity, an average permeability of $0.265 \times 10^{-3} \mu\text{m}^2$, and an average breakthrough pressure of 9.0 MPa, suggesting high sealing performance. Moreover, active oil and gas shows were observed after drilling through the anhydrite layer.

2.3. 2D seismic exploration

The Project involves the construction of 2D reflection seismic exploration over a length of nearly 1160 km (Fig. 1). Owing to a large number of new techniques, methods, and devices that combine large-tonnage, low-frequency seismic vibrators with shot holes, as well as enhanced quality control of the field construction, the Project made significant progress in addressing the technological challenges of seismic exploration (Fu XG et al., 2020b; Wang J et al., 2022b).

The 2D reflection seismic exploration yielded encouraging seismic data primarily in the Bandaohu, Tuonamu-Shenggen, and Esima-Maqu areas of the Qiangtang Basin. The newly obtained seismic data mainly reflect that: (1) The Jurassic and Triassic strata of the Mesozoic in the Qiangtang Basin host continuous sedimentary successions, and the Mesozoic strata in the basin have a thickness of up to more than 6000 m; (2) The Upper Cretaceous Abushan Formation and the Eocene Suonahu Formation almost entirely lack folds and are in angular unconformable contact with the underlying Jurassic-Triassic fold system formed during the Late Yanshanian; (3) The strata in the North Qiangtang depression exhibit weak deformations and gentle folds, allowing clear identification of the extremely thick anhydrite layer in the Quemo Co Formation and the gypsum-bearing mudstones in the Xiali Formation. These caprocks are present as a layer of weak seismic reflections on the seismic profile. The strata in the North Qiangtang depression are relatively gentle and highly continuous, without large-scale fracturing and dislocation. These strata exhibit continuous and stable lateral extension in a certain range, suggesting the characteristics of regional distribution; (4) Three third-order traps and 41 fourth-order traps can be distinctly identified in the Bandaohu area. They are primarily of the anticlinal, faulted anticlinal, fault-nose, fault-block, and structural-stratigraphic types. The trap structures in the hinterland area are well preserved (Fig. 10); (5) The South Qiangtang depression is subjected to relatively strong tectonic deformations and thus holds relatively developed fault structures.

3. Problems and discussions

As stated in the above sections, the primary findings newly obtained by the Project are as follows: (1) The sedimentary successions of the Mesozoic strata in the Qiangtang Basin were established. These continuous transgression-retrogradation-overlap successions lay an important foundation for the formation of large-scale oil and gas fields; (2) Two sets of seals were discovered, namely the extremely thick anhydrite layer in the Quemo Co Formation and the gypsum-bearing mudstones in the Xiali Formation; (3) Hydrocarbon anomaly shows were identified in multiple beds, verifying that the Bagong Formation hosts high-quality source rocks. These new discoveries pose a new challenge to the previous views on the Qiangtang Basin, such as poor oil and gas preservation conditions (Zhao ZZ et al., 2001b; Xu ZQ et al., 2011) and the absence of high-quality source rocks (Zhao ZZ et al., 2001a; Fan XJ et al., 2020). Therefore, it is necessary to conduct a new round of evaluation and discussion of the oil and gas preservation conditions, source rocks, and hydrocarbon-generating potential of the Qiangtang Basin.

3.1. Hydrocarbon preservation conditions

Hydrocarbon preservation conditions play a crucial role in the hydrocarbon exploration and evaluation of basins and are the most important scientific problem with the analysis of basins' hydrocarbon resource potential (Li MC et al., 1997; Li YL et al., 2005; Jin ZJ, 2005; Zhao WZ et al., 2015). The Qiangtang Basin is a deformed basin resulting from late transformation (Zheng ML et al., 2004; Wang J et al., 2020). In particular, the Himalayan uplift of the Tibetan Plateau caused the general uplift and denudation of the Qiangtang Basin (Liu CY et al., 2009; Ren ZL et al., 2016), which possibly transformed and disrupted the hydrocarbon reservoirs formed previously. As a result, the oil and gas preservation conditions in the Qiangtang Basin can be significantly influenced by the characteristics and sealing performance of caprocks, the structures and tectonic uplift of the basin, magmatic activities, and groundwater.

3.1.1. Characteristics and sealing performance of caprocks

As shown by previous studies, the major caprocks in the Qiangtang Basin occur in Mesozoic strata and are composed primarily of mudstones (shales), marls, micritic limestones, gypsum rocks, and tight sandstones (Wang J et al., 2009, 2020). Owing to its high breakthrough pressure and high plasticity, anhydrite serves as the most effective seals, especially thick, widely distributed anhydrite layers (Surkov et al., 1991; Ma YS et al., 2006). Based on the analysis of the caprocks in the Biluo Co-Angdaer Co area of the South Qiangtang depression using data from shallow boreholes, previous researchers proposed that this area hosts significant nappe structures (Wu ZH et al., 2011, 2012). They also observed faults that not only have considerable destructive effects but also lack sealing capacities, leading to poor oil and

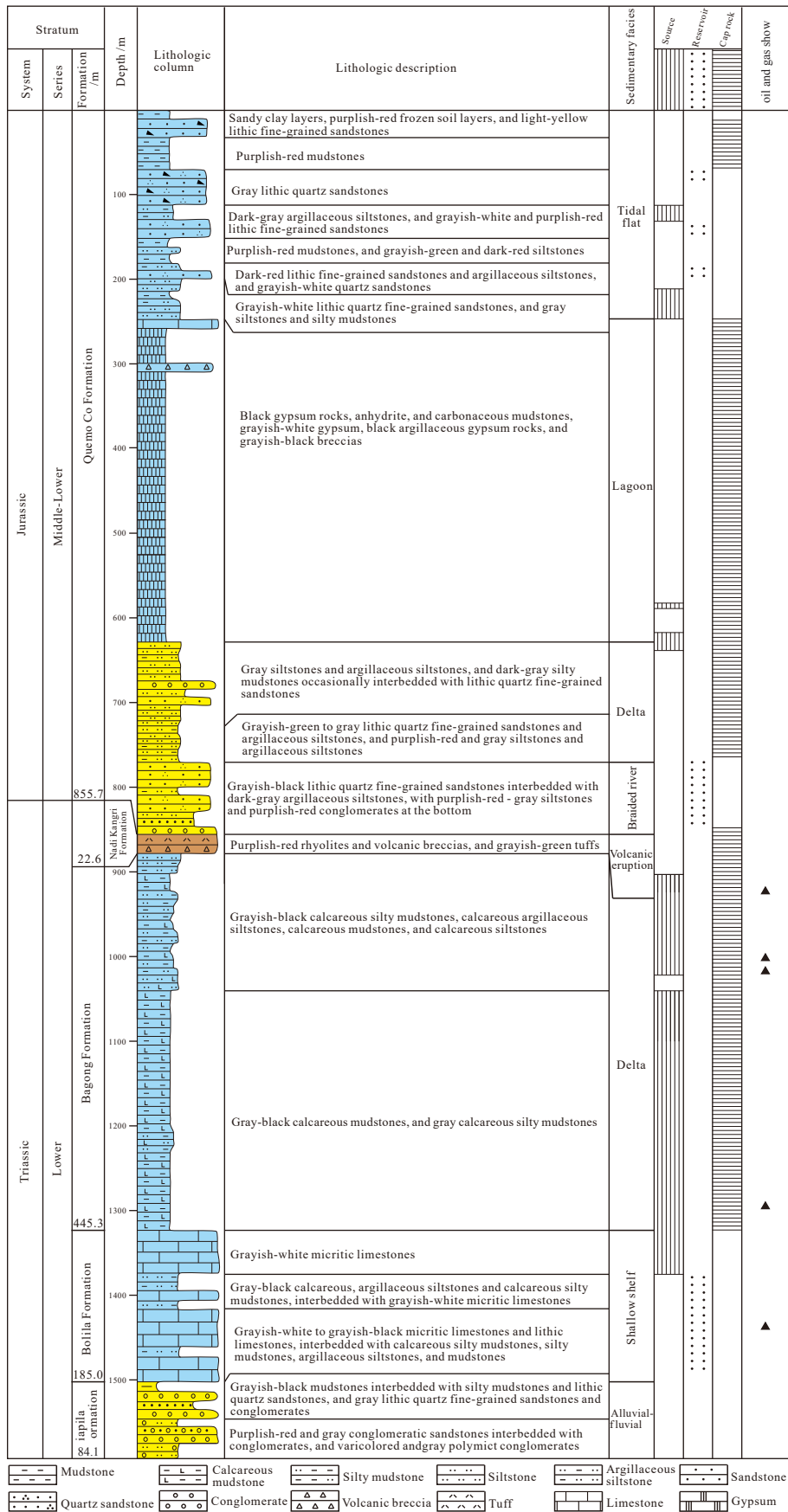


Fig. 9. Comprehensive stratigraphic column revealed by shallow borehole QZ-16.

gas preservation conditions in this area. In contrast, the latest results obtained by the Project indicate that two sets of

continuous, stable, and thick seals with favorable lithologies occur in the Xiali and Quemo Co formations in the North

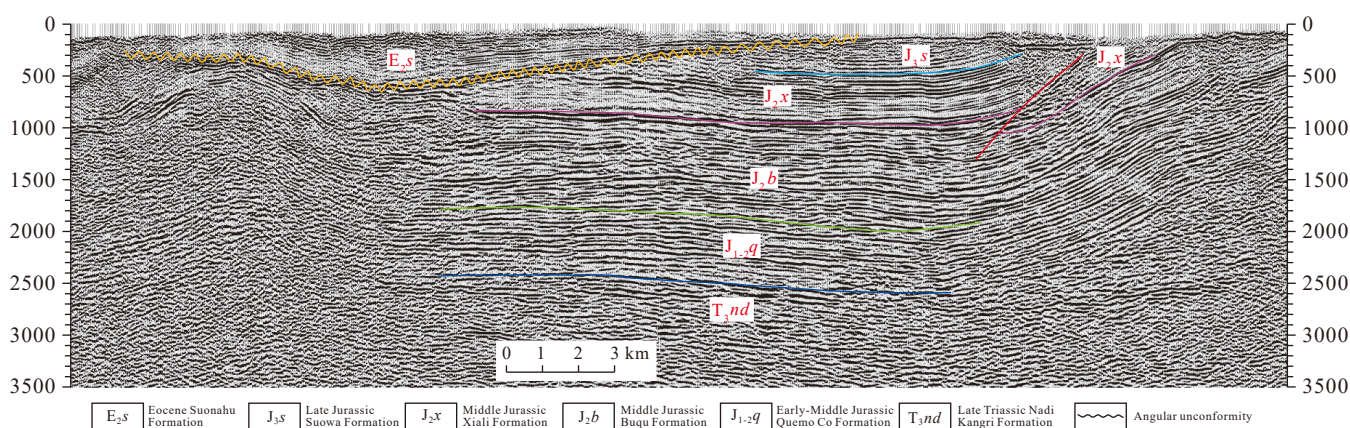


Fig. 10. Stratigraphic-structural deformations on the 2D reflection seismic profile (2015-09E) in the Bandaohu area of the North Qiangtang depression.

Qiangtang depression.

(i) Characteristics of caprocks

The gypsum-bearing mudstones in the Xiali Formation serve as the first set of seals of the Mesozoic hydrocarbon systems in the Qiangtang Basin. They are distributed mainly in the lower part of the Xiali Formation. Well QK-1 and shallow borehole QD-17 (Figs. 4, 6) reveal the gypsum-bearing mudstones in the Xiali Formation with thicknesses of 230 m and 252 m, respectively. Moreover, oil and gas shows were observed below the caprocks, indicating that these caprocks enjoy high sealing performance. The gypsum-bearing mudstones in the Xiali Formation are primarily exposed at the peripheries of the North Qiangtang depression. As shown by the seismic profiles, these gypsum-bearing mudstones are present as a layer of weak reflections, and they show continuous and stable lateral extension in a certain range, suggesting the characteristics of regional distribution. In addition, these gypsum-bearing mudstones are in the form of gentle folds in local areas and tectonically continuous, without large-scale fracturing and dislocation, thus forming the caprocks of traps in general (Fig. 5).

The anhydrite in the Quemo Co Formation serves as the second set of seals of the Mesozoic hydrocarbon systems in the Qiangtang Basin and is distributed mainly in the middle-lower part of the Quemo Co Formation. Well QK-1 and shallow borehole QZ-16 (Figs. 4, 9) reveal the anhydrite in the Quemo Co Formation with thicknesses of 365 m and 372 m, respectively. In addition, oil and gas shows were observed below these caprocks, also indicating that these caprocks enjoy high sealing performance. As indicated by the 2D seismic data, the anhydrite in the Quemo Co Formation extends continuously and stably, exhibiting the characteristics of regional distribution (Fig. 5). The anhydrite in the Quemo Co Formation is only exposed in the Central Uplift of the Qiangtang Basin and the fold belts at the peripheries of the basin, with a thickness of generally 200–400 m.

Overall, as revealed by the Project, the Qiangtang Basin hosts two sets of major seals, namely, the anhydrite in the Quemo Co Formation and the gypsum-bearing mudstones in the Xiali Formation. The Project also discovered that these

caprocks are thick and widely distributed, exhibiting the characteristics of regional seals. The gypsum-bearing mudstones in the Xiali Formation effectively seal the underlying biological reef-shoal reservoirs in the Buqu Formation. In contrast, the anhydrite layer in the Quemo Co Formation serves as crucial regional seals for the underlying clastic-carbonate reservoirs in the Bagong and Bolila formations.

(ii) Sealing performances of the caprocks

The surface outcrop samples of the anhydrite and gypsum-bearing mudstones exhibited significantly different sealing performances from their core samples. As shown by the analytical results, the outcrop samples of the anhydrite had porosities of 3.75%–31.7%, permeabilities of $(0.02\text{--}96.4) \times 10^{-3} \mu\text{m}$, displacement pressures of 0.40–7.31 MPa, and saturated water breakthrough pressures of 1.5–16.8 MPa. These results reflect that the exposed gypsum rocks have high porosity and permeability and low breakthrough and displacement pressures, which suggest poor sealing performance (Li YL et al., 2008; Wang J et al., 2009). However, the test and analysis results of the core samples obtained by the Project indicate that subsurface samples had much higher sealing performance than surface samples. As shown by the logs, the anhydrite samples from the Quemo Co Formation had porosities of 0.6%–2.1% and permeabilities of $0.0342 \times 10^{-3}\text{--}0.161 \times 10^{-3} \mu\text{m}^2$, thus belonging to Class I caprocks. Moreover, the gypsum-bearing mudstones in the Xiali Formation have thicknesses of 230 m and 252 m, respectively. They have an average porosity, permeability, and saturated water breakthrough pressure of 1.42%, 0.0012 Md, and 18.37 MPa, respectively, and thus also belong to Class I caprocks (Wang J et al., 2009). The variations in the sealing performance between the surface and subsurface gypsum rocks could be attributed to the fact that the surface gypsum rocks undergo hydrolysis due to their long-term exposure to the surface environment, significantly diminishing their sealing capacity (Li YL et al., 2008; Li ZX et al., 2008).

Therefore, the subsurface cores of anhydrite and gypsum-bearing mudstones have low porosities, low permeabilities,

and high breakthrough pressures. Therefore, the subsurface anhydrite and gypsum-bearing mudstones enjoy extremely high sealing capacities. This finding provides a new basis for re-evaluating and understanding the oil and gas preservation conditions of the Qiangtang Basin.

3.1.2. Effects of tectonic uplift on oil and gas preservation

It is generally considered that more intense tectonic uplift is associated with poorer oil and gas preservation conditions. Therefore, research on the effects of tectonic uplift on oil and gas preservation conditions is critical to the exploration of hydrocarbon reservoirs (Ma YS et al., 2006; Guo ZJ et al., 2008; Wu ZH et al., 2009, 2019). The destructive effects of tectonic uplift on hydrocarbons primarily include: (1) the evolutionary stasis of source rocks; (2) intense tectonic unloading can produce unloading and tectonic fractures in regional caprocks, thus decreasing the pressure and sealing performance of caprocks (Fu G and Wang JQ, 2000; Cao CR et al., 2003); and (3) intense denudation makes hydrocarbon reservoirs to be exposed to the surface and then suffer weathering and denudation.

As revealed by the latest 2D reflection seismic data with high signal-to-noise ratios obtained by the Project, the Upper Cretaceous Abushan, Suonahu, and Kangtuo formations, which overlap the Jurassic folded strata by an angular unconformity, are characterized by gentle attitudes and the absence of folds (Figs. 5, 10) and show parallel unconformities inside. These results reflect that the Qiangtang Basin has primarily experienced tectonic uplift in general since the Late Cretaceous (Wang J et al., 2019; 2020a; 2022b) but weak folding caused by horizontal compression. However, this basin has undergone multiple uplifts and denudations caused by tectonic movements, leading to very complex relationships between tectonic uplifts and oil and gas preservation conditions in this basin (Wang CS et al., 2004; Xu HX and Qin JZ, 2004; Wang J et al., 2004, 2009; Wu ZH et al., 2009, 2014, 2015). Each uplift-denudation process caused the deep fillings of the basin to migrate toward the shallow crust. In addition, the tectonic unloading produced unloading fractures in the regional caprocks during each uplift-denudation process, thus accelerating the leakage of oil and gas to the surface and the downward infiltration of meteoric water.

(i) The Late Jurassic-Early Cretaceous tectonic uplift

The Late Jurassic-Early Cretaceous tectonic uplift showed relatively high amplitude at the margins of the southern and northern parts of the North Qiangtang depression. As a result, the Middle-Lower Jurassic and Upper Triassic strata in these zones were exposed, and the Jurassic hydrocarbon reservoirs might have been completely depleted. By contrast, the Late Jurassic-Early Cretaceous tectonic uplift was weak in the central part of the North Qiangtang depression. As a result, the central part was relatively slightly denudated, and the Jurassic hydrocarbon reservoirs in the central part might be preserved to a certain extent. Moreover, the western part of the North Qiangtang depression is characterized by

widespread Upper Jurassic outcrops, while its eastern part witnesses the Cretaceous strata overlapping the Middle Jurassic strata by an angular unconformity. These phenomena reflect intense uplift in the eastern part and weak denudation in the western part, indicating that the Jurassic hydrocarbon reservoirs are well preserved in the western part.

The Late Jurassic-Early Cretaceous tectonic uplift gradually intensified from south to north in the South Qiangtang depression. As a result, the Upper Jurassic strata are extensively preserved in the southern part of the depression, while the Middle Jurassic and even the Upper Triassic strata are exposed in its northern part due to the strong unroofing. This result indicates that the Upper Triassic - Jurassic reservoirs in the South Qiangtang depression are well-preserved in the south but are relatively poorly preserved in the north.

(ii) Late Cretaceous tectonic uplift

The Eocene strata overlie the Late Cretaceous granites by an angular unconformity in the southern Niriacuogai, Maerguochaka, and Jiaburecuo areas, implying that the Late Cretaceous tectonic uplift has high amplitude and exposed deep geobodies to the surface through unroofing. In addition, based on the strong deformations of the Abushan Formation near the EW-NWW-trending fault zone in the Chaquzhuoma area of the South Qiangtang depression, it can be speculated that this area suffered the intense thrusting of faults and high-degree differential uplift. The Late Cretaceous tectonic uplift - denudation might have led to the denudation of the Jurassic reservoirs and the formation of unloading fractures, thus accelerating the oxidation of the hydrocarbon reservoirs (Zhang JL et al., 2012).

(iii) The Cenozoic tectonic uplift

The poor oil and gas preservation conditions of the Mesozoic strata in the Qiangtang Basin are primarily caused by the destructive effects related to the uplift of the Tibetan Plateau. Some researchers considered that the Qiangtang Basin hosts well-developed faults and accordingly poor oil and gas preservation conditions due to the strong transformation caused by the plateau uplift, which, together with subsequent tectonic movements, severely destroyed the oil reservoirs (Zhao ZZ et al., 2001a). As shown by the latest data obtained by the Project (Figs. 5, 10), the Cenozoic strata (i.e., the Suonahu and Kangtuo formations) in the Qiangtang Basin generally show weak deformations, gentle attitudes, and open and gentle folds (Fig. 5; Shen LJ et al., 2020, 2023), and the Tibetan Plateau was generally uplifted during the Cenozoic (Guo ZJ et al., 2008; Liu CY et al., 2009; Wang J et al., 2019). The Himalayan uplift of the Tibetan Plateau transformed the Qiangtang Basin to a certain extent, forming a huge thrust nappe system (Wu ZH et al., 2011, 2012). Overall, the basin transformation caused by the plateau uplift is generally more intense in the South Qiangtang depression than in the North Qiangtang depression, more intense in the eastern part of the North Qiangtang depression than in its western part, and more intense in the northern and southern parts of the North Qiangtang depression than in its central

part. Therefore, the central and western parts of the North Qiangtang depression subjected to weak basin transformation enjoy favorable preservation conditions of hydrocarbon reservoirs (Wang J et al., 2009; Wu ZH et al., 2009, 2014; Ji CJ et al., 2019).

3.1.3. *Effects of magmatic and volcanic activities on oil and gas preservation*

The areas with widely developed magmatic rocks in the central and eastern parts of the Qiangtang Basin have always been considered as forbidden areas for oil exploration (Zhao ZZ et al., 2001b; Nan ZB et al., 2010). However, with the discovery of hydrocarbons in magmatic and volcanic rocks at home and abroad in recent years, hydrocarbon reservoirs in magmatic rocks have received wide attention from petroleum geologists (Li MC et al., 1997; Ma YS et al., 2006; Xu TS, 2021). The Qiangtang Basin experienced multi-stage magmatic activities that occurred extensively (Wang J et al., 2022b). However, the magmatic activities influencing the hydrocarbon reservoirs in the basin primarily occurred during the Middle Cenozoic, as indicated by the hydrocarbon characteristics of the basin.

The magmatic and volcanic activities related to oil and gas preservation in the Qiangtang Basin can be divided into four major magmatic-volcanic eruption stages, namely the Late Triassic, the Late Cretaceous, the Oligocene-Miocene, and the Pliocene (Zhong DL and Ding L, 1996; Nan ZB et al., 2010). With the discovery of many hydrocarbon reservoirs in volcanic rocks at home and abroad, hydrocarbon reservoirs in volcanic rocks have also attracted wide attention (Niu JY et al., 2003; Zhang Q et al., 2016; Zhang GJ et al., 2019; Xu TS, 2021). It is generally considered that the volcanic activities occurring before hydrocarbon generation and expulsion have positive effects on hydrocarbon accumulation (Ma YS et al., 2006). In contrast, the volcanic and magmatic activities occurring after hydrocarbon accumulation can damage oil reservoirs; however, their thermal energy can promote the secondary maturation of source rocks (Zhang Q et al., 2016; Zhao Y and Liu CY, 2016; Xu TS, 2021). Related studies show that the Qiangtang Basin has three dominant hydrocarbon generation and expulsion stages, namely the Late Triassic, the Late Jurassic, and the Pliocene (Wang J et al., 2009). Multi-stage volcanic and magmatic activities undoubtedly have profound effects on hydrocarbon accumulation, preservation, and destruction (Wang et al., 2022b) since (1) there are complex relationships between the former and the latter and (2) the volcanic activities of different stages differ in distribution, intensity, and rock characteristics, thus producing different effects on oil and gas preservation.

The Late Triassic magmatic-volcanic activities are intense and occurred extensively, and the primary relationships between them and hydrocarbons are as follows: (1) the magmatic-volcanic activities of this stage increased the crustal heat-flow values and geothermal gradients and accelerated the thermal evolution of the source rocks in the underlying

Triassic sedimentary strata; (2) the activities of this stage are characterized by intermittent volcanic eruptions, forming multiple sets of widely distributed, tight, and hard overflow lavas, which are much tighter than mudstones and can serve as excellent regional caprocks for the Upper Triassic hydrocarbon reservoirs; (3) besides multiple sets of volcanic breccias, pyroclastic rocks, tuffs, and weakly welded tuffs, the magmatic-volcanic activities of this stage formed relatively thick volcanoclastic rocks during the intermittent periods of volcanic eruptions. These volcanoclastic rocks can serve as favorable reservoirs. The above-mentioned reservoirs and caprocks of volcanic rocks were formed before the major hydrocarbon expulsion and generation stage (the Late Jurassic) of the Qiangtang Basin, creating favorable conditions for the formation of hydrocarbon reservoirs in volcanic rocks (or reservoirs of the basement type and the upper-source and lower-reservoir type).

The Late Cretaceous and Oligocene-Miocene magmatic-volcanic activities occurred after the dominant hydrocarbon generation and expulsion stage of the Qiangtang Basin. However, the magmatic-volcanic activities of these two stages had minimal destructive effects on hydrocarbons in the basin for the following reasons: (1) the magmatic-volcanic activities of both stages exhibited above-water eruptions and effusions. As hot molten lavas flowed along the Jurassic weathering surfaces, they typically formed bleached zones up to several meters thick near the contact areas with the Jurassic strata, while exerting minimal effects on the layers below. Therefore, the lava flow of both stages had minimal effects on the Jurassic source rocks and primary hydrocarbon reservoirs; (2) the magmatic-volcanic activities of both stages are characterized by central eruptions. As the magmas migrated along volcanic conduits toward the surface, they inevitably cut through source-reservoir-caprock assemblages. Their strong upward invasion not only formed numerous fissures around volcanic conduits but also reactivated existing faults and joints, thus disrupting the original hydrocarbon system in equilibrium. As a result, hydrocarbons could further migrate toward favorable structural parts and accumulate, forming secondary hydrocarbon reservoirs; (3) the thermal energy of magmas in volcanic conduits might cause the over-maturity of the Jurassic source rocks in adjacent areas.

The Pliocene magmatic-volcanic activities mainly occurred in thrust zones with poor oil and gas preservation conditions, suggesting that the magmatic-volcanic activities of this stage have little impact on the oil and gas preservation of the Qiangtang Basin.

3.1.4. *Effects of groundwater motion on oil and gas preservation*

The Qiangtang Basin hosts two types of groundwater, namely formation water and spring water. It is generally believed that formation water can reflect the oxidation-reduction environment and hydrodynamic conditions, while spring water is indicative of the infiltration depth of meteoric water to some extent. Therefore, analyzing groundwater

motion is of great significance for research on oil and gas preservation conditions (Zhao KB et al., 2008; Wang J et al., 2009; Zhang ZP et al., 2011; Zeng SQ et al., 2021).

Based on the criteria for groundwater classification (Su L BA, 1956), Wang J et al. (2009) conducted a hydrochemical analysis of 18 formation water samples from the Qiangtang Basin, obtaining the following results: These formation water samples can be divided into the Na_2SO_4 (nine samples, 50%), NaHCO_3 (seven samples, 38.89%), and CaCl_2 (two samples, 11.11%) types. These samples differed greatly in the total dissolved solids (TDS) content, which varied in the range of 508.16–106179 mg/L. Accordingly, these samples comprised seven moderately-deep water samples with TDS contents of 1000–10000 mg/L, nine shallow samples with TDS contents of < 1000 mg/L, and two deep samples with TDS contents of > 10000 mg/L, which accounted for 38.89%, 50%, and 11.11% of the total samples, respectively. Moreover, these samples had metamorphism coefficients of generally 0.9–2.0, with individual values reaching a maximum of 10.902. Regarding the desulfurization coefficient, these samples consisted of four samples with desulfurization coefficients <10, three samples with desulfurization coefficients of 10–50, four samples with desulfurization coefficients of 50–100, and seven samples with desulfurization coefficients >100. In terms of the carbonate equilibrium ratios, these samples comprised six samples with carbonate equilibrium ratios <1, five samples with carbonate equilibrium ratios of 1–2, and seven samples with carbonate equilibrium ratios >2 (maximum: 4.03).

The Qiangtang Basin hosts numerous spring outcrops, which primarily include cold seeps (0–10°C), low-temperature springs (10–20°C), medium- to low-temperature springs (20–30°C), medium-temperature springs (30–40°C), medium- to high-temperature springs (40–50°C), and high-temperature springs (> 50°C) (Wang J et al., 2009). In general, the springs in the Qiangtang Basin are primarily distributed in the South Qiangtang depression, followed by the Central Uplift, with the fewest occurring in the North Qiangtang depression (concentrated near the central uplift zone). Horizontally, cold seeps are relatively concentrated in the western part, and springs gradually increase eastward. From the perspective of local structures, the springs in the Qiangtang Basin mostly occur in fault zones, especially in N-S-trending faults. Wang J et al. (2009) conducted a hydrochemical analysis of 30 spring water samples with temperatures of > 30°C and projected them onto the $\text{Cl-SO}_4\text{-HCO}_3$ ternary diagram. As a result, nine samples fell into the zone of steam-heated water/steam condensed water, indicating the presence of local thermal geobodies underground; three samples fell into the zone of deep Cl type of water; and ten samples fell into the transitional area between the zone of the diluted Cl-HCO_3 type of water and the zone of mixed Cl and SO_4 types of water/volcanic condensed water.

As indicated by the above analytical results of formation water and spring water, the formation water environment in the Qiangtang Basin shifted from the original reducing state to

a weakly reducing or weakly oxidizing environment since the Mesozoic strata in the basin were exposed due to intense tectonic movements. Accordingly, the corresponding hydrodynamic conditions changed from retarded water exchange to slow or relatively intense water exchange, resulting in extremely low TDS content and very high desulfurization coefficients and metamorphism coefficients, which suggest poor oil and gas preservation conditions. However, the basin enjoyed excellent oil and gas preservation conditions before being uplifted, as indicated by the carbonate equilibrium ratio, desulfurization coefficient, and metamorphism coefficient of the formation water. The Mesozoic strata in the central and northwestern parts of the North Qiangtang depression are deeply buried and well preserved. Notably, these strata contain multiple sets of gypsum-bearing mudstones and anhydrite, which exhibit high sealing capacity. As a result, the oil and gas preservation conditions within the Qiangtang Basin are poor in local areas but are favorable in general. In particular, the North Qiangtang depression generally enjoys favorable preservation conditions. These characteristics are consistent with the regional caprocks newly discovered by the Project.

3.2. Source rocks

Source rocks are another critical factor restricting the evaluation of the resource potential of oil and gas in the Qiangtang Basin. Furthermore, the availability of high-quality source rocks is the key to the resource potential evaluation and hydrocarbon exploration breakthrough in the basin. Some researchers believe that the Qiangtang Basin lacks high-quality source rocks (Zhao ZZ et al., 2001a). In contrast, some researchers believe that extensive hydrocarbon generation and migration once occurred in the Qiangtang Basin (Tan FW et al., 2002; Wang CS et al., 2004; Wang J et al., 2004, 2009), indicating that this basin has great hydrocarbon-generating potential. The new discoveries made by the Project support the opinion that the Qiangtang Basin might host high-quality source rocks (Fu XG et al., 2020a; Wang J et al., 2020b, 2022b).

3.2.1. Oil and gas shows

As shown by incomplete statistics, more than 200 oil and gas shows have been identified in the Qiangtang Basin, including six liquid oil seepages, one paleo-reservoir zone, two oil-shale zones, and multiple exhalative mud volcanic clusters (Fu XG et al., 2015). Meanwhile, the Project completed recently revealed significant gas logging anomalies in 13 beds of formations such as Buqu and Quemo Co. These oil and gas shows are primarily distributed in uplifted areas and basin margins subjected to strong tectonic deformations (Wang J et al., 2020a, b). Moreover, 97% of the oil and gas shows are concentrated in the Jurassic and Upper Triassic strata, while the rest are sporadically distributed in other strata (Tan FW et al., 2002; Wang CS et al., 2004; Wang J et al., 2004, 2009). Therefore, the large-scale oil and gas shows in the Qiangtang Basin suggest that extensive hydrocarbon

generation and migration once occurred in this basin and that this basin has great hydrocarbon-generating potential.

3.2.2. Bagong Formation source rocks

The Qiangtang Basin hosts multiple sets of source rocks, which are dominated by the black mud shales in the Upper Triassic Bagong Formation. The black mud shales of this formation were encountered in boreholes QZ-6, QZ-7, QZ-8, QZ-13, QZ-15, and QZ-16. They have thicknesses of 35–167 m and are the thickest in the eastern part of the basin (Wang J et al., 2009, 2020b; Fu XG et al., 2020a).

(i) Distribution of source rocks

According to data from the geological surveys of the shallow boreholes and field outcrops, the Upper Triassic Bagong Formation has thick, widely distributed argillaceous source rocks. The Bagong Formation source rocks are primarily distributed in the Zangxiahe-Ganggairi and eastern Woruoshan-Geladandong areas in the North Qiangtang depression, with thicknesses of 42–645.8 m, forming two centers. At one center, dark mudstones (mud shales) have a thickness of more than 305 m. At the other center, coal measures-bearing argillaceous source rocks have a thickness of 563 m and thin outwards. Along the Qumo Co section in the northeastern Qiangtang Basin, the prodeltaic black mudstones have a thickness of up to 594 m, serving as the most important source rocks of the basin. In addition, the argillaceous source rocks of the Tumengela Formation are widely distributed in the South Qiangtang depression, with a thickness of up to 420 m (Wang J et al., 2004, 2009; Chen WB et al., 2014, 2015; Song CY et al., 2018; Wang J et al., 2020a; Wang ZW et al., 2021).

(ii) Abundance of organic matter

As a set of major seals in the Qiangtang Basin, the Upper Triassic Bagong Formation is widely distributed in the region and is composed primarily of the dark mud shales and coal-bearing mud shales of the deltaic - neritic shelf facies (Chen WB et al., 2015; Wang J et al., 2020b). The Upper Triassic strata were encountered in boreholes QZ-6, QZ-7, QZ-8, QZ-13, QZ-15, and QZ-16, where the Upper Triassic source rocks have a thickness of 35.15–167 m. The Upper Triassic source rocks are thickest in borehole QZ-7 drilled in the eastern Qiangtang Basin, with a cumulative thickness of 167 m. The Upper Triassic source rocks in these boreholes have high TOC contents of 0.21%–3.56%, suggesting poor- to medium-quality source rocks, while those in boreholes QZ-7 and QZ-8 are mostly medium- to high-quality source rocks.

The Upper Triassic Bagong Formation source rocks in the Qiangtang Basin have low chloroform bitumen “A” contents of 0.0005%–0.0585% and low hydrocarbon-generating potential (S1+S2) of 0.03–0.54 mg/g (Fu XG et al., 2020a). Specifically, the 14 samples from borehole QZ-7 had chloroform bitumen “A” contents of 0.0096%–0.0585% (average: 0.0194%) and hydrocarbon-generating potential of 0.04–0.17 mg/g (average: 0.10 mg/g); the 14 samples from borehole QZ-8 had chloroform bitumen “A” contents of 0.0035%–0.0136% (average: 0.0098%) and hydrocarbon-

generating potential of 0.03–0.54 mg/g (average: 0.12 mg/g); and the samples from borehole QZ-16 had chloroform bitumen “A” contents of 0.0005%–0.002% (average: 0.0014%).

(iii) Organic matter types

The kerogen macerals of the Upper Triassic Bagong Formation source rocks are dominated by sapropelinites (Chen WB et al., 2015; Wang J et al., 2022b). The Upper Triassic mudstone samples from boreholes QZ-7, QZ-8, and QZ-13 had sapropelinite contents of 25%–48%. The sapropelinites in these samples were primarily brown, amorphous, and transparent to translucent, with a thick center and thin edges. These mudstone samples had inertinite and vitrinite contents of 20%–36% and 18%–42%, respectively, and their inertinites and vitrinites were primarily tabular or angular in shape and dark brown to black in color. These mudstone samples had exinite contents of only 2%–9%. Overall, the macerals of the Upper Triassic mudstones are dominated by sapropelinites, vitrinites, and inertinites, with a very low exinite content. As shown by the triangular diagram of kerogen macerals, the kerogens of the Upper Triassic source rock samples from borehole QZ-7 clearly had a mixed source. In contrast, the Upper Triassic mudstone samples from borehole QZ-16 had exinite, vitrinite, and inertinite contents of 68%–76% (average: 71.75%), 20%–28%, and 3%–8%, respectively but contained no sapropelinites. The Upper Triassic Bagong Formation source rock samples had kerogen type indices (KTIs) of –33.5–19, and their organic matter was dominated by type II₂–III kerogens, with the samples from borehole QZ-6 mainly containing type II₂ kerogens. As shown by the results of 14 source rock samples from borehole QZ-7, the kerogens of these samples had $\delta_{13}C$ values of –28.4‰–24.5‰ (average: –26.2‰), and those of 12 samples had $\delta_{13}C$ values of more than –27‰. These results indicate that the organic matter in the Bagong Formation source rocks is type II–III kerogens, which is roughly consistent with the results observed using a microscope.

(iv) Thermal evolution of organic matter

As shown by the tests and analysis results of the vitrinite reflectance (R_o) of the Upper Triassic source rock samples from boreholes QZ-6, QZ-7, QZ-8, QZ-13, and QZ-16 (Table 1), the samples of the subsurface Upper Triassic source rocks were highly mature to overmature, with R_o values of 1.38%–2.77% and T_{max} values of 373–602°C. The detailed results of various boreholes are as follows:

The source rock samples from boreholes QZ-6, QZ-7, and QZ-8 had R_o values of 1.38%–1.90% and T_{max} values of 373–572°C, suggesting highly mature source rocks. In contrast, the samples from boreholes QZ-13 and QZ-16 had R_o values of 2.20%–2.77% and T_{max} values of 536–602°C, indicating that these samples were overmature source rocks and primarily generated dry gas.

As shown in Table 1, the mudstone samples from boreholes QZ-7 and QZ-16 had concentrated $C_{29}aaa_{20S}/(20S+20R)$ ratios of 0.35–0.48 (average: 0.39) and 0.43–0.47 (average: 0.45) (Table 1), respectively. In

Table 1. Maturity of organic matter of the Upper Triassic source rocks from shallow boreholes in the Qiangtang Basin.

Boreholes	Lithology	R_o /%	T_{max} /°C	$C_{29}\alpha\alpha\alpha 20S/(20S+20R)$	$C_{29}\alpha\beta\beta/(\alpha\alpha\alpha+\alpha\beta\beta)$	$Ts/(Ts+Tm)$
QZ-6	Mudstone	1.38	<u>433–443</u> 437(11)			
QZ-7	Mudstone	<u>1.46–1.9</u> 1.62 (14)	<u>470–537</u> 503 (14)	<u>0.35–0.48</u> 0.39(14)	<u>0.30–0.45</u> 0.35(14)	<u>0.53–0.57</u> 0.55(14)
QZ-8	Mudstone		<u>373–572</u> 502 (14)			
QZ-13	Mudstone	<u>2.20–2.29</u> 2.24 (4)	<u>549–576</u> 564 (4)			
QZ-16	Mudstone	<u>2.44–2.77</u> 2.62 (8)	<u>536–602</u> 580 (4)	<u>0.43–0.47</u> 0.45 (8)	<u>0.38–0.41</u> 0.39 (8)	<u>0.45–0.50</u> 0.48 (8)

addition, they had $C_{29}\alpha\beta\beta/(\alpha\alpha\alpha+\alpha\beta\beta)$ ratios of 0.30–0.45 (average: 0.36) and 0.38–0.41 (average: 0.39), respectively. These results generally reflect a certain degree of thermal evolution. Furthermore, the mudstone samples from boreholes QZ-7 and QZ-16 had $Ts/(Tm+Ts)$ ratios of 0.53–0.57 and 0.45–0.50, respectively, which were mostly greater than 0.5. These results generally reflect a relatively high degree of thermal evolution, which is roughly consistent with the result derived from the T_{max} and R_o results.

Overall, the subsurface Upper Triassic source rocks in the Qiangtang Basin have high degrees of thermal evolution and are in a highly mature–overmature stage.

(v) Distribution of source rocks

The Upper Triassic strata, which are among the major source rocks in the Qiangtang Basin, are widely distributed and consist primarily of dark mud shales and coal-bearing mud shales of the deltaic - neritic shelf facies. As previously mentioned, from the perspective of sedimentary environments, the Upper Triassic source rocks in the Qiangtang Basin mainly include the coastal-deltatic silty mudstones in the Zangxiahe-Duoseliangzi-Quemo Co area and on both sides of the central uplift; the prodeltaic - neritic shelf carbonaceous and argillaceous source rocks detected in the central coverage area of the basin; and the slope-basin mud shales in the South Qiangtang depression.

As shown by the analysis of the lithofacies paleogeographic framework of the Bagong Formation source rocks during the sedimentation period, the high-quality source rocks in the Qiangtang Basin are primarily distributed in deep-water sedimentary areas in the central and southern parts of the basin. Boreholes QZ-7 and QZ-8 were drilled in the coastal delta area near the paleo-continental denudation area, where the sedimentary environment was subjected to the strong transformation caused by terrigenous clasts, leading to relatively high oxic interfaces and relatively poor preservation conditions for organic matter. In contrast, the prodeltaic - continental shelf area (coverage area) adjacent to both boreholes is likely to have more favorable formation and preservation conditions for organic matter. Therefore, the vast prodeltaic - continental shelf area (coverage area) in the North Qiangtang depression and the slope-basin area in the South Qiangtang depression might host source rocks with quality higher than the source rock samples from boreholes QZ-7 and QZ-8.

3.3. Resource potential

As shown by the temporal-spatial configuration relationships of source rocks, reservoirs, and caprocks, the Mesozoic hydrocarbon systems in the Qiangtang Basin include three sets of major source-reservoir-caprock assemblages, namely the Upper Triassic Bagong Formation (the Xiaochaka Formation)-Middle-Lower Jurassic Quemo Co Formation assemblage, the Lower Jurassic Quse Formation - Middle Jurassic Xiali Formation assemblage, and the Middle Jurassic Buqu-Xiali Formation assemblage.

The Upper Triassic Bagong Formation - Middle-Lower Jurassic Quemo Co Formation assemblage serves as the most important Mesozoic hydrocarbon system of the Qiangtang Basin. Studies show that this hydrocarbon system has the following characteristics: (1) The prodeltaic black carbonaceous and argillaceous rocks in the Bagong Formation are the most important source rocks of the Qiangtang Basin, with a large thickness and a high TOC content; (2) The source rocks of this system mainly contain type II₁ kerogens, with type I kerogens occurring marginally. In contrast, the argillaceous source rocks of this system mainly contain type II₂ and type III kerogens, and their organic matter shows a high thermal evolution degree and is generally in the highly-mature-overmature stage; (3) The reservoirs of this system have high porosities and permeabilities, creating favorable reservoir conditions; (4) The caprocks in the Quemo Co Formation are composed primarily of anhydrites and anhydrites interbedded with argillaceous rocks, with high breakthrough pressures, large thicknesses of hundreds of meters, and continuous and stable regional distribution, suggesting favorable oil and gas preservation conditions. The comprehensive evaluation shows that this hydrocarbon system has the strongest possibility that hydrocarbon exploration breakthroughs can be achieved among the Mesozoic strata of the Qiangtang Basin.

Previous researchers primarily estimated the prospective resources of the Qiangtang Basin based on organic carbon resources (also referred to as the organic carbon method) or using the analogy method. Despite their great differences, the estimated results generally indicate that the Mesozoic source rocks in the Qiangtang Basin have great hydrocarbon-generating potential (Wang CS et al., 2001; Liu JD et al., 2007; Wang J et al., 2004, 2009) and that the Qiangtang Basin possesses the petroleum geological conditions necessary for

the formation of large and medium-sized oil and gas fields.

The organic carbon resources were estimated primarily based on the distribution area, cumulative thickness, and density of effective source rocks; TOC content; the recovery coefficient, conversion factor, and migration and accumulation coefficient of organic carbon. Among them, the distribution area of effective source rocks was determined mainly according to the lithofacies paleogeographic distribution of various strata in the basin, as well as the distribution of the coverage areas, exposed areas, and denudated areas at various horizons. The thickness of source rocks and the TOC content were predicted based on the statistical data of existing sections, followed by the distribution of source rocks under the lithofacies paleogeographic control. By referencing the Tarim Basin and foreign petroliferous basins, the migration and accumulation coefficient was determined at a minimum of 1% for the analysis of the effective resources. As indicated by the organic carbon resources estimated using the mentioned-above principles, the Mesozoic hydrocarbon systems of the Qiangtang Basin have total prospective resources of more than 10×10^9 t (Table 2).

4. Conclusions

(i) Despite the overall poor oil and gas preservation conditions of the Qiangtang Basin, the scientific drilling project identified two sets of high-quality seals, namely the extremely thick anhydrite layer of the Quemo Co Formation and the gypsum-bearing mudstones of the Xiali Formation. This discovery indicates the Qiangtang Basin has favorable oil and gas preservation conditions in local areas.

(ii) In addition to high-quality Upper Triassic source rocks, extensive oil and gas shows have been identified in the Qiangtang Basin, indicating that this basin possesses a solid material basis for hydrocarbon generation and great hydrocarbon-generating potential.

(iii) As verified by the scientific drilling project, the Qiangtang Basin has the sedimentary filling successions and geological conditions necessary for the formation of large-scale oil and gas fields, thus forming a new view different from the existing opinions such as poor oil and gas preservation conditions and the lack of high-quality source

rocks.

CRedit authorship contribution statement

Li-jun Shen: Investigation, writing—original draft, discussion. Jian-yong Zhang: Discussion. Shao-yun Xiong: Discussion. Jian Wang: Funding acquisition, Conceptualization, Supervision. Xiu-gen Fu: Supervision, Resources. Bo Zheng: Investigation, Writing—review & editing, Investigation. Zhong-wei Wang: Investigation. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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Table 2. Estimation of prospective resources of oil and gas in the Qiangtang Basin.

Source	Estimation method	Horizons for prospective resources estimation	Total prospective resources/ 10^9 t	Northern Qiangtang depression/ 10^9 t		Southern Qiangtang depression/ 10^9 t	
				Western part	Eastern part	Western part	Eastern part
Zhao ZZ et al. (2001b)	Organic carbon method, and hydrocarbon-generating potential method	Mesozoic	5.29	0.95	1.99	1.10	1.25
The third round of national petroleum resource evaluation, 2007	Organic carbon method, and analogy method	Paleozoic, and Mesozoic	Prospective resources of oil: 8.635×10^9 t Prospective resources of natural gas: 1255.355×10^9 m ³				
Wang J et al. (2004)	Organic carbon method	Mesozoic	11.33	3.61	5.04	2.68	
Wang J et al. (2009)	Organic carbon method	Mesozoic	10.44	6.08		4.36	

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