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Hydrocarbon accumulation conditions and favorable exploration zones in the Lunpola Basin, Tibet

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By systematically reviewing and summarizing the previous studies on the petroleum geology of the Lunpola Basin, combined with the latest oil and gas exploration results, the oil and gas accumulation conditions of this basin are summarized, and the favorable zones with the most exploration potential are pointed out. The results show that: ① The Paleogene mainly develops three sets of source rocks, including Niu-1 section, Niu-2 section and lower Niu-3 subsection. The lithology is mainly semi-deep and deep lacustrine gray-dark shale. Among them, the source rock of Niu-2 section is the best. However, the source rock of Niu-1 section is only developed in the Jiangjiacuo depression. The effective source rocks have the largest thickness in the central and western parts of the basin and have the best hydrocarbon-generating capacity. The thickness and abundance of the source rocks have decreased eastward. The organic matter are mainly Type I and Type II_1, with a maturity of 0.58%–1.08%. ② The study area is dominated by clastic rock reservoirs, which can be divided into three types according to the strata distribution, and the overall reservoir conditions are not good. The reservoir porosity is between 0.1% and 32.6%, mainly between 2.0% and 10.0%, with an average of 6.5%; the permeability is between 0.0005 mD and 116.0 mD, mainly between 0.01 mD and 0.5 mD, which means ultra-low porosity and ultra-low permeable fracture-porous reservoirs. ③ Three sets of seals are mainly developed in the Lunpola Basin, including two regional seals of the middle Niu-2 subsection and Dingqinghu section, and a direct seal of upper Niu-2 subsection. These three sets of seals are well developed and have good preservation conditions in the relatively stable central depression and the footwall of thrust nappe structural belt . ④ The oil and gas reservoirs in the Lunpola Basin have the distribution law of "structural traps in the north and south, and lithologic traps in the center". Structural traps are mainly distributed in the thrust nappe belt in the north and the Changshan uplift in the south, forming "self-generation and self-storage" or "lower-generation and upper-storage" reservoirs. While lithologic traps are mainly distributed in the central sag, forming "self-generation and self-storage" reservoirs. ⑤ The source-reservoir-caprock combination conditions are good in the structural traps in the footwall of the northern thrust nappe belt and the lithologic traps in the southern slope belt of Jianjiacuo depression,, and they are the most favorable oil and gas exploration zones in the Lunpola Basin.

KEYWORDS

lunpola basin, hydrocarbon accumulation conditions, hydrocarbon accumulation pattern, controlling factor, favorable oil and gas exploration zones

1 Introduction

In 2020 and 2021, China's crude oil production is 195 million tons and 199 million tons, respectively. Meanwhile the crude oil import is 542 million tons and 513 million tons, respectively. The foreign dependence of crude oil is as high as 73.5% and 72%, respectively. Therefore, oil imports have remained high (Snowball column for incoming calls and power outages, 2021). With the continuous advancement of China's industrialization process, energy consumption is increasing year by year. It is expected that China's dependence on foreign oil and gas resources will continue to rise for a long period of time in the future, which will inevitably affect China's national energy security and social and economic development to a certain extent. Finding large-scale strategic replacement areas for oil and gas resources and building reserve bases for oil and gas resources are of great significance to improving China's energy security. At present, in addition to the Tarim mega-basin, only the Tibet basin has potential to be another large-scale oil and gas resource strategic replacement area (Qiu, 1997). The Lunpola Basin is located on the southern side of the middle section of the Bangong Lake-Nujiang Great Fault Zone in the northern Tibet Plate. It is a Paleogene continental basin on the junction zone of the Qiangtang block and the Gangdise block (Bangong-Nujiang suture) (Figure 1). The basin is narrowly distributed in the east-west direction, with north-south zones and east-west blocks (Zhang and Zou, 1995; Lei et al., 1996; Lu et al., 1997). The range of the basin is 88°30′–90°30′ in longitude and 31°20′–32°20′ in latitude, with a length of about 200 km from east to west, a width of 10–30 km from north to south, and an area of about 3600 km^2. The Lunpola Basin is one of the numerous Paleogene continental basins in the Tibet. So far, it has the best petroleum geological conditions and has the highest exploration degree in the Tibet. Moreover, the industrial oil and gas flow has been initially obtained (Zhang and Zou, 1995; Lei et al., 1996; Ma et al., 1996; Lu et al., 1997), which further highlights the great significance of the oil and gas resource survey in the Lumpola Basin.

Previous studies on the Lunpola Basin mainly focused on the structural geological characteristics of the basin (Luo, 1993; Pan, 1994; Pan, 1995; Xiao and Huang, 1996; Ai et al., 1998; Kapp et al., 2005; DeCelles et al., 2007; DeCelles et al., 2007; Ma et al., 2013; Wu et al., 2016; Liu and Li, 2017), sedimentary evolution characteristics (Li and Fan, 2015a; Liu Y. et al., 2017; Lou and Liu, 2017; Wei et al., 2017; Zhao et al., 2019), source rock characteristics (Xu et al., 1996; Gu et al., 1999; Yuan and Xu, 2000; Sun et al., 2012; Pan et al., 2016; Liu Z. et al., 2017; Li, 2018a; Geng et al., 2019; Wang et al., 2019), reservoir conditions (Huang, 1994; Huang and Xiao, 1997; Li H. et al., 2022), geochemical characteristics of crude oil (Li and Tang, 1998; Fu et al., 2003; Li and Fan, 2015b; Li et al., 2016), comprehensive study of petroleum geology (Luo et al., 2016;

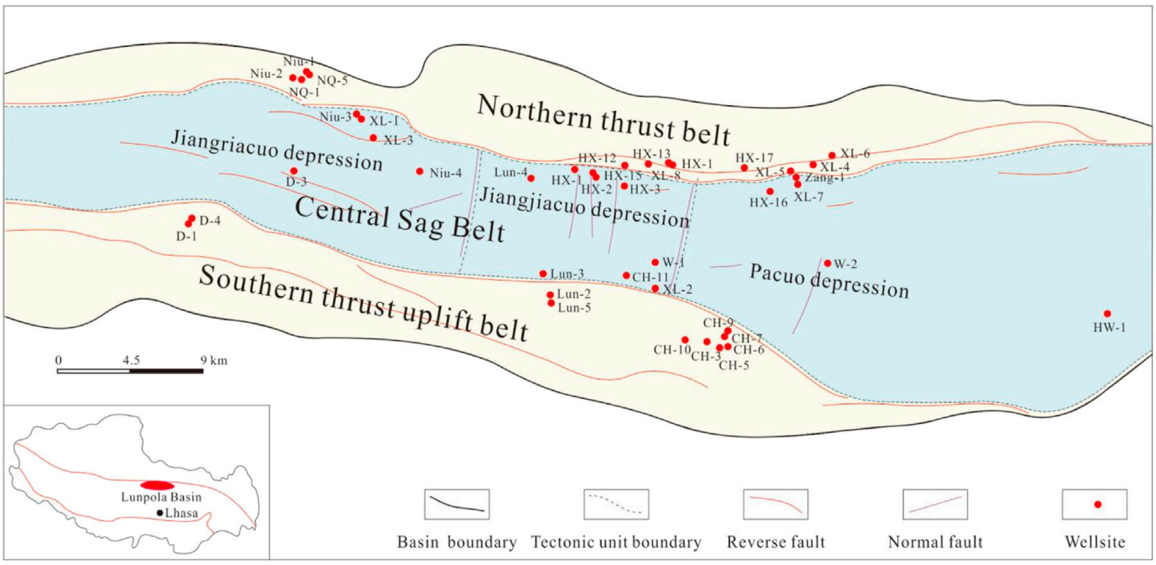

FIGURE 1
The tectonic division map of the Lunpola basin.

Lei and Fu, 1995; Zou et al., 1997; Fu and Xiao, 1998; Zhang et al., 2000; Sun et al., 2015; Fan et al., 2015; Pan et al., 2019), and oil and gas resource evaluation (Qiu, 1997; Gu et al., 1999; Chen et al., 2017; Wang et al., 2020),. Previous studies proposed the northern thrust nappe belt (Luo et al., 1994; Pan, 1994; Lei and Fu, 1995; Zou et al., 1997; Ai et al., 1998; Wu et al., 2016; Geng et al., 2019), southern slope belt (Luo, 1993; Fan et al., 2015; Liu Y. et al., 2017), and the central depression (Luo, 1993; Luo et al., 1994; Ma et al., 1996; Zou et al., 1997; Du et al., 2004; Pan et al., 2016; Wang et al., 2019), especially the Jiangriacuo depression (Pan, 1994; Liu Z. et al., 2017; Geng et al., 2019; Wang et al., 2019), the Jiangjiacuo depression or the tectonic-transformed area in the central depression (Lei et al., 1996; Xiao and Huang, 1996; Geng et al., 2019; Pan et al., 2019) is a favorable zone for oil and gas exploration in the Lunpola Basin. However, with the continuous advancement of oil and gas exploration, the exploration focus has changed from structural traps to lithologic traps. Two exploratory wells, Wang one and Wang 2, were designed for the lithologic trap targets, but the drilling results were not good (Li F. et al., 2018; Li H. et al., 2019). Therefore, it is urgent to reinvestigate the characteristics of oil and gas accumulation in the Lunpola Basin to clarify the main controlling factors of oil and gas accumulation, and point out the next exploration direction for oil and gas exploration in the Lunpola Basin.

2 Geologic overview

The Lunpola Basin is a basin developed on the basis of Yanshan Orogeny, which is deposited through subsidence, pull-apart and faulting process (Du et al., 2004). At the end of the Late Oligocene, the strong Himalayan movement caused the basin to be compressive and deformed, and the Oligocene Dingqinghu Formation was subjected to strong denudation, resulting in the current faults and the “dumbbell-shaped” structural features of the north-south zone and east-west block of the basin (Lei et al., 1996; Yuan and Xu, 2000; Li and Fan, 2015a). The basin gradually deepens from east to west. The eastern Pacuo area is generally a pattern of northward deepening and southward thrusting. The central Jiangjiacuo area is a south-north converging area and the west is a southward deepening and northward thrust pattern. From north to south, the basin can be divided into three first-order tectonic belts: the northern thrust nappe belt, the central depression belt and the southern thrust-uplift belt (Lei and Fu, 1995; Fu and Xiao, 1998; Liu Z. et al., 2017; Li J. et al., 2022). The central depression belt is further divided into three secondary tectonic units, including Jiangriacuo, Jiangjiacuo and Pacuo depressions (Figure 1).

Based on a comprehensive study of drilling data and seismic data, it is found that from bottom to top, the Eocene Niubao Formation (E_2n), the Oligocene Dingqinghu Formation (E_3d) and the Quaternary (Q) were successively deposited in the Cenozoic (Figure 2). The Niubao Formation (E_2n) is a set of brown-red clastic rocks intercalated with dark gray shale and gray-white marl, with a depositional thickness of 3000 m. From bottom to top, Niubao Formation can be divided into Niu-1, Niu-2 and Niu-3 section. The sedimentary characteristics of the Niu-1, Niu-2 and Niu-3 section has changed dramatically from the base to top, with grain size changing from coarse to fine tocoarse, the lithological color from red to black tored, which reflects the sedimentary cycles of proluvial fluvial facies - shallow lacustrine - semi-deep lacustrine facies - shallow lacustrine facies through time. This means that the sedimentary water body changes from shallow to deep and then to shallow. The sedimentary types mainly include alluvial fan (Niu-1section - lower Niu-2 subsection), fan delta (upper Niu-2 subsection - Ding-2 section), shallow lake (upper Niu-2 subsection - Dingqinghu Formation), semi-deep lacustrine - deep lacustrine (Niu-2 section, Ding-1 and Ding-2 sections). In the northeastern and southwestern steep slopes of the basin, sandy conglomerate bodies of nearshore subaqueous fans are mainly developed, while in the southeastern and northwestern parts, fan delta are mainly developed. The Changshan area in the southeast is the most important provenance area of the basin. Dingqinghu Formation (E_3d) is a set of semi-deep lacustrine-shallow lacustrine sedimentary assemblages mainly composed of gray-dark shale with oil shale, marl and fine sandstone, with a maximum deposition thickness of 1400 m. Dingqinghu Formation is also a good regional seal for the basin.

3 Hydrocarbon accumulation conditions

At present, a number of heavy oil and conventional oil and gas reservoirs have been discovered in the Lunpola Basin, including the Hongxingliang heavy-oil field and the Luomadiku conventional oil field in the central and eastern part of basin (Zou et al., 1997). In general, oil fields (reservoirs) are usually distributed in traps related to faults, and oil and gas are mainly distributed in Niu-2 and Niu-3 sections. On the plane, oil and gas reservoirs are mainly distributed on the northern and southern sides of the basin. In the northern basin, the heavy oil is mainly distributed in the northern thrust nappe belt from Ejiazu to Diezong area, which was formed at the end of the Oligocene. The buried depth of oil layer is only 200–500 m. In the southern basin, the petroleum is found in the thrust uplift belt in the south, from Lunpori to Changshan area, and adjacent to Jiangjiacuo and Pacuo oil-generating depressions in the north. Fan delta is developed in the Niubao Formation-Dingqinghu Formation in this area, especially near the Changshan structure, which is an inherited uplift anticline. The northern slope of the central depression zone, including the northern slopes of Jiangriacuo and Jiangjiacuo depressions, are another oil and gas accumulation

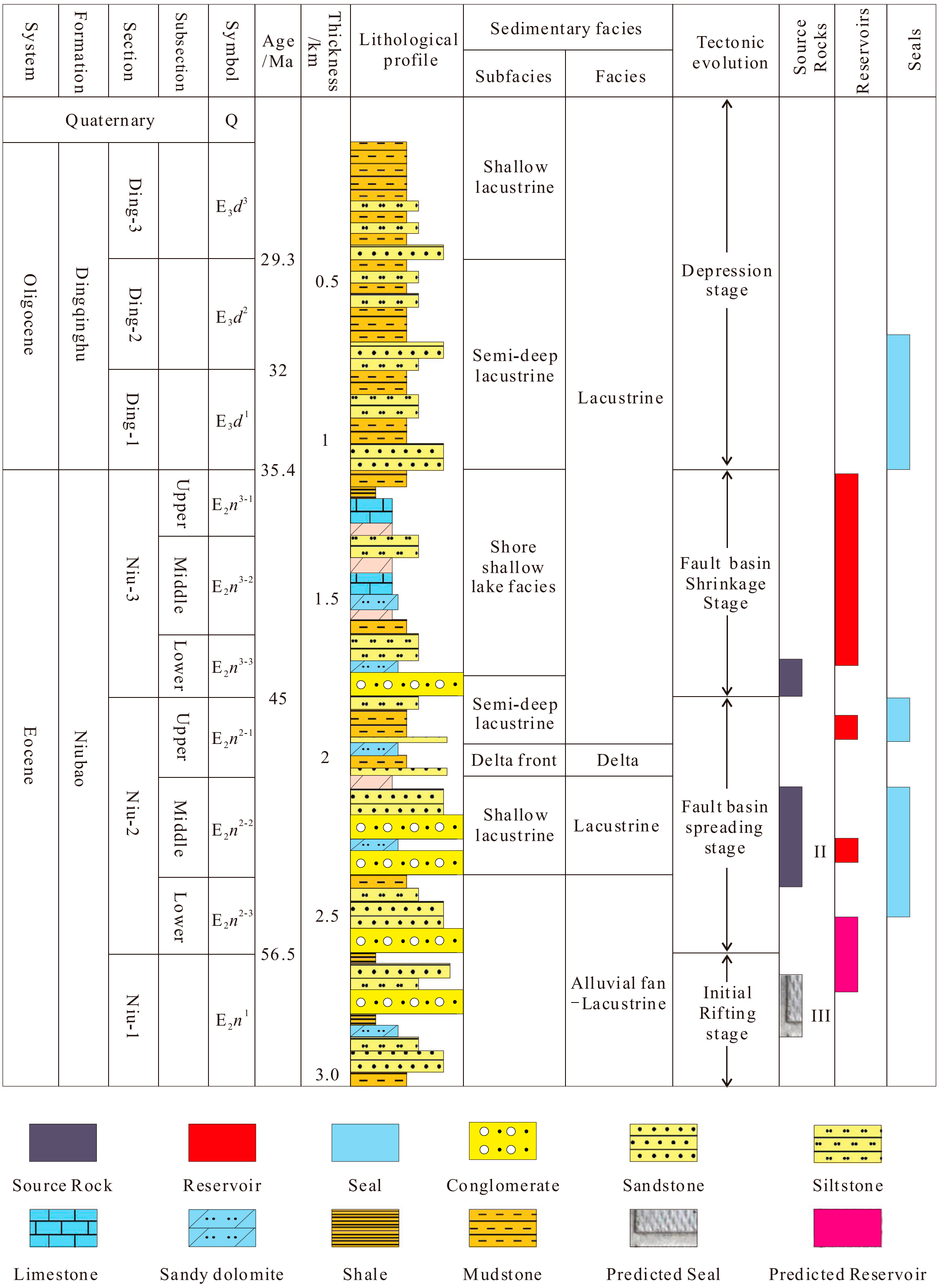

FIGURE2
The comprehensive histogram of the Lunpola basin.

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TABLE 1 Organic matter microscopic components in downhole samples in Lunpola Basin.

Well name	Depth/m	Layer	Component and content (%)									Types of organic matter
			Bacterioalgae	Lipid group	Mirror group	Inert group	Humus matrix	Mixed matrix	Semi-filament and semi-lens	Fluorescence vitrinite	Shell debris	
Zang-1	1780	E2n2	9.30	2.10	3.68	0.88	80.00		1.05	2.11	0.88	I
	1994	E2n2	3.59	3.00	3.39	1.40	44.71	37.72	3	2.00	0.2	II_1
XL-1	297.25	E2n3-2	6.53	9.42	2.69	0.96	73.32	3.46	1.34	1.34	0.96	I
	815	E2n3-1	4.67	2.91	3.11	0.78	85.22		0.78	2.34	0.19	I
	900	E2n3-1	0.18	2.57	3.67	2.57	44.04	42.57	1.84	1.47	1.10	II_1
XL-2	940.32	E3day1	3.17	1.87	1.68	2.24	87.31		2.43	1.12	0.19	I
	1305	E2n3-2	0.18	2.17	2.66	0.71	90.94		1.07	1.78	0.53	I

area. In addition, HX-3 and HX-4 wells in the northern Jiangjiacuo depression also show good oil and gas performance. The abundant oil and gas shows indicate that the basin has good hydrocarbon-bearing properties and hydrocarbon accumulation conditions, but it also indicates that the oil and gas distribution in the study area is extremely complex after the later reworking (Fu and Xiao, 1998). Therefore, based on the previous research results, the author uses the research data of Wang-1 and Wang-2 wells to investigate the hydrocarbon accumulation conditions in the Lunpola Basin, and establish the hydrocarbon accumulation pattern in the study area.

3.1 Hydrocarbon source rock features

The source rocks are the primary geological element in the petroleum system. The study of source rocks is an important geological basis for reducing the risk of oil and gas exploration. The existence of source rocks determines the existence of petroleum systems and the direction of oil and gas exploration. Previous studies (Gu et al., 1999; Pan et al., 2016; Li Y. et al., 2018; Geng et al., 2019; Wang et al., 2019) believe that the main source rocks in the Lunpola Basin are mainly developed in Niu-2 section (E_2n^2) and lower Niu-3 subsection (E_2n^{3-1}). (Liu Y. et al., 2017). concluded that the southwestern depositional center had well-developed source rocks during the depositional period of Niu-1 section, through detailed field geological survey, seismic data reprocessing, and sedimentary fillings (thickness change), *etc.* This understanding breaks the point of view that Niu-1 section is a set of red beds without source rocks (Liu Z. et al., 2017).

3.1.1 Basic characteristics

Using the geochemical data of various samples, the source rocks of Niubao Formation were evaluated in terms of development scale, organic matter abundance, type and maturity. The results show that the Paleogene in Lunpola Basin mainly developed three sets of main source rocks, Niu-1 section, Niu-2 section and lower Niu-3 subsection. The source rock of Niu-1 section only develops in the Jiangriacuo depression in the southwest of the basin, and is exposed to the surface near the Bangor-382 Bridge in the southwest of the basin (Liu Y. et al., 2017). The lithology is semi-deep lacustrine-deep lacustrine black mud shale and few fine sandstone, with a thickness of 100–200 m. The organic parent material mainly comes from lower aquatic organisms, and the type of organic matter is mainly type I, with a small amount of type II_1~III mixed (Liu Z. et al., 2017). The lithology of the source rocks in Niu-2 section is mainly semi-deep lacustrine-deep lacustrine gray-dark gray mudstone and shale, with an average thickness of 300 m. The types of organic matter are mainly type I and II_1 (Table 1), and the organic matter abundance is 0.50%–3.52%. The type of organic matter is mainly

TABLE 2 Characteristics of main source rocks in the lumpura basin.

Layer	Average thickness/m	Maximum thickness/m	Organic matter abundance/ %	Organic matter type	Maturity of organic matter (ro)/%	Remarks
E2n3-1	150	200	0.56–2.69% /1.00	Type I is predominant Small amount of type III	0.58–0.80	Changshan, Palongyaoma, Luomadiku, Hongxingliang and Jiangriacuo all developed
E2n2	300	600	0.50–3.52% /1.03	Type I is predominant Small amount of type III	0.66–1.14	Changshan, Palongyaoma, Luomadiku, Hongxingliang and Jiangriacuo all developed
E2n1	100–200			Type I is predominant Small amount of type II1 and III mixed		Only developed in Jiangriacuo depression

type I, and the maturity is 0.66%–1.14%. This set of source rocks is widely distributed in the basin and has the most favorable conditions for hydrocarbon generation. The organic matter abundance and type of lower Niu-3 subsection are superior, but the maturity is low. Considering the current oil and gas exploration situation, the thickness and abundance of the source rock in Niu-2 section show a decreased trend from west to east, and the source rock conditions in the central and western parts of the basin are generally better than those in the east (Gu et al., 1999; Li Y. et al., 2018; Geng et al. et al., 2019). For example, the Well XL-3 has good oil shows with oil bubble found on the core, reflecting the favorable oil source conditions in the Jiangriacuo depression and its periphery in the western part of the basin.

3.1.2 Oil-source correlation

Two indicator of light hydrocarbon components, cyclohexane and methylcyclohexane, can reflect the type of Kerogen. It is generally considered that light component cyclohexane <27% and methylcyclohexane <35% is sapropelic parent material, light component cyclohexane> 27% and methylcyclohexane>50% is humic parent material, and Methylcyclohexane between 35% and 50% is a mixed parent material. The distribution of methylcyclohexane in the source rock of Niu-2 section (E_2n^2) is 25%–50%, and the parent material type is characterized by sapropelic to mixed type. Methylcyclohexane in the source rock of Niu-3 lower subsection (E_2n^{3-1}) is between 40% and 60%, reflecting the mixed parent material type. The methylcyclohexane in crude oil is basically bounded by 20%–50%, which indicates that the parent material type is sapropel type to mixed type. The distribution of light hydrocarbon composition is between Niu-2 section and Niu-3 subsection. Accordingly, it is believed that the crude oil mainly comes from the source rocks of Niu-2 section and lower Niu-3 subsection.

In addition, the comparison of the carbon number distribution characteristics between the source rock extracts and crude oil reveals: ① the carbon number distribution of the crude oil from Niu-2 upper subsection (E_2n^{2-3}, 1730–1740 m) and Niu-2 middle subsection (E_2n^{2-2}, 1934–1942 m) in Well Zang-1, and Niu-2 section in Well XL-1 (E_2n^2,1457–1470 m), are similar with the source rock extracts from Niu-2 section, reflecting the feature of “Self-generation and self-storage”. ② The carbon number distribution characteristics of the crude oil from middle Niu-3 subsection in Well XL-5 (E_2n^{3-2}, 1354.6–1350.6 m) and lower Niu-3 subsection in Well XL-4 (E_2n^{3-1}, 1446 m), are the same as the source rock extracts from Niu-3 subsection in Well XL-5 (E_2n^{3-1}), indicating that the crude oil comes from the source rock of lower Niu-3 subsection. The crude oil in middle Niu-3 subsection in Well XL-5 is characterized by “lower-generation and upper-storage”, while Well XL-4 shows the feature of “self-generation and self-storage”. ③ The carbon number composition distribution of saturated hydrocarbons in the crude oil of lower Niu-3 subsection in Well Wang-1 is similar to that in the crude oil of lower Niu-3 subsection in Well XL-4, middle Niu-3 subsection in Well XL-5 and Well Zang-1. Therefore, it is considered to have a certain relationship among them. To sum up, it has been found that the crude oil in the Lunpola Basin mainly comes from the source rocks of Niu-2 section and Niu-3 subsection, which is consistent with previous studies (Lu et al., 1997; Li and Tang, 1998).

3.2 Reservoir characteristics

The reservoir rocks in Lunpola Basin are dominated by clastic rock reservoirs (Ai et al., 1998), including Niu-1, Niu-2 and Niu-3 sections. The overall physical properties of the reservoirs are not good, and they are mainly located in the southern uplift belt and the northern thrust nappe belt in the basin. The sedimentary facies of the reservoir are mainly delta plain subfacies and subaqueous distributary channels, such as the sandy conglomerates of the distributary channel in Niu-3 section in Well Wang-1, and the scour surface at the bottom of the core is obvious (Figure 3). Based on previous researches (Lei and Fu, 1995; Zhang and Zou, 1995) and the latest research results, the reservoirs of Niubao Formation can be divided into three types

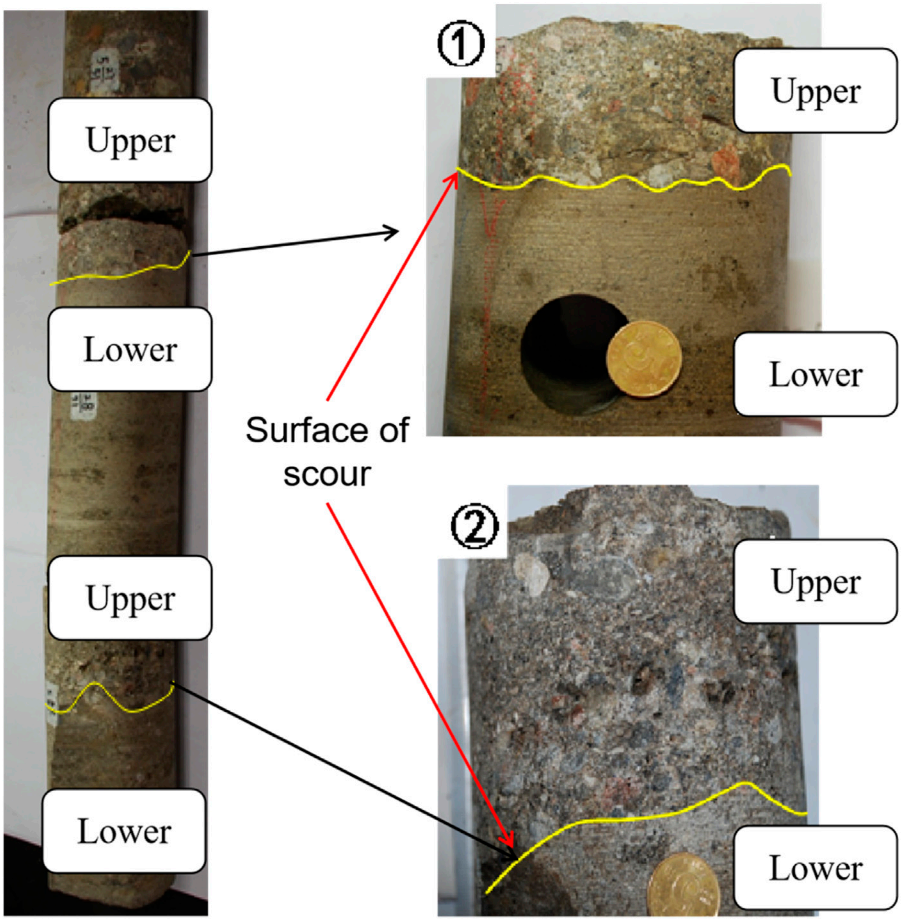

FIGURE 3
The core of underwater distributary channel in Well Wang-1.

according to their strata distribution: ①The first type is the coastal delta sandstone in lower Niu-3 subsection with a burial depth of 900–1600 m generally. It is characterized by large reservoir thickness (>5 m) and good physical properties, but shallow burial depth and poor sealing conditions. ② The second type is the coastal beach sandstone interbedded with dark-grey mudstone and shale in Niu-2 section, with a buried depth of 1200–2300 m. The reservoir sealing conditions are good, but the thickness of this type of reservoir is relatively thin, mostly less than 1 m. Therefore, its oil and gas production capacity is not optimistic. ③ The third type is the channel sandstone and nearshore subaqueous fan sandstone developed at the bottom of Niu-2 section and the top of Niu-1 section. The depth is generally greater than 2300 m. This type of reservoir has a large thickness and relatively coarse lithology. Its lower part is directly connected to the source rock of Niu-1 section. While its upper part is covered by the dark-gray mudstone and shale of Niu-2 section. It should be noticed that this set of reservoirs is deeply buried and less affected by the later tectonic movement. Therefore, its potential oil-gas bearing capacity and productivity cannot be underestimated. Therefore, the Niu-1 section may be an exploration target for obtaining major breakthroughs in oil and gas.

There are various types of pores in the reservoir, mainly including intergranular dissolved pores, intragranular dissolved pores, fractures and a very small amount of primary intergranular pores (Figure 4). The overall performance is fractured-porous reservoir. The reservoirs are mainly developed in the Niu-2 and Niu-3 sections. The measured porosity is mostly less than 15%, with an average of 7.12%. The permeability is usually less than 40.4mD, and the geometric mean is 0.1031mD. Statistics show that the reservoir porosity of Niu-2 section is –14%, with an average of 5.2%. The permeability is 0.0062–19.27mD, and the geometric average is 0.08mD. The reservoir porosity of Niu-3 section is 0.1%–32.6%, with an average of 7.73%. The permeability ranges from 0.0005 to 116 mD, and the geometric mean is 0.12 mD (Table 3). According to "Oil and gas reservoir evaluation

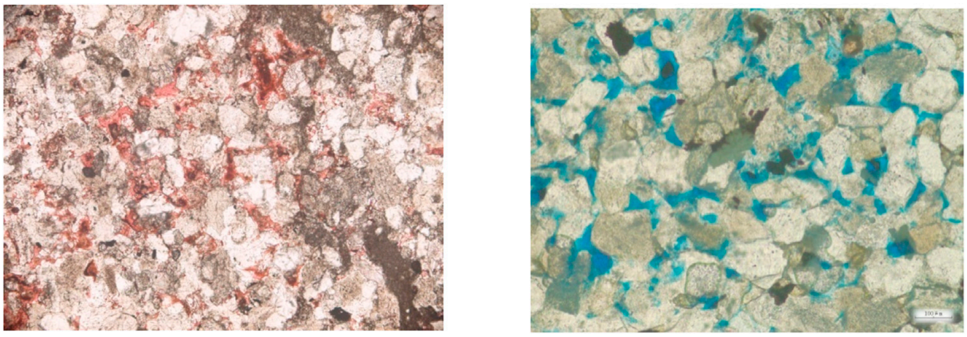

FIGURE 4
Reservoir space types of clastic rocks in Niubao Formation.

TABLE 3 Statistical of the physical properties of drilling reservoirs in the lumpura basin.

Layer	Sample number	Porosity/%	Permeability/10−3μm2
Niu-3 section	194	0.1–32.6	0.0005–116
		7.73	0.12
Niu-2	62	0.5–14.0	0.04–3.61
section		5.2	0.08
Average		7.12	0.1031

method of SY6285-2011-T″, the reservoir porosity in this area is between 0.1% and 32.6%, mainly between 2.0% and 10.0%, with an average of 6.5%, which belongs to ultra-low porosity reservoir. A few wells has porosity of −30.0%, which is a medium-high porosity reservoir. The permeability is between 0.0005 mD and 116.0 mD, mainly between 0.01 mD and 0.5 mD, which is an ultra-low permeability reservoir. Occasionally, the permeability of some samples is between 1.0 mD and 500 mD, which is a medium-low permeability reservoir. According to comprehensive evaluation, the reservoirs in this area are generally ultra-low porosity-ultra-low permeability fracture-pore reservoirs, and medium-low porosity and medium-low permeability fracture-pore reservoirs are locally developed. In addition, the physical properties of the reservoirs developed at the bottom of Niu-2 section and the upper part of Niu-1 section have not been verified by drilling, but it is inferred from the results of regional data analysis that these reservoirs have good physical properties.

3.3 Sealing characteristics

The Lunpola Basin has undergone late uplift and denudation, and Niubao Formation or Mesozoic and older strata are widely exposed in the northern thrust nappe tectonic belt and the southern thrust uplift belt. Therefore, the sealing condition is one of the controlling factors for the hydrocarbon accumulation in the study area. During the stage of prototype basin and basin reformation, several sets of thick semi-deep lacustrine-deep lacustrine shale were deposited, which played a good role in sealing oil and gas. Except for the poor sealing capacity of Niu-1 section, the other layers have a certain degree of sealing ability. There are two types of seals developed in the Lunpola Basin, namely the direct seal of upper Niu-2 subsection and the regional seals of middle Niu-2 subsection and Dingqinghu Formation. According to the drilling results of Well Wang-1, there is a set of high-quality seal about 100 m thick developed in upper Niu-2 subsection, which can play a good role in sealing the hydrocarbon in the lower Niu-2 section or its own. Most of the fluorescent thin sections of Niu-2 section in Well Wang-1 show normal blue light, and the logging shows that the total hydrocarbons are higher than the above strata, which confirms the good capping ability of upper Niu-2 subsection. Similarly, the dark shale in middle Niu-2 subsection is both a good source rock and a regional seal with good sealing ability (Du et al., 2004), which is widely distributed in the basin (Table 4). It can be seen that in the relatively stable central depression belt, several sets of seals are

TABLE 4 Macroscopic development characteristics of Paleogene seals in Lunpola basin.

Single-layer feature	Niu-2 section	Dingqinghu formation
Lithology	Mudstone, shale	Mudstone, shale
Sedimentary facies	Shallow-semi-deep-deep lacustrine	Shallow-semi-deep-deep lacustrine
Maximum cumulative thickness/m	1258	975
Maximum single-layer thickness/m	78	52.9
Depth/m	1600–3000	0–1400
Formation time	Before oil generation	Before main oil generation
Plasticity	Better	Good
Distribution	Stability	More stable
Evaluation	Good	Better

relatively developed, which is conducive to the preservation and accumulation of generated oil and gas in the basin. In the areas with relatively strong tectonic movements on the northern and southern sides of the basin, due to the deep burial depth, the damage degree of the seals of Niubao Formation is relatively low, and thus it still has a good sealing ability.

3.4 Hydrocarbon accumulation pattern

On the basis of the tectonic evolution of the basin, the hydrocarbon accumulation conditions of source rocks, reservoirs and seals in the Lunpola Basin were comprehensively analyzed, and the hydrocarbon accumulation pattern of Lunpola Basin was constructed (Figure 5). As shown in Figure 5, the structural traps are located in the thrust nappe belt in the north and the Changshan uplift area in the south, and lithologic traps in the central basin. The oil and gas generated from the source rocks of Niu-2 and Niu-3 sections migrated to the traps along the faults or sandstones, forming "self-generation and self-storage" or "lower-generation and upper-storage" reservoirs. While lithologic traps are mainly developed in the central depression belt. The oil and gas generated by the source rocks are transported to nearby sand bodies to form "self-generation and self-storage" reservoirs. It can be seen that the hydrocarbon accumulation in the Lunpola Basin is mainly controlled by source rocks, reservoirs and preservation conditions.

Since the end of the Eocene, the source rocks of Niu-2 began to mature and generate hydrocarbons, and oil and gas migrated along micro-fractures, faults and sandstones, forming oil and gas reservoirs in the paleo-uplift developed in the Changshan area in the south and the Hongxingliang area in the north. At the end of the Oligocene, under the influence of the north-south oriented compression, the two belts in the north and south of the basin were thrust and overthrow successively. The paleo-reservoirs formed in the northern part of the basin were adjusted to shallow depth to form bituminous plugs. At the same time, for the oil reservoirs of Niubao Formation in the southern Changshan area, due to thrust and folds (the anticline shape is still complete), the oil from Niubao Formation migrated to the overlying Dingqinghu Formation along the micro-fractures, unconformity surface and permeable rock strata. Since the Late Miocene, affected by the strong uplift of the Qinghai-Tibet Plateau, the paleo-reservoirs in the north and south of the basin have been further adjusted and destroyed, resulting in the loss of oil and gas and the formation of heavy oil reservoirs by water washing, oxidation and biodegradation of the ancient reservoirs at the edge of the basin. However, the mid-deep buried subtle traps in the northern thrust belt and the lithologic traps in the central depression belt have good preservation conditions and can still form normal oil reservoirs (Li F. et al., 2018; Li Y. et al., 2019). The industrial oil flow tested in Well Zang-1 has well confirmed the oil and gas enrichment law of the subtle structures in the lower part of the northern thrust nappe belt (Lu et al., 1997; Gu et al., 1999). The source rock of Niu-1 section in the Jiangriacuo depression has a larger burial depth and is less affected by tectonic movements in the later period. Therefore, it has better preservation conditions and other oil and gas geological elements for lithologic oil and gas reservoirs formation.

4 Favorable area prediction

The lithology and lithofacies of continental deposits change frequently and the reservoir distribution is relatively limited. Therefore, it is difficult for large-scale and long-distance hydrocarbon migration after oil and gas generation, resulting in the oil and gas reservoirs often developed in the center of oil-generating depressions and its periphery (Ju et al., 2016;; Li, 2022a). As mentioned above, the good source rocks are widely developed in the Lunpola Basin. The reservoir is mainly low porosity - ultra-low permeability fracture - porosity reservoir with poor physical property. In addition, the strong tectonic

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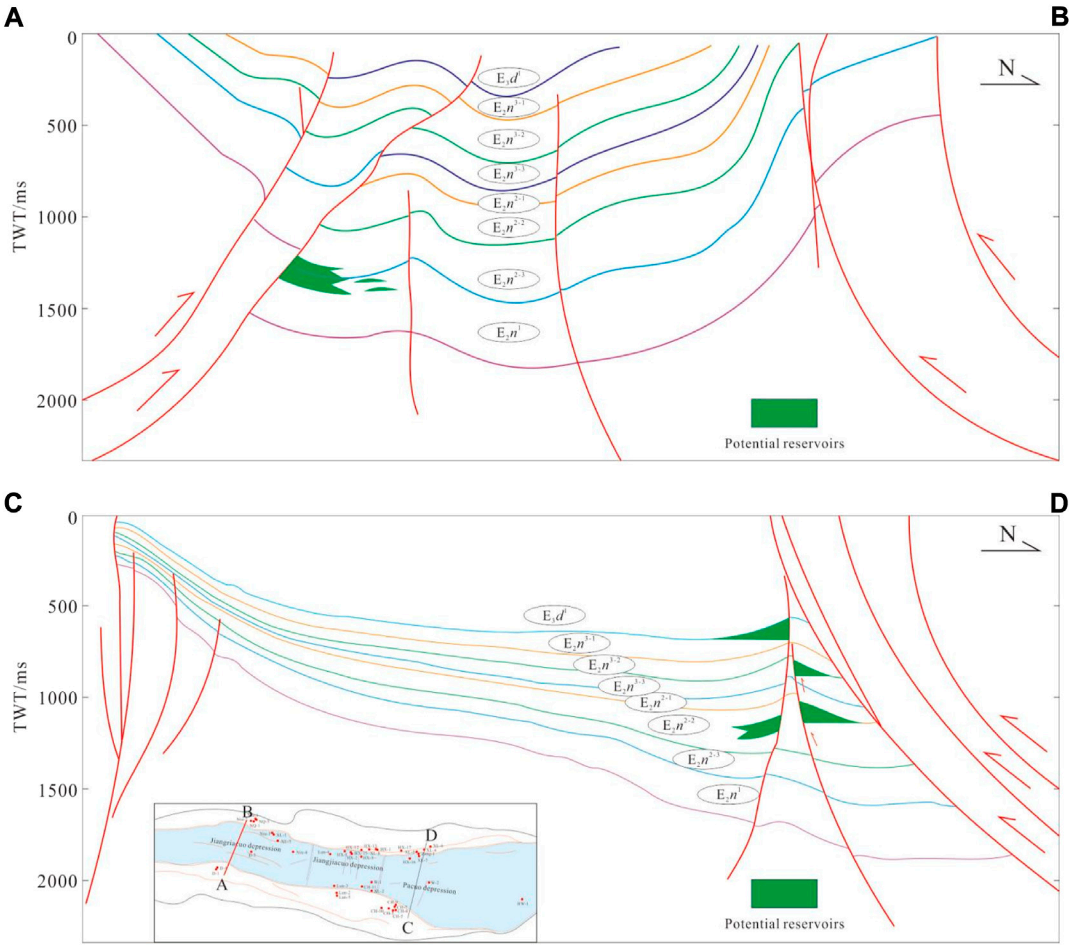

FIGURE 5
Prediction diagram of hydrocarbon accumulation pattern in Lunpola Basin.

movements have a great destructive effect on the oil and gas reservoirs that have been formed in the early stage. Therefore, reservoir conditions and post-preservation conditions are the main controlling factors for hydrocarbon accumulation in the study area. Based on this, two favorable exploration zones are proposed, the footwall of the northern thrust nappe belt and the southern slope of the Jiangriacuo depression (Figure 6).

4.1 Footwall of the northern thrust nappe belt

The northern thrust nappe belt is located between the Hongxingliang fault zone and the Dayushan North fault zone, and is represented by a set of thrust nappe rock bodies (such as Dayushan, Hongxingliang, Niubao, *etc.*) formed by thrusting from north to south. The stratum is mainly composed of Niubao Formation, with coarse lithology, steep slope, and basin marginal sedimentary facies. Because the upper wall of the main thrust fault shields or absorbs most of the tectonic stress, the two flanks of the anticline and the overlying Niu-3 section formed in this area have been completely eroded, resulting in the accumulated oil and gas in it to leak out completely. On the other hand, the deformation of the footwall of the thrust fault is relatively slight, and most of the strata remain horizontal or form some wide and gentle folds. Some extensional structures formed during the basin construction period, such as normal faults and their associated structures, are preserved, which is conducive to the preservation of oil and gas (Figure 7) (Pan, 1994; Zhang and Zou, 1995; Ai et al., 1998). This is also confirmed by the exploration practice of Well Zang-1 and Well HX-16.

It can be seen from Figure 7 that the northern thrust nappe belt is adjacent to the hydrocarbon-generating center of the Jiangjiacuo-Pacuo depressions, and there is a set of Tertiary sediments in the footwall of the thrust fault, indicating that the

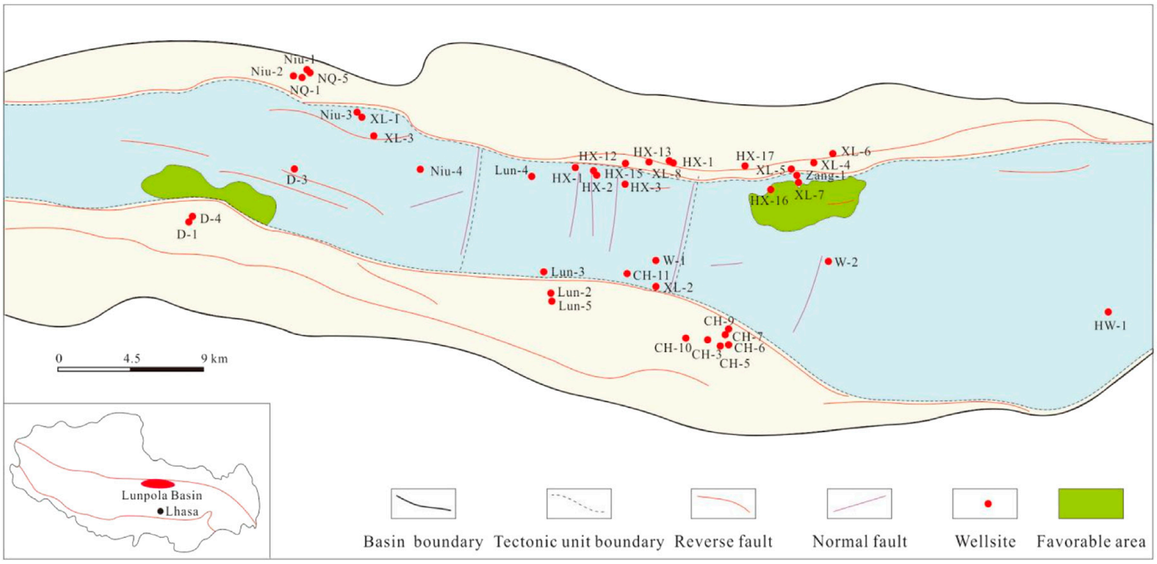

FIGURE 6
Prediction of the favorable areas for oil and gas exploration in the Lunpola Basin.

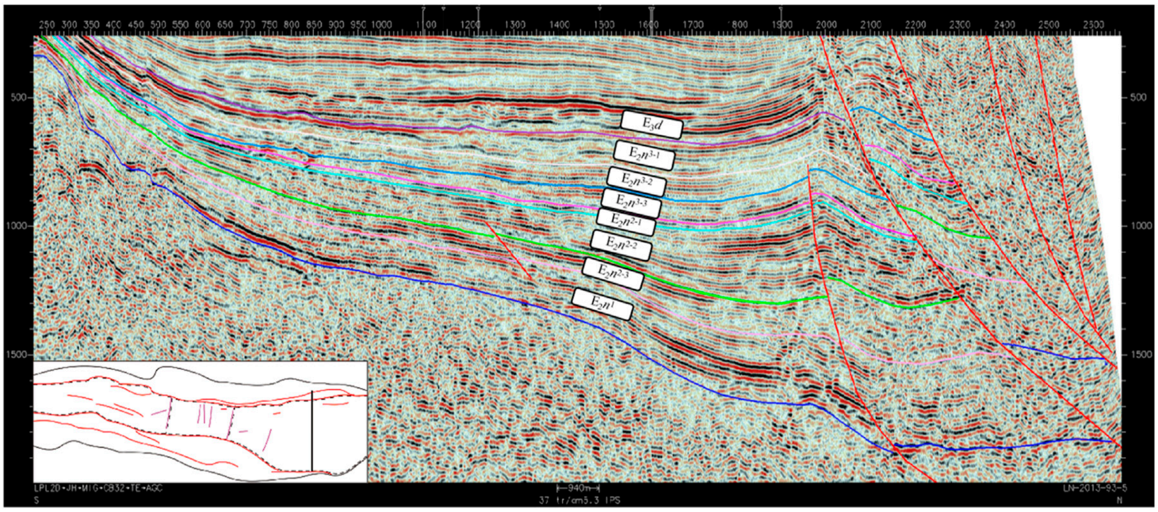

FIGURE 7
Seismic interpretation along line LN 2013–93.5 in NS direction in the eastern Lunpola Basin.

oil source conditions in this area are good. Along the main fault footwall in the northern boundary of Lunpola Basin, sedimentary systems such as nearshore subaqueous fans, fan deltas and alluvial fans are developed connecting or overlapping with normal faults, improving the reservoir physical conditions (Li H. et al., 2019; Li H. et al., 2022). After the Oligocene, the local structures developed were sealed by thrust faults or the regional seals in the area, forming a good hydrocarbon preservation condition. In addition, the northern uplift zone was the oil and gas migration and accumulation zone at the end of the Eocene (Lei et al., 1996). It can be seen that regardless of oil source

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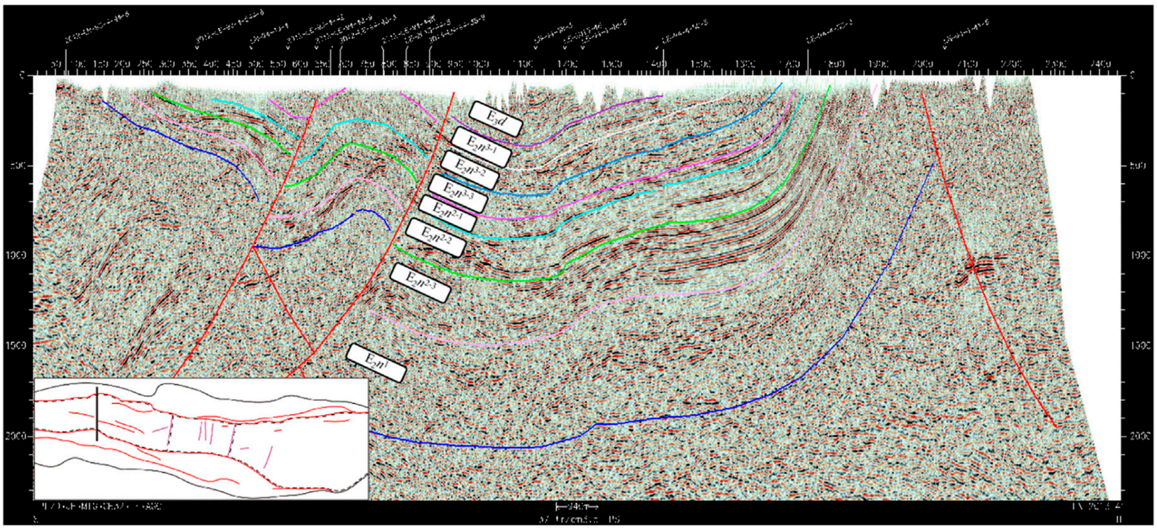

FIGURE 8
Seismic interpretation along line LN 2013–41 in NS direction in the western Lunpola Basin.

conditions, storage conditions, structural conditions, and later preservation conditions in this area, the footwall of the northern thrust nappe belt has best configuration and superposition of hydrocarbon accumulation elements, especially in the eastern Luomadiku area. We suggest the future exploration will focus on structural traps in the footwall of the northern thrust nappe belt, by using 3D seismic data to identify traps and design wells, to achieve new breakthroughs in oil and gas exploration.

4.2 Deep exploration zone in the south slope of jiangjiacuo depression

Sedimentological studies reveal that in the early depositional stage of Niubao Formation, there were obvious syn-depositional faults developed on the southern side of Jiangriacuo (Figure 8). A set of semi-deep lacustrine-deep lacustrine dark shale were deposited in the southwestern depositional center, with an effective thickness of 100–200 m, which is a set of potentially effective source rocks (Liu Z. et al., 2017). As the water depth gradually became shallower, a set of nearshore subaqueous fan sandbodies were deposited in the upper part of Niu-1 section (Liu Y. et al., 2017). This set of sand bodies, together with the coarse-grained sediments deposited in the lower part of Niu-2 section, constituted the third type of reservoir in the study area. This set of reservoirs has a large thickness, relatively coarse lithology, and relatively good reservoir conditions. The regional seals of Niu-2 section are widely developed. In addition, because this set of reservoirs is deeply buried, and negative influence from the later tectonic movement, e.g., the uplift of the Qinghai-Tibet Plateau, is relatively weak. This reservoir has the best oil and gas preservation condition at present. Therefore, its potential oil and gas bearing capacity and productivity should not be underestimated.

5 Conclusion

1) The Paleogene in the Lunpola Basin mainly has three sets of main source rocks, lower Niu-3 subsection, Niu-1 and Niu two sections. The lithology is mainly semi-deep lacustrine-deep lacustrine gray-dark gray mudstone and shale. Among them, the source rock of Niu-1 section is only developed in the Jiangriacuo depression in the western part of the basin, while the source rock of Niu-2 section are the most favorable in the region. The effective source rocks have the largest thickness in the central and western parts of the basin, and have the best hydrocarbon-generating capacity. To the east, the thickness and abundance of the source rocks show a decreased trend. The types of organic matter are mainly Type I and Type II_1, with a maturity of 0.58–1.08%.
2) The study area mainly develops clastic rock reservoirs, which can be divided into three types according to the characteristics of strata distribution. The reservoir conditions are generally poor. The reservoir porosity is between 0.1% and 32.6%, mainly between 2.0% and 10.0%, with an average of 6.5%. The permeability is between 0.0005mD and 116.0mD, mainly between 0.01mD and 0.5mD. It can be defined as a fracture-

porous reservoir with ultra-low porosity and ultra-low permeability

3) There are mainly two types and three sets of seals developed in the Lunpola Basin, including two sets of regional seals in middle Niu-2 subsection and Dingqinghu Formation, and one set of direct caprock in upper Niu-2 subsection. In the relatively stable central depression belt and the footwall of the thrust nappe belt in the northern part of the basin, the seals are relatively developed and have good preservation conditions.
4) The oil and gas reservoirs in the Lunpola Basin have the distribution law of "structural traps in the north and south, and lithologic traps in the center". Structural traps are mainly developed in the thrust nappe belt in the north and the Changshan uplift area in the south, forming "self-generation and self-storage" or "lower-generation and upper-storage" reservoirs. While lithologic traps are mainly developed in the central depression belt, forming "self-generation and self-storage" reservoirs.
5) The footwall of the northern thrust nappe belt and the deep strata of the southern slope of Jiangriacuo depression are the most favorable oil and gas exploration areas in future exploration in the Lunpola Basin.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

ZY completed the writing and revision of the manuscript, XJ completed the polishing of English, and others completed the drawing and other related content.

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Conflict of interest

The reviewer JZ declared a shared affiliation with the author JX to the handling editor at the time of review

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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