Insights into the Origin of Natural Gas Reservoirs in the Devonian System of the Marsel Block, Kazakhstan

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ABSTRACT: The genetic type and accumulation model of the Devonian reservoirs in the Marsel Block remain unclear, despite decades of exploration history. According to the well testing, logging interpretations and sample testing results, the Devonian natural gas reservoir in the Marsel Block has five typical characteristics: (1) It is obvious that the traps contain continuous gas accumulations. Not only the apaxes of the structures are enriched in natural gas, but also the slopes and depressions contain gas accumulations. (2) The gas reservoirs are classified as tight reservoirs, but there are also reservoirs with high porosity and permeability in some areas. (3) The general negative or low-pressure in the gas reservoir is obvious, although the pressure in the target layers of some wells is close to normal. (4) The yields of single wells in the Devonian reservoir are quite different: some wells have low yields or are dry, whereas the gas production from high-yield wells has reached 700 000 m³/day. (5) The gas-water relationship is complicated: there is no obvious gas-water interface, but the water-producing layer is generally located at the apaxes of structures. Research and analysis have shown that using the model of the conventional gas reservoirs genetic type can only explain the characteristics of parts of the gas reservoir, while the model of accumulation in a deep-basin gas reservoir cannot fully explain the distribution characteristics of the Devonian reservoir. However, the model of accumulation in a stacked complex continuous oil and gas reservoir can reasonably explain the geological and distribution characteristics of the Devonian reservoir. Moreover, the predicted gas distribution along a cross-section of the reservoir is also in agreement with the geological background and tectonic environment of the Marsel Block, therefore, the genetic type of the Devonian natural gas reservoir in the Marsel Block is a stacked complex continuous tight-gas reservoir. Finally, by comprehensively analyzing the source rock, reservoir and cap rocks, as well as the structural characteristics, it is verified that Devonian in the Marsel Block has favorable geological conditions for formation of a superimposed continuous tight gas reservoir.

KEY WORDS: stacked complex continuous, tight-gas reservoirs, Devonian, Kazakhstan.

0 INTRODUCTION

The Marsel Block, located in the Chu-Sarysu Basin, is one of the most promising exploration blocks in South Kazakhstan (Zhang et al., 2018; Wang et al., 2017; Zhao et al., 2017; Pang et al., 2014a, b; Zhao et al., 2014; IHS, 2013). Exploration work in the Marsel Block began in mid-1950s, and followed by decades of researches and development by the former Soviet Union, Condor Petroleum, Geo- and the Jade Petroleum Corporation, successively (Pang et al., 2014b). Since 1950s, 85 wells were drilled in the Marsel Block, about 34 structures were found and several commercial gas fields were identified, such as West Ooppak, Ortalyy, and Priderozhnoy gas fields (Wang et al., 2017; Pang et al., 2014a). Adjaently, the Kumkol oil field was found in 1984 in the southern Turgay Basin with good exploration potential (Zhao et al., 2017; Karabaev, 2013; Wang et al., 2012; Marten, 2007). Previous exploration and development revealed that the Marsel Block had favorable geological conditions for oil and gas accumulation and was worth further researches (Zhao et al., 2018; Wang et al., 2017).

However, the origin and formation mechanism of the natural gas reservoirs in the Devonian system in Marsel Block were still unclear (Pang et al., 2014b; Zhao et al., 2014). Some believed that the distribution of the Devonian gas reservoir was obviously different from that of conventional structural and stratigraphic traps, and cannot be fully explained by the theory...
of deep-basin gas reservoirs (Zhao et al., 2012, 2010; Law et al., 2002; Rose et al., 1986; Gies, 1984). Another viewpoint thought it was the continuous tight-gas reservoir, because similar phenomena also occurred in the Bohai Bay basins, which could be satisfactorily explained by the theory of continuous tight-gas reservoirs (Zhao et al., 2012, 2010; Zou, 2009; Zhang et al., 2006; Yang et al., 2003; Schenk, 2002; Schmoker, 2002). But Pang et al. (2014b) considered that the Devonian gas reservoir not only has the characteristics of continuous gas reservoirs but also has some characteristics of conventional structural gas reservoirs, which were different from the Bohai Bay basins, thus it couldn’t be totally explained as continuous oil and gas reservoirs, and therefore put forward a new point of “stacked complex continuous gas reservoir in Devonian system”. The concept “stacked complex continuous oil and gas reservoirs” stated that the formation and distribution of oil and gas reservoirs that cannot be explained by either the classical buoyancy accumulation mechanism or the non-buoyancy accumulation mechanism. Although these kinds of oil and gas reservoirs are generally tight, the compression of a reservoir may be impaired during the evolution process after formation owing to the effects of tectonic movements, and some conventional oil and gas reservoirs have undergone alterations in parts that are controlled by buoyancy, that’s why the term “stacked complex continuous oil and gas reservoirs” is therefore used (Pang et al., 2014a, b, 2013, 2003).

Origins of oil and gas accumulation play important roles in oil and gas exploration and development plan for a prospected area; hence for the natural gas reservoirs in Devonian system in Marsel Block, figuring out its origin and formation mechanism is vital. In this study, we collect the physical log interpretation and productivity tests of a few wells in Marsel Block, then comprehensively analyze the geological characteristics and distribution laws of gas reservoir in Devonian, on basis of this, discuss in-depth the possible opinions on the origin of natural gas reservoir, finally, roughly analyze the formation conditions of the superimposed continuous tight gas reservoirs.

1 GEOLOGICAL BACKGROUND

The Marsel Block is located in the center of the Chu-Sarysu Basin with the exploration area of 18 500 km², and geographically, it is across the center of the Kokpansor depression and the north of the Baykodau depression, near the Turgay Basin (Fig. 1). The nearest gas transmission pipeline is at a straight-line distance of only 100 km, which provides convenient facilities for the transport of gas after the startup of production.

The Marsel Block underwent an initial rifting stage during the Devonian Period, and the Chu-Sarysu Basin mainly consists of multiple isolated depressions bounded by faults. From bottom to top, the stratigraphic strata are the Upper Paleozoic metamorphic crystalline basement, Upper Paleozoic terrigenous clastic sediments, carbonate platform deposits, and Mesozoic–Cenozoic sediments (Fig. 2), of which the Carboniferous and Devonian strata contain important production layers (Zhang et al., 2018; Zhao et al., 2017; Pang et al., 2014a, b). The Devonian strata occur in the Chu-Sarysu Basin in the eastern part of the anticline with large thicknesses. Owing to erosion and pitchout, the Devonian strata disappear to the west in the study area and are in contact with a steep boundary. Only in the northern, central, and southern parts of the block, the Devonian strata are found having an angular unconformity with the metamorphic basement. According to the relationships between seismic reflection terminations and the drilling characteristics of the interfaces, four rock sequences have been identified in

![Figure 1. Tectonic location of the Marsel Block and surrounding oil and gas fields.](image-url)
the Devonian system, which can be divided into three third-order sequences denoted as D_{fm}{1,2,3} (Fig. 2). The Devonian reservoirs represent one of the most important targets for exploration in the Marsel Block, 31 wells have...
been drilled and 26 of them, including well Tamgalytar 1-G, Kendyrlik 5-RD, Assa 1, and Oppak 1-G, all encountered Devonian strata with thicknesses ranging from 40 to 889 m. The distribution of the Devonian gas reservoir is limited and mainly concentrated in three gas fields (West Oppak, Ortalyk, and Pridorozhnaya). The northern block had gas shows in the structures named Oppak and Kendyrlik. The highest yield of a single well reached 700,000 m³/day, with an average yield of 160,000 m³/day, and the estimated reserves are 16×10⁹ m³, which indicates high exploration potential of the Devonian reservoir in Marsel Block (Fig. 3).

2 EXPLANATION AND TESTING DATA

Plenty of productivity test data were collected from 20 wells of the Devonian strata in the Marsel Block, among them, 4 wells showed no dry layer and the remainder wells all had different degrees of gas shows or gas flow, as shown in Fig. 4. The test data mainly comprised three monitoring operations, namely, production capacity tests, pressure recovery tests, and gradient tests, relevant parameters are shown in Table 1.

Well logging curves from 17 wells were also obtained, consisting of HSGR, NPHI, RHOB, DTCO, RLA5, etc. According to the logging curves processed by the appropriate software, we can determine the parameters such as shale volume, calcium volume, porosity, permeability, and water saturation, some of them are presented in Table 1. There are three wells with obvious thick aquifers, namely, Naiman 1-P, Kendyrlik 5-RD, and Kendyrlik 3-G.

Seven wells including West Oppak 1-G, West Oppak 2-G, West Oppak 3-G, Oppak 1-G, Pridorozhnaya 3-G, Pridorozhnaya 5-G, and Pridorozhnaya 6-G, were organized by the former Soviet Union, and other wells were organized by Condor and the Marsel company.

3 RESULTS

Although the distribution of the gas reservoir in the Marsel
Block is limited, the distribution characteristics of natural gas still obey some obvious rules, which are analyzed in detail in this part.

3.1 Coexisting Gas Accumulations at Higher and Lower Positions

The testing gas deposits by exploratory wells generally show that the accumulation of natural gas in the Devonian strata in the Marsel Block has the characteristics of continuous gas accumulations, which means that not only there is much gas present at the apexes of structures, but also there are gas accumulations on slopes and in depressions (Li et al., 2016; Wandrey et al., 1997).

According to the testing gas deposits by exploratory wells (Fig. 4), we can see that in general some exploratory wells had gas shows located both at the apexes and sides of structures. Three gas fields, namely, West Oppak, Ortalyk, and Pridorozhnaya, were found that are located in the center of the lower part of the block. However, there are also two local structures, namely, Oppak and Kendyrlik, which have gas shows located at relatively high positions in the block, whereas other areas were not found to contain natural gas in the Devonian strata. Regarding local structures, gas shows can be found both inside and outside the structural traps. For example, among the wells drilled in the Pridorozhnaya gas field, Pridorozhnaya 4 is located in the upper part of the structure and its gas production rate is 7.31 m³/day, however, although Pridorozhnaya 5 is located outside the structural traps, it still has faint gas shows. The above analysis shows that gas in the Devonian strata in the Marsel Block can not only accumulate at the apexes of structures but also at their bases, slopes, and depressions. This phenomenon makes the study area possess the characteristics of continuous gas accumulations.

![Figure 4. Plane distribution of exploratory well testing for gas in Devonian strata in the Marsel Block (Pang et al., 2014a).](image-url)
<table>
<thead>
<tr>
<th>Well name</th>
<th>Structure</th>
<th>Porosity (%)</th>
<th>Permeability (mD)</th>
<th>Gas saturation (%)</th>
<th>Test interval (m)</th>
<th>Fluid situation</th>
<th>Gas yield ($10^4$ m$^3$/day)</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Oppak 1-G</td>
<td>West Oppak</td>
<td>3.98–8.46</td>
<td>0.13–5.46</td>
<td>52–62.5</td>
<td>1 809–1 878</td>
<td></td>
<td>7</td>
<td>Water shows</td>
</tr>
<tr>
<td>West Oppak 2-G</td>
<td></td>
<td>3.37–11.06</td>
<td>0.46–8.13</td>
<td>55.13–81.21</td>
<td>1 906–2 030</td>
<td></td>
<td>0.13</td>
<td>Water shows</td>
</tr>
<tr>
<td>West Oppak 3-G</td>
<td></td>
<td>2.62–8.79</td>
<td>0.18–8.93</td>
<td>50.38–79.28</td>
<td>1 997–2 242</td>
<td>No fluid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oppak 1-G</td>
<td>Oppak</td>
<td>7</td>
<td>7</td>
<td></td>
<td>1 224–1 372</td>
<td>No fluid</td>
<td></td>
<td>Water shows</td>
</tr>
<tr>
<td>Kendyrlik 3-G</td>
<td>Kendyrlik</td>
<td></td>
<td></td>
<td></td>
<td>2 238–2 384</td>
<td></td>
<td></td>
<td>Water layer</td>
</tr>
<tr>
<td>Kendyrlik 5-RD</td>
<td></td>
<td>2.63–9.34</td>
<td>0.18–1.35</td>
<td>55.44–86.22</td>
<td>1 679–1 680</td>
<td>No hydrocarbon</td>
<td>10</td>
<td>Water layer</td>
</tr>
<tr>
<td>Ortalyk 1-G</td>
<td>Ortalyk</td>
<td>4.32</td>
<td>0.1–0.78</td>
<td>57.49–60.42</td>
<td>2 606–2 690</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ortalyk 2-G</td>
<td></td>
<td>5.28–8.7</td>
<td>0.41–2.19</td>
<td>55.42–82.44</td>
<td>2 118–2 614</td>
<td>Dry layer</td>
<td>3.0</td>
<td></td>
</tr>
<tr>
<td>Ortalyk 3-G</td>
<td></td>
<td>5.24–7.92</td>
<td>0.37–5.33</td>
<td>64.39–78.56</td>
<td>2 500–2 680</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pridorozhnaya 3-G</td>
<td>Pridorozhnaya</td>
<td>2.380–2 435</td>
<td>102</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pridorozhnaya 5-G</td>
<td></td>
<td>2 225–2 450</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pridorozhnaya 6-G</td>
<td></td>
<td>2 526–2 690</td>
<td>3.0</td>
<td></td>
<td></td>
<td>Weak hydrocarbon</td>
<td>7.4</td>
<td></td>
</tr>
<tr>
<td>North</td>
<td>North</td>
<td>7.61–15.7</td>
<td>0.45–11.1</td>
<td>58.8–65.23</td>
<td>2 644–2 798</td>
<td>Dry layer</td>
<td>1.2</td>
<td>Water shows</td>
</tr>
<tr>
<td>Pridorozhnaya 7-G</td>
<td>Pridorozhnaya</td>
<td>2 876–3 048</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Water shows</td>
</tr>
<tr>
<td>South Pridorozhnaya 17-G</td>
<td>South Pridorozhnaya</td>
<td>2 413–2 580</td>
<td>38.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assa 1</td>
<td>Assa</td>
<td>4.5–14.3</td>
<td>0.1–3.2</td>
<td>50.2–67.82</td>
<td>2 413–2 580</td>
<td></td>
<td>1 407–1 690</td>
<td>Water layer</td>
</tr>
<tr>
<td>Nainman 1-P</td>
<td>Nainman</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulak 2-G</td>
<td>Bulak</td>
<td></td>
<td></td>
<td></td>
<td>2 940–3 015</td>
<td></td>
<td></td>
<td>Dry layer</td>
</tr>
</tbody>
</table>
3.2 Abnormal Physical Properties of the Gas Reservoirs

In the process of well logging interpretation, by combining logging features with the results of gas logging and testing, carrying out a comprehensive analysis of the lithology, physical properties, and electrical properties of the reservoir, and then selecting appropriate processing parameters, we can generate a resistivity-porosity intersection diagram and a gas saturation-resistivity intersection graph to obtain the logging interpretation of the porosity of the target layers. Results show that the main reservoir, namely, the Devonian Famennian reservoir, has generally low porosity, which is generally less than 12% and mostly in the range of 4%–9%, with an average of 6.28%. However, there are still some logging interpretations of reservoir porosity that are greater than 12% (Fig. 5). For example, some gas reservoirs fractures and cavities have developed in individual well sections, which resulted in a logging interpretation of high porosity. It can be concluded that the gas-bearing reservoir of the Devonian system in the Marsel Block can be classified as a tight reservoir, but locally develops layers with high porosity and permeability (Zhao et al., 2018; Qiu et al., 2017; Pang et al., 2014a).

3.3 Abnormal Pressure Properties of the Gas Reservoirs

We tested the pressure in three gas-bearing structures in the Upper Devonian strata in the Marsel Block, namely, the Oppak West, Pridorozhnaya, and Kendyrlik structures. Then, we analyzed the pressure data for the formation and calculated the formation pressure, the hydrostatic pressure, and the corresponding pressure coefficient of each well in each depth segment (Table 2), the relationship between the actual formation pressure and the hydrostatic pressure was also established (Fig. 6). Results show that the actual formation pressure in the Devonian system is generally lower than the hydrostatic column pressure. Eleven test points in five wells were used for data collection. The measured data points are all to the left of the line representing the hydrostatic column pressure and corresponding to negative pressure, as their pressure coefficient is generally less than 1. For example, the Assa 1 well in the Assa structure was tested for gas deposits in the two layers of the Upper Devonian in 2 402–2 426 and 2 530–2 580 m segments. Daily gas production was 0.81–6.14 million m$^3$ and 21.5–38.35 million m$^3$, respectively, the formation pressures in the two gas-bearing strata were 24.58 and 26.01 MPa, respectively, and the pressure coefficient was 0.87, which indicated negative pressure characteristics. There were also some points where the pressure was close to normal, for example, the average depth of the Kendyrlik 4 well was 2 236 m, its formation pressure was 26.10 MPa, and its pressure coefficient was 0.998, which is close to the hydrostatic pressure, belonging to the normal pressure. It can therefore be concluded that the characteristics of negative or low-pressure in the gas reservoir are obvious, and some of the wells have pressure that is close to normal in the target layer (Li et al., 2018; Pang et al., 2014a, b; Roy and Ryan, 2013).

3.4 Complicated Gas-Water Relationships of the Gas Reservoirs

Results show that the characteristics of water deposits are not obvious in the Devonian system in the Marsel Block. At the base of the depression, we can see that there is essentially no water present on testing. Only the Kendyrlik 5-RD and Kendyrlik 3-G wells, which are located in the northern part of the study area, and the Naiman 1-P well, which is located in the southern part of the uplifted anticline, contain an obvious water

![Figure 5. Porosity and permeability of gas reservoir in the Devonian system.](image)

**Table 2** Well pressure tested in the Marsel Block

<table>
<thead>
<tr>
<th>Well name</th>
<th>Mid-depth (m)</th>
<th>Layer</th>
<th>Formation pressure (MPa)</th>
<th>Hydrostatic pressure (MPa)</th>
<th>Pressure coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kendyrlik 4</td>
<td>2 236</td>
<td>D3</td>
<td>26.10</td>
<td>26.16</td>
<td>0.998</td>
</tr>
<tr>
<td>Kendyrlik 4</td>
<td>2 420.5</td>
<td>D3</td>
<td>25.78</td>
<td>28.32</td>
<td>0.910</td>
</tr>
<tr>
<td>Pridorozhnaya 4</td>
<td>2 401.5</td>
<td>D3</td>
<td>25.58</td>
<td>27.54</td>
<td>0.929</td>
</tr>
<tr>
<td>Pridorozhnaya 4</td>
<td>2 420.5</td>
<td>D3</td>
<td>25.26</td>
<td>28.32</td>
<td>0.892</td>
</tr>
<tr>
<td>Pridorozhnaya 4</td>
<td>2 246.5</td>
<td>D3</td>
<td>25.58</td>
<td>26.28</td>
<td>0.973</td>
</tr>
<tr>
<td>Pridorozhnaya 4</td>
<td>2 250</td>
<td>D3</td>
<td>25.26</td>
<td>25.80</td>
<td>0.979</td>
</tr>
<tr>
<td>West Oppak 1</td>
<td>1 861</td>
<td>D3</td>
<td>18.40</td>
<td>21.77</td>
<td>0.845</td>
</tr>
<tr>
<td>West Oppak 1</td>
<td>1 842</td>
<td>D3</td>
<td>15.33</td>
<td>21.55</td>
<td>0.711</td>
</tr>
<tr>
<td>Assa 1</td>
<td>2 555</td>
<td>D3</td>
<td>26.01</td>
<td>29.89</td>
<td>0.870</td>
</tr>
<tr>
<td>Assa 1</td>
<td>2 414</td>
<td>D3</td>
<td>24.58</td>
<td>28.24</td>
<td>0.870</td>
</tr>
<tr>
<td>Tamgalytar 1-G</td>
<td>2 294.5</td>
<td>D3</td>
<td>22.43</td>
<td>26.31</td>
<td>0.853</td>
</tr>
</tbody>
</table>
layer in the Upper Devonian. In the former two wells, the water-type is sodium chloride, and in the latter it is sodium sulfate and potassium sulfate. The Assa 1 well, which is located on the slope in the study area, contains an obvious gas-bearing formation. The logging interpretation of the porosity of oil-, gas-, and water-bearing reservoirs in the Devonian also shows that the relationship between gas and water deposits in the Marsel Block is complex, and the characteristics of the water deposits located beneath the gas deposits are not obvious (Fig. 7).

4 DISCUSSION

There are three stages of petroleum exploration in the Marsel area so far; however, the findings of exploratory well testing have not been ideal. According to the above analysis, we find that it has some typical features such as continuous gas accumulations, low porosity, and density, but locally high porosity; coexistence of high pressure and normal pressure in a gas reservoir; coexistence of wells with high and low production yields; and water deposits at the apexes of structures with a complex relationship between gas and water deposits. However, these characteristics can neither be explained by the genetic mechanism of conventional gas reservoirs nor by that of unconventional deep-basin gas reservoirs. Analysis shows that the gas reservoir in the Devonian strata in the Marsel Block is formed by the superposition of different types of gas reservoirs via various reservoir-forming mechanisms and can be considered as a superimposed continuous tight gas reservoir.

4.1 Failures of Accumulation Mechanisms of Conventional Structural Gas Reservoirs

There are 15 petrolierous basins in Kazakhstan, five of which have entered industrial development at present. Among them, the Kumkol oil field is a large anticlinal sandstone reservoir with gas cap and edge water, as shown in Fig. 8. Besides structural traps, the potential exploration areas in the future are mainly concealed lithological structural composite traps and stratigraphic traps (Zhao et al., 2017; Karabaev, 2013; Marten, 2007). The Marsel Block is adjacent to the Kumkol oil field, so it has always drawn lessons from Kumkol with respect to the search for oil and gas in structural traps (Istekova et al., 2012). However, the results were not ideal. Except for a few wells, most oil and gas wells are located in slopes and depressions, and this distribution features cannot be fully explained by the conventional theory of structural traps, as is displayed in Fig. 4.

Otherwise, in terms of structural traps, a water-type reservoir is generally formed (Fig. 8), which means the weight of the air column is less than that of the water column, the general pressure at any point in the gas reservoir is greater than the hydrostatic pressure at the same point and the pressure coefficient is greater than 1. However, the pressure in the Devonian gas reservoirs in Marsel Block is mainly negative, although there are also some cases where the pressure approaches atmospheric pressure, the characteristics of the gas and water deposits in the target layer are complex, and water will be present in the apexes of structures (Figs. 6, 7). The traditional accumulation model of structural gas reservoirs has been unable to explain the distribution features of the Devonian gas reservoir in the Marsel Block and its complex distribution pattern of gas and water (Hu et al., 2015). In particular, this mechanism does not provide a good explanation of the formation of such a large area of gas reservoirs.
4.2 Failures of Accumulation Mechanisms of Deep-Basin Gas Reservoirs

Since Masters (1979) put forward the concept of deep-basin gas for the first time at the end of the 1970s, it has led to much investigation and development by many researchers (Law, 2002; Rose et al., 1986; Gies, 1984). From a study of a deep-basin gas reservoir in the Alberta Basin in Canada, Masters (1979) considered that a typical deep-basin gas reservoir should be located in a syncline structure or down dip region and has a large scale distribution. Since then, many researchers have come to a general consensus on the characteristics of deep-basin gas reservoirs after undertaking studies (Zou et al., 2013; Zhao et al., 2012, 2010; Law, 2002; Rose et al., 1986; Gies, 1984). The consensus can be summarized as follows: (1) the reservoir is located at the axis or in the tectonic down dip region of a syncline basin and has a large scale distribution; (2) the reservoir is mostly tight sandstone; (3) the relationship between gas and water layers is inverted; (4) the pressure in the gas layer is abnormal; (5) the reservoir has separate gas-water interfaces in the up dip direction, but not in the down dip direction; (6) the reservoir is buried deeply; (7) the source rock is mainly coal-bearing strata (Fig. 9).

The distributions of the gas reservoir in the Devonian strata in the Marsel Block and a typical deep-basin gas reservoir (Alberta Basin) have many similarities. For example, gas deposits are located in the down dip regions of structures and the gas-bearing area is extensive; the gas-bearing formation in the Devonian system is a tight sandstone reservoir, the pressure in the gas layers is abnormal; and the depth of the gas reservoir changes abruptly. Therefore, the original theory of deep-basin gas reservoirs can be used to explain some distribution characteristics of the gas reservoirs in the Devonian series. However, there are also some unique features that cannot be explained by the theory of deep-basin gas reservoirs. For instance, although natural gas in the target layer accumulates partly in slope and depression areas, part of the gas still accumulates at the apexes of structural traps. In addition, the relationship between gas and water deposits is complex: the limited number of data points show that water accumulates mainly at the apex of the structure, but the inversion phenomenon is not obvious and separate gas-water interfaces do not form in the up dip and down dip directions. Finally, the main source rocks of the Devonian strata are mudstone and marl, and they do not have the development environment of coal-bearing strata.

Therefore, it is considered as a result of analysis that the natural gas reservoirs in the Devonian strata in the Marsel Block may have various genetic types. Some of their features can be explained by the conventional theory of structural gas reservoirs, others by the theory of tight-gas reservoirs, but neither theory can accurately explain the formation of all the features of the gas reservoirs in the Devonian strata in the Marsel Block.

4.3 Explanation of the Genesis of Superimposed Continuous Tight Gas Reservoirs

In the mid-1990s, the United States Geological Survey (GSC, 1995) put forward the concept of “continuous oil and gas reservoir” or “continuous accumulation,” which was certified by the SPE, SPEE, WPC, and other international authorities (2007) (Etherington and Rittter, 2008). A continuous oil and gas reservoir was defined as an accumulation of oil and gas that was distributed widely and had no clear boundary, of which the existence was more or less independent of the water column. Deep-basin gas, coal bed gas, and so on, were classified as continuous oil and gas accumulations (Gautier et al., 1996). This kind of oil and gas reservoir can be exploited on a large scale and has great resource potential, and has therefore received the attention of researchers all over the world and has been used as a model for guiding the exploration and production of the Alberta, Bohai Bay, Ordos, and other basins (Gao and Wang, 2017; Zhao

Figure 8. Profile of oil reservoir in the Kumkol oil field at a SW-NE direction (Zhao et al., 2014).
et al., 2010; Zou, 2009; Schenk, 2002; Schmoker, 2002). The geological characteristics and formation conditions of continuous oil and gas reservoirs have been summarized by many researchers and mainly include the following features: the reservoir and source rocks are in close proximity; the gas supply is adequate; dense reservoirs are contiguous; structures are stable with gentle dips; the relationship between gas and water deposits is inverted and the pressure is abnormal; oil and gas deposits are not controlled by structural features; buoyancy is not a driving force; don't need cover to cover; and reserves are huge with low productivity. The theory of continuous hydrocarbon accumulations can explain the characteristics of many unconventional oil and gas reservoirs. However, the theory of continuous oil and gas reservoirs cannot fully explain reservoirs that not only have the geological features and development conditions of unconventional oil and gas reservoirs but also exhibit some features of conventional gas reservoirs.

With this aim, Pang et al. (2014b) put forward the concept of the “superimposed continuous oil and gas reservoir,” which was defined as unconventional oil and gas reservoir that was widely distributed in a petrolierous basin, appeared continuously in a belt formation, and was not controlled by buoyancy. These are usually associated with their hydrocarbon source rocks, the target formation is relatively tight, and they can usually be seen in basins that have undergone the deposition of cyclic sediments and stable tectonic evolution. Because the oil and gas reservoir has experienced different processes, dynamic effects, and stages of recombination, its geological features are very complex and can neither be explained and predicted by the theory of the genesis of conventional reservoirs nor fully explained by the formation mechanism of oil and gas reservoirs in tight deep basins. Although the reservoir is essentially dense, the tight nature of the reservoir may have been destroyed owing to the tectonic changes during the evolution process after its formation, and modified gas reservoirs controlled by buoyancy may also occur locally. We therefore classified these reservoirs as superimposed continuous oil and gas reservoirs, whose distribution pattern is shown in Fig. 10a. The concept was proposed based on the analysis of several typical superimposed continuous oil and gas reservoirs in China, such as Ordos Basin, Sichuan Basin, Songliao Basin, the example of distribution characteristics of superimposed continuous gas reservoirs in Ordos Basin is shown in Fig. 10b. This kind of oil and gas reservoir has four obvious characteristics, that is: (1) The reservoir is generally tight, upper and lower gas deposits coexist, where the apexes of structures are enriched in oil and gas, hydrocarbons accumulate in the slope areas, and the low-lying areas are also rich in oil and gas, which are obviously not controlled by buoyancy. (2) The reservoir is widely distributed in general, and its yield is complex and variable, being high at some times but very low at other times; it occurs widely in petroliferous basins in the form of local deposits and belt formations. In this area, the enrichment of natural gas is not under the control of conditions related to upper and lower positions in the structure, and the production capacity is complex and changeable and varies from place to place. (3) Many target layers are vertically superimposed and amalgamated; oil and gas at high and low pressures coexist; multiple sets of source rocks have formed during the sedimentary cycle, of which source rocks between, below, and above the target layers are all

![Figure 9. Section through the deep-basin gas reservoir in the Alberta Basin in western Canada (after Masters, 1979).](image-url)
favorable for the formation and distribution of tight-gas reservoirs; high- and low-pressure reservoirs exist in the same region of oil and gas deposits and even coexist in a single layer of oil and gas. (4) The resource potential is huge, although the yields of oil, gas, and water cannot be forecasted easily, the upper segment of the reservoir, which is located at shallow depths, contains many aquicludes and has a high water output, whereas the lower segment of the reservoir, which is located at greater depths, has a low water output, and the productivity of the intermediate regions is between that of the former segments. The relationship between gas and water deposits is complex, and the oil and gas capacity is difficult to predict, but the resources are on a large scale.

From a study of the geological and distribution characteristics of gas reservoirs in the Devonian system in the Marsel Block, the characteristics of these gas reservoirs are typical of some conventional reservoirs, in the following respects: some gas is present at the apexes of structures (Fig. 4); above the reservoirs there are cap rocks that provide sealing protection; some reservoirs display abnormal pressure (Fig. 6); and the area of oil and gas in structural traps is usually small. In contrast, some gas reservoirs in the Devonian strata have typical features of tight-gas reservoirs, for example, many of them are located in depressions and on slopes, the relationship between water and gas layers is inverted, pressure in the layers is negative, porosity and permeability are very low, gas deposits are contiguous and their scale is large, the source rocks and gas reservoirs are in close contact.

We can therefore deduce that during the process of burial evolution, the Devonian reservoir has experienced a transformation process from low to high density and from a situation where buoyancy fulfilled the main function to one where...
buoyancy does not play a role. When this is combined with the generation and expulsion of source rocks, different types of oil and gas reservoirs will be present at different stages, which are in general vertically superimposed and amalgamated, which then enables the formation of a wide range of continuous gas deposits. However, the results of drilling for natural gas, seismic monitoring of the gas reservoir, and logging interpretations of the distribution of gas reservoir can all be explained by the genetic model of a superimposed complex continuous tight-gas reservoir. Further studies have also indicated that the reason why the Devonian system in the Marsel Block has such a gas distribution characteristic is due to the interaction of a tight conventional gas reservoir, a tight deep-basin gas reservoir, and a dense composite gas reservoir. An analysis based on measured data has predicted the gas and water distribution in the Marsel Block along a geological section (Fig. 11), and it can be seen that this is similar to the pattern of the distribution and development of superimposed continuous oil and gas reservoirs. It can therefore be concluded that the original type of gas reservoir in the Marsel Block is a superimposed continuous tight sandstone gas reservoir.

4.4 Formation Conditions of the Superimposed Continuous Tight Gas Reservoirs

Devonian source rocks in Marsel Block have abundant gas supplies in and around the reservoirs (above or below reservoirs). The reservoirs are extensively developed and located next to each other in the same plane. Since the formation is generally tight, buoyancy doesn’t work here. The structure has a long-term stability and the formation is flat, therefore, the geological conditions are conducive for formation of superimposed continuous tight gas reservoirs.

4.4.1 Stable structural configuration

From Fig. 4, we can see the structural morphological features of the Devonian base in Marsel Block. It is found that the structural interface of the Devonian is relatively flat, especially in the northern part of the exploration area, which is conducive to the formation and distribution of oil and gas reservoirs. The southern of the exploration area, especially the southeast corner, which is complex in structure morphology, is not favorable to the formation and preservation of oil and gas reservoirs.

According to an integrated analysis of regional unconformity, seismic reflection profile characteristics, tectonic deformation styles and regional tectonic evolution history, the tectonic evolution of the Marsel Block can be divided into four stages, the initial rifting stage, a passive continental margin period, a period of subduction and collision, and a period of intercontinental depression (Fig. 12). During the Devonian period the basin began to form and was in the early stages of rift basin development at that time. There was a major fault in the interior of the basin, and the strata to the east of the fault were thicker than those to the west. The basin became a passive continental margin basin during the Carboniferous. The sedimentary basin was in a stable state of sediment deposition with level strata during the Devonian and Carboniferous. At the end of the Permian the basin underwent folding, and the sedimentary strata in the west became thicker than the strata in the east. The eastern strata were uplifted on a large scale and the Permian sedimentary formations underwent denudation to some extent, while the western Permian sedimentary strata remained thick. At that time the basin became a transpressional basin as a result of plate subduction and collision. The basin entered a continental depression stage and the sedimentary strata were more homogeneous after the Mesozoic (Fig. 2). Based on the regional tectonic evolution and its intensity, it is believed that the northern part of the Marsel exploration area, especially the northwestern region, which has not experienced tectonic deformation, is favorable to the formation, distribution and preservation of extensive continuous oil and gas reservoirs.

4.4.2 Good source-reservoir-cap combination

Figure 2 illustrates that the Marsel exploration area has developed the well-combined source rock-reservoir-cap conditions. The Devonian strata are characterized by the interceded sandstone and mudstone, covered by a set of salt rocks which...
is the direct cap rocks of the Devonian strata. The mudstone developed inside the Devonian strata is the main source rock, which is well developed in the northern and central regions with thickness of 20–120 m, TOC is 0.2%–1.2%. Alluvial fan, fan delta sandstone, braided river delta sandstone of D3 fm1, D3 fm2 constitutes the reservoirs. Based on the development of source rocks, reservoirs and cap rocks, the Devonian can be divided into a large source-reservoir-cap rock combination, and the Upper Permian salt rock strata are regional cap rocks. The existence of salt cap rocks is favorable to the preservation of oil and gas in the study area. On the other hand, the mutual development and close proximity of source rocks and reservoirs are another important condition favoring the oil and gas exploration in the study area.

In the Permian, during which large amount of gas and oil was accumulated, the structure forms of reservoirs were overall gentle. In the early period, oil and gas tend to migrate from the north, the oil and gas generation and expulsion center, to the east and south, and the structural high part in this direction was conducive to the formation of conventional oil and gas reservoirs. In the late stage, after the reservoirs were completely compacted, dense deep basin oil and gas reservoirs were formed in the center of the source rocks and the surrounding tight reservoirs. Under the conditions that the oil and gas source was sufficient, oil and gas migrated outward to the surrounding structure and formed dense combined reservoirs. In general, the combination of source-reservoir-cap rocks and the structural features of the study area are favorable to the formation and distribution of extensive continuous reservoirs.

5 CONCLUSIONS
(1) The natural gas reservoirs in the Devonian system in the Marsel Block have five distinct characteristics, namely, gas accumulations at upper and lower positions can coexist; the gas...
reservoir has low porosity and locally high porosity and high permeability; the formation has obvious characteristics of negative pressure, and some areas have normal pressure; gas wells with high and low yields coexist; and the characteristics of gas and water deposits are complex, and water accumulates at the apexes of structures.

(2) The genetic types of the gas reservoirs in the Marsel Block cannot be fully explained by the theory of the formation of conventional structural gas reservoirs or the theory of hydrocarbon accumulation in deep-basin gas reservoirs. An analysis shows that the original type of gas reservoir in the Marsel Block is a superimposed continuous tight sandstone gas reservoir.

(3) In Marsel Block’s Devonian system, source rocks are well-developed, and reservoirs are tight, superimposed and unevenly distributed. The cap rock is quite thick and stable. Structural activities are not active, the stratum is flat, and source-reservoir-seal matches well. These conditions thus verify that the study area has geological formation conditions of superimposed continuous tight gas reservoirs.

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