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Differential Genetic Mechanisms of Deep High-Quality Reservoirs in the Paleogene Wenchang Formation in the Zhu-1 Depression, Pearl River Mouth Basin

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Abstract: The Lufeng Sag and Huizhou Sag, both located in the Zhu-1 Depression, have similar geographical locations, but their reservoir characteristics in the Paleogene Wenchang Formation show obvious differences. Primary intergranular pores are mainly developed in the Lufeng Sag. However, secondary pores are the main reservoir space in the Huizhou depression. Overall, the reservoir properties of the Lufeng Sag are better than those of the Huizhou Sag. To analyse the differences between the Paleogene reservoirs in these two areas, this study mainly uses assay data, such as rock thin sections, scanning electron microscope images, drilling, and logging, to analyse the differential development mechanisms of high-quality reservoirs, and two types of reservoir development models were concluded. The results show that the anti-compaction primary porosity preservation mode is mainly developed in the Lufeng Sag. High compositional maturity quartz sandstone is the congenital condition of primary porosity development. The top and bottom calcareous cementation formed of the large set of thick sand bodies increases the rock’s anti-compaction ability. The early shallow burial slows down the compaction action of overlying strata. Under the low geothermal temperature, it can delay the time for deep reservoirs to enter the middle diagenetic stage. The reservoirs in the Huizhou Sag are developed with the secondary dissolution pore development model. The Wenchang Formation reservoir in the Huizhou Sag has a large area of contact with source rocks, and organic acids can migrate to sandstone reservoirs for dissolution. Additionally, the secondary dissolution pores are more developed because the Wenchang Formation reservoirs in the Huizhou Sag contain more easily dissolved substances.

Keywords: Pearl River Mouth Basin; Paleogene; high-quality reservoir; primary porosity; secondary porosity; differences in genetic mechanism

1. Introduction

High-quality reservoir refers to the development of reservoirs with relatively good physical properties under the background of low porosity and low permeability [1]. Previous studies suggested that primary intergranular pores basically disappeared, mainly secondary dissolution pores, due to the large burial depth and strong compaction of deep reservoirs, such as the Flemish Pass, offshore Newfoundland, the Southern Campos Basin, the Shwebo Basin, Myanmar, and the Bohai Bay Basin, China [2–5]. The research about the pores of deep high-quality reservoirs is also mainly focused on the genetic mechanism of secondary pores, and it is believed that the release of organic acids after the maturity of source rocks to dissolve the soluble minerals in reservoirs is the main reason for the development of secondary pores in reservoirs [6–13]. However, the exploration
practice in recent years has gradually revealed the existence of deep high-quality reservoirs dominated by primary pores, such as the Gulf of Mexico (GOM) Basin, the South Pars Gas Field, Iran, and the Southeast Hainan Basin, China [1,14,15]. Studies have shown that reservoirs with high quartz content can increase the anti-compaction ability of rocks to protect primary pores [16]. The first hydrocarbon charging decreased water saturation, inhibited the cementation, and preserved some pores [17]. The abnormal high-pressure development in sandstone reservoirs can effectively resist the compaction of overlying strata and hinder the formation of cements. Secondly, the abnormal pressure is beneficial for taking away the corrosion products and increasing the corrosion of easily corroded particles (such as feldspar and lithic) [18–20]. Additionally, early diagenesis blocking pore space can effectively inhibit the destruction of primary pores by compaction [21].

In recent years, with increasing exploration and an expansion of the exploration field, a series of significant exploration progresses has been achieved in several sub-sags of the Zhu-1 Depression, Pearl River Mouth Basin. For example, in 2009, high-yield oil and gas layers were discovered in the Wenchang Formation below 3700 m in the Huizhou Sag, and drilling in the Lufeng Sag in 2014 also confirmed that the Wenchang Formation below 4000 m can form industrial production layers [22]. The results of Paleogene exploration show that high-quality reservoirs can also be developed in the Paleogene under deep burial conditions [23–27]. Both the Lufeng Sag and the Huizhou Sag are located in the eastern part of the Zhu-1 Depression, separated only by the Hui-Lu Low Uplift. However, the Paleogene Wenchang Formation reservoirs in the two areas show great differences. Primary intergranular pores are mainly developed in the Lufeng Sag, with a small proportion of secondary pores. However, the adjacent Huizhou Sag presents different reservoir characteristics, mainly secondary dissolution pores, and primary intergranular pores contribute less to the reservoir pores. In view of the different characteristics of reservoirs in different sags, previous studies on Paleogene reservoirs in the Lufeng and Huizhou areas have maintained that sedimentation, diagenesis, and early oil and gas injection control the development of reservoirs, and these work together to ultimately form high-quality reservoirs [28–31]. For deep-buried sandstone reservoirs, the research about pore preservation has made some progress in preservation mechanism and applicable conditions, but there are still many challenges. Exploration has also shown that the geothermal environment, sand body thickness, and rock type where the Paleogene reservoirs are located in the two sags are different, but the above factors have not been studied previously. Therefore, the key genetic information of reservoir porosity differences in the study area may have been ignored.

This study focuses on the Paleogene Wenchang Formation strata in the Lufeng Sag and Huizhou Sag in the Zhu-1 Depression of the Pearl River Mouth Basin as the research object to analyse the differences in reservoir pore types, physical properties, and petrological characteristics between the two regions. Systematic genetic mechanism analysis was carried out according to the differences in characteristics between the reservoirs in the two regions. Based on the differences in rock grain maturity in Paleogene sandstone reservoirs, this paper analyses the geothermal environment, sand body thickness, burial mode, and later dissolution reformation, aiming to determine differences in the genetic mechanism of high-quality reservoirs in the Wenchang Formation in these two areas. Then, the evaluation and prediction of high-quality reservoirs in different sags are conducted to further promote the exploration of high-quality reservoirs in the Paleogene of the Zhu-1 Depression and provide a reference for similar hydrocarbon-bearing basins in the world.

2. Geological Setting

The Pearl River Mouth Basin is located in the vast continental shelf and slope area between Hainan Island and Taiwan Island, south of Guangdong Province. It is a NE-SW trending Cenozoic continental margin extensional basin developed on different types of Pre-Paleogene [32]. The tectonic evolution can be divided into a syn-rift and a post-rift
stage [33,34]. During the syn-rift period (56.5–30 Ma), grabens and half-grabens were widely formed in the Pearl River Mouth as a result of crustal thinning and normal faulting [35]. The post-rift stage (30 Ma to the date), characterised by stable thermal subsidence, is generally divided into two stages [36,37]. The Zhu-1 Depression is located in the northern part of the Pearl River Mouth Basin. The NW-trending low uplift and NE-trending fault system that is developed in the internal depression jointly control the tectonic framework inside the depression. From east to west, the Zhu-1 Depression is divided into the following seven tectonic units: the Hanjiang Sag, Haifeng Uplift, Lufeng Sag, Huilu Low Uplift, Huizhou Sag, Xijiang Sag, and Enping Sag (Figure 1a). The Lufeng Sag and Huizhou Sag are located in the eastern part of the Zhu-1 Depression, separated by the Huilu Low Uplift.

There is a high degree of exploration throughout the Paleogene, which is the main hydrocarbon accumulation zone of the Zhu-1 Depression [38].

The Pearl River Mouth Basin is filled with formations deposited in continental to marine environments [39–41]. Eight sets of sedimentary strata were developed from bottom to top, namely, the Shensu Formation, Wenchang Formation, Enping Formation, Zhuhai Formation, Zhujiang Formation, Hanjiang Formation, Yuehai Formation, and Wanshan Formation (Figure 2). The deposits of Shenhu, Wenchang, and Enping formations belong to the continental environment during the syn-rift stage, and they are mainly composed of alluvial, fluvial, deltaic, and lacustrine conglomerates, sandstones, siltstones, and claystones [42]. A large-scale transgression occurred in the Pearl River Delta during the sedimentation of the Zhuhai Formation. The Zhujiang Formation, Hanjiang Formation, Yuehai Formation, and Wanshan Formation consist of marine deposits. The Paleogene reservoirs have developed in the Wenchang Formation, Enping Formation, and Zhuhai Formation from bottom to top, of which the Wenchang Formation can be divided into two large members and subdivided into six sub-members (from bottom to top: Wen 6 to Wen 1). The entire Wenchang Formation depositional period constitutes a complete rift cycle Wen 6–Wen 5 corresponds to the initial rifting stage, with a small sedimentation range. The sediment supply mainly came from the low uplift in the basin, where braided river delta and fan delta sedimentary systems were developed. Wen 4–Wen 3 correspond to the rift expansion period. A wider lake basin, deeper water body and large sets of lacustrine mudstone were developed. During the sedimentary period of Wen 3, which was affected by the Huizhou movement, there was a series of structural phenomena such as the north–south transformation of rifting, the migration of concave-controlling faults, the uplift of the base, the diapir of magma and denudation [43]. During this period, the depositional range was wide, and the lake basins were distributed contiguously. Wen 2–Wen 1 corresponds to the rift atrophy period. Sedimentary water became shallow, and most areas of depression became exposed. Large braided river delta and small fan delta deposits were developed in this period.
Figure 1. Structural unit division figure of Zhu-1 Depression (a) and well location figure of Zhu-1 Depression (b).
Figure 2. Comprehensive histogram of strata in Zhu-1 Depression.
3. Samples and Methods

3.1. Sampling and Data

In order to reveal the difference of quality reservoir characteristics and formation mechanisms among different depressions in the Zhu-1 Depression, the cores from 11 wells were selected, with a total of 248 samples. At the same time, a total of 20 logging data and 548 porosity and permeability data were collected. The core samples of each well are mainly from the Paleogene Wenchang Formation. Well locations in the study area are selected as shown in the figure (Figure 1b). All of the samples were cut into cylindrical plugs of 2.5 cm in diameter and 5 cm in length for laboratory experiments. Samples were randomly selected for optical microscopy of thin section experiment and scanning electron microscopy experiment. Among them, there are 248 optical microscopies of thin sections and 46 samples by scanning electron microscopy. Scanning electron microscopy experiment is only used to analyse the difference of pore types between the two sags, so 46 samples are sufficient to analyse the different characteristics of high-quality reservoirs.

3.2. Scanning Electron Microscopy (SEM)

Scanning electron microscopy is a common imaging technique used to examine microstructures and pore types of sandstone reservoir rocks at micro-to nano-scales due to the need to widen fields of view and to increase image resolutions [44–46]. To observe the characteristics of pores in lacustrine shale, SU8010 cold field emission scanning electron microscopy (SEM) equipped with low and high secondary electron (SE) probes (1.0 nm/15 kV, 1.3 nm/1 kV) at China University of Petroleum (Beijing) was used to image the samples. It is worth noting that the core chips needed to be polished to 0.1 mm thickness using helium ion beams and cut into pieces measuring 0.5 cm × 1 cm × 0.2 mm before SEM imaging.

3.3. Optical Microscopy of Thin Sections

Optical microscopy was used to observe the 31 samples, which were milled into thin sections under reflected and transmitted light (polarised). The thin sections were impregnated with blue or red dyed epoxy resins to identify grain sizes, minerals, pore types and pore-size distributions (PSDs) of the reservoir rocks at milli- to micro-scales [47].

3.4. Burial History Reconstruction

In this study, based on the PetroMod software developed by IES Company in Germany, the burial history of key single wells in the Zhu-1 Depression was simulated by using the parameters of stratum stratification, stratum sedimentary age, stratum lithology, the terrestrial heat flow value in each geological history period, and source rock geochemistry. The burial history of different sags in the Zhu-1 depression are simulated. It is difficult to fully grasp the geological conditions in the geological history period, so the simulation results need to be calibrated and corrected by using the measured Ro data and the simulated Ro data to ensure the reliability of the detection simulation results.

4. Results

4.1. Characteristics of Reservoir Petrology

The QFR (Quartz, Feldspar, rock debris) three-terminal sandstone classification scheme is used to classify the sandstone reservoirs in the Zhu-1 Depression. The statistical analysis results show that there are great differences in petrological characteristics between the Lufeng Sag and the Huizhou Sag. The Lufeng Sag is dominated by lithic quartz sandstone with high quartz and low feldspar, followed by feldspar quartz sandstone (Figure 3a). Quartz content is generally 62–90% (average content is 83.6%) and the feldspar content is generally 2–19% (average content is 7.6%). The sorting is mainly medium, and the rounding is mainly based on sub-edge-sub-circle (Figure 4a). The statistical results of
the Huizhou Sag show that feldspar lithic sandstone is the main type, followed by lithic quartz sandstone (Figure 3b). Quartz content is generally 9–79% (average content is 32.6%) and feldspar content is generally 4–51.3% (average content is 21.6%). The sorting is mainly medium-poor, and the rounding is mainly based on the sub-edge-sub-circle and the sub-edge (Figure 4b). Compared with the Huizhou Sag, the Lufeng Sag has higher compositional maturity and textural maturity, so it is more conducive to the preservation of primary pores.

![Figure 3. Reservoir lithology triangles of the Paleogene Wenchang Formation in the (a) Lufeng Sag and (b) Huizhou Sag in the Zhu-1 Depression.](image)

![Figure 4. Reservoir sorting and rounding statistics for the Paleogene Wenchang Formation in the Lufeng Sag (a) and Huizhou Sag (b) in the Zhu-1 Depression.](image)

### 4.2. Characteristics of Reservoir Pore Types

According to the research, the pore types are significantly different in the Lufeng Sag compared to the Huizhou Sag. On the whole, the dissolution of the Wenchang Formation reservoir in the Lufeng Sag is weak, mainly consisting of primary intergranular pores. Under polarised light microscope and scanning electron microscope, the primary intergranular pores present mostly irregular polygons and triangles (Figure 5a–e). Compared with the primary intergranular pores, the secondary pores in the Lufeng Sag account for a smaller proportion, and the degree of dissolution is weaker, making less contribution to the pores in the study area (Figure 5f–i). The primary intergranular pores in the Wenchang Formation in the Huizhou Sag are less preserved (Figure 6a–c), and the pores are mainly secondary pores. Under the microscope, it can be clearly seen intragranular dissolved pores and intergranular dissolved pores that formed by the internal dissolution of feldspar and debris particles (Figure 6d–g,i), as well as secondary pores that formed by the dissolution of early carbonate cements (Figure 6h). Statistical analysis shows that primary pores in the Lufeng Sag occupy 72.5% of the entire pore space, and intragranular dissolved pores, intercrystalline pores, and casting film pores account for 12.9%, 4.6%, and 9.8%, respectively (Figure 7a). The primary intergranular pores in the Huizhou Sag account for a relatively small proportion, accounting for 40.3% of the entire pore space, but the intragranular dissolved pores, intergranular dissolved pores, and intercrystalline pores account for 33.5%, 23.6%, and 2.6%, respectively (Figure 7b). Through comparative analysis,
the pore types of the Lufeng Sag are mainly primary intergranular pores, while secondary dissolution pores make a small contribution to pores. However, only a small amount of primary intergranular pores occurs in the Huizhou Sag, while secondary dissolution pores are the main reservoir space.

Figure 5. Microscopic pore images of the Paleogene Wenchang Formation in the Lufeng Sag. (a) Point contact and primary intergranular pore development. Well LF14-1A, 4047.5 m, Wenchang Formation, plane-polarised light; (b) Point contact and primary intergranular pore development. Well LF16-1A, 3584 m, Wenchang Formation, plane-polarised light; (c) Point-line contact and primary intergranular pore development. Well LF14-3A, 3726.9 m, Wenchang Formation, plane-polarised light; (d) Point-line contact and primary intergranular pore development. Well LF14-3A, 3944.5 m, Wenchang Formation, plane-polarised light; (e) Primary intergranular pore development. Well LF14-1A, 4168.756 m, Wenchang Formation, SE; Q represent quartz; (f) Calcite corrosion and dissolved pore development. Well LF14-1A, 4169.25 m, Wenchang Formation, plane-polarised light; (g) Feldspar corrosion and dissolved pore development. Well LF14-1A, 4169.25 m, Wenchang Formation, plane-polarised light; (h) Dissolved pore development. A represent intragranular dissolved pores, and B represent casting film pores. Well LF14-3A, 4161.5 m, Wenchang Formation, plane-polarised light; (i) Intercrystalline pore development. Well LF14-3A, 4161.5 m, Wenchang Formation, SE; I represent illite.
Figure 6. Microscopic pore images of the Paleogene Wenchang Formation in the Huizhou Sag. (a) Point contact and primary intergranular pore development. Well HZ25-2A, 3756.64 m, Wenchang Formation, plane-polarised light; (b) Point contact and primary intergranular pore development. Well HZ25-3A, 3748.3 m, Wenchang Formation, plane-polarised light; (c) Point contact and primary intergranular pore development. Well HZ25-1A, 3415.2 m, Wenchang Formation, plane-polarised light; (d) High feldspar content and strong dissolution, and dissolved pore development. Well HZ25-3A, 3915 m, Wenchang Formation, plane-polarised light; (e) Feldspar dissolution and dissolved pore development. Well HZ26-1A, 3235 m, Wenchang Formation, plane-polarised light; (f) Feldspar dissolution and dissolved pore development. Well HZ25-2A, 3564 m, Wenchang Formation, plane-polarised light; (g) Effusive rock debris dissolution and dissolved pore development. Well HZ25-3A, 3481 m, Wenchang Formation, plane-polarised light; (h) Carbonate cementation dissolution and dissolved pore development. Well HZ25-3A, 3861.5 m, Wenchang Formation, plane-polarised light; (i) Intracrystalline dissolved pore development. Well HZ25-3A, 3861.5 m, Wenchang Formation, SE.

Figure 7. Distribution of reservoir pore types in the Lufeng Sag (a) and Huizhou Sag (b) of the Paleogene Wenchang Formation in the Zhu-1 Depression.

4.3. Characteristics of Reservoir Physical Properties

The statistics of the physical properties of the rock samples show that the porosity of the Lufeng Sag is between 4% and 28%, mainly distributed between 8% and 20%; the permeability is between 0.01 and 10,000 mD, mainly distributed between 1 and 1000 mD (Figure 8a,b). The porosity of the Huizhou Sag is between 4% and 24%, mainly distributed
between 8 and 16%; the permeability is between 0.01 and 100 mD, mainly distributed between 10 and 100 mD (Figure 8a,b). From the statistical analysis and comparison chart, it can be seen that the reservoirs with porosity of 16–20% represent 20% of reservoirs in the Lufeng Sag, and only 5% in the Huizhou Sag. The reservoirs with permeability between 100 and 1000 mD represent 20% of reservoirs in the Lufeng Sag, and such reservoirs are basically not developed in the Huizhou Sag. Comparative analysis shows that the reservoir physical properties of the Wenchang Formation in the Lufeng Sag are generally better than those in the Huizhou Sag. The porosity-permeability cross plot reveals that the overall correlation of the Lufeng Sag reservoir ($R^2 = 0.64$) is also better than that of the Huizhou Sag reservoir ($R^2 = 0.40$) (Figure 8c).

Figure 8. Reservoir porosity distribution figure of Wenchang Formation in Zhu-1 Depression (a); Reservoir permeability distribution figure of Wenchang Formation in Zhu-1 Depression (b); Porosity-permeability distribution figure of Wenchang Formation reservoir in Zhu-1 Depression (c).

5. Discussion
5.1. Analysis of Differences in Genetic Mechanisms of Reservoirs in the Zhu-1 Depression
5.1.1. Difference in Reservoir Anti-Compaction Ability Caused by Component Maturity

The structure of clastic rocks refers to the size, shape, and spatial combination of minerals and rock fragments that constitute clastic rocks. The structural components of clastic rocks include clastic particles and fillings [48]. The microlithofacies of a subaqueous distributary channel in the braided river delta front in the Lufeng Sag experienced a strong dynamic environment during the deposition period. Long-distance transport results in higher quartz content in the reservoir and higher compositional maturity of the rock. Studies have shown that the high compositional maturity of rocks not only affects the original porosity of sandstone reservoirs but is also conducive to the preservation of intergranular pores and the occurrence of diagenesis [49]. Therefore, regardless of the strength of later diagenesis, the compositional maturity of the original rock particles will directly affect the size of sandstone porosity and the preservation of primary pores. Generally speaking, the higher the maturity of rock composition, the more conducive it is to

![Figure 8](image-url)
the development of primary pores in sandstone reservoirs, and the higher the porosity [50–53]. Statistical analysis of the rock components of the Wenchang Formation reservoirs in the Lufeng Sag and Huizhou Sag in the Zhu-1 Depression shows that the quartz content in the Lufeng Sag is high, and the corresponding compositional maturity of rocks Q/(F + R) is high, while the quartz content and rock composition maturity Q/(F + R) are low in the Huizhou Sag (Table 1). In terms of rock types, lithic quartz sandstone with high quartz content is mainly developed in the Lufeng Sag, while feldspathic lithic sandstone is mainly developed in the Huizhou Sag. Therefore, there are great differences in the composition of rock particles between the two regions, which directly leads to the difference in the original porosity. High quartz content is one of the main reasons for the development of primary intergranular pores in the Lufeng Sag. The brittleness of rock in the Huizhou Sag reservoir is weak owing to its low quartz content. With the continuous deposition of sediments, the rock particles are rapidly compressed and deformed, and the primary intergranular pores are destroyed, resulting in a decrease in the physical properties of the sandstone reservoir. Therefore, the innate high-energy sedimentary environment and the compositional maturity of the rock are the fundamental reasons for the differences in reservoir pores between the two sags.

Table 1. Statistical summary of rock particle composition of sandstone reservoirs of the Paleogene Wenchang Formation in the Zhu-1 Depression.

<table>
<thead>
<tr>
<th>Area</th>
<th>Well</th>
<th>Formation</th>
<th>Quartz (%)</th>
<th>Feldspar (%)</th>
<th>Rock Debris (%)</th>
<th>Q/(F + R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lufeng Sag</td>
<td>LF14-1A</td>
<td>WengChang</td>
<td>80.80</td>
<td>7.83</td>
<td>11.37</td>
<td>4.21</td>
</tr>
<tr>
<td></td>
<td>LF14-2A</td>
<td></td>
<td>82.31</td>
<td>7.94</td>
<td>9.75</td>
<td>4.65</td>
</tr>
<tr>
<td></td>
<td>LF14-3A</td>
<td>WengChang</td>
<td>84.91</td>
<td>3.69</td>
<td>11.41</td>
<td>5.63</td>
</tr>
<tr>
<td></td>
<td>LF8-1A</td>
<td></td>
<td>80.68</td>
<td>3.53</td>
<td>15.79</td>
<td>4.18</td>
</tr>
<tr>
<td></td>
<td>LF9-1A</td>
<td></td>
<td>83.67</td>
<td>5.14</td>
<td>11.19</td>
<td>5.12</td>
</tr>
<tr>
<td>Huizhou Sag</td>
<td>HZ25-1A</td>
<td>WengChang</td>
<td>31.67</td>
<td>18.33</td>
<td>50.00</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>HZ25-2A</td>
<td>WengChang</td>
<td>37.00</td>
<td>24.87</td>
<td>38.13</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>HZ25-3A</td>
<td></td>
<td>38.58</td>
<td>25.27</td>
<td>36.15</td>
<td>0.63</td>
</tr>
</tbody>
</table>

5.1.2. Difference in Reservoir Anti-Compaction Ability Caused by Sand Body Thickness

The cementation is generally considered to be an important reason for the deterioration of reservoir physical properties [49], but for the same set of thick sand bodies, the diagenesis is also different at different locations. It is found that the cementation at the top and bottom of the thick channel sand body is strong, and the physical properties of the reservoir are poor. The cementation in the middle of the channel sand body is weak, and the physical properties are good [54,55]. The development of thick sand bodies in the Wenchang Formation of the Lufeng Sag can effectively inhibit compaction and protect primary intergranular pores. With the enhancement of compaction, feldspar began to dissolve. Under the sedimentary environment of acidic stratum water, kaolinite began to generate in large quantities [56–58]. The continuous dissolution of feldspar content changed the acidic environment of stratum water, and the pH value of stratum water increased. Then, feldspar and clay minerals were converted to high concentrations of Ca²⁺, Mg²⁺, Fe²⁺, CO₃²⁻ ions [59]. Therefore, the dissolution of detrital minerals in sandstone and mudstone and the transformation of clay minerals provided a large amount of Ca²⁺, Mg²⁺, Fe²⁺, CO₃²⁻ ions to large sets of delta sand bodies in the Lufeng Sag reservoir. In the contact area of sandstone and mudstone, with increasing compaction action, the pore pressure of mudstone increased, which caused a greater amount of stratum water carrying CO₃²⁻ to enter the adjacent sandstone reservoir. Because of the large pore space of sandstone, the stratum water carrying CO₃²⁻ precipitated due to the decrease in pressure, and finally formed carbonate cementation [60]. The thickness of the sandstone reservoir is large, and the pressure produced by upward compaction action was not enough to make the stratum
water carrying $\text{CO}_3^{2-}$ enter the sandstone reservoir, so carbonate cementation only formed at the top and bottom of the sandstone reservoir. The formation of carbonate cementation at the top and bottom of channel sand bodies increases the anti-compaction ability of rocks, which is conducive to the preservation of primary pores (Figure 9b). Compared with the thick sand body, under the overlying formation pressure, the stratum water carrying $\text{CO}_3^{2-}$ entered the entire thin sand body reservoir, resulting in the cementation of the entire sand body, the disappearance of primary pores, and the reduction of reservoir physical properties (Figure 9a). Exploration has also shown that the Wen 5 member of the Lufeng Sag corresponds to the initial rifting stage, which is controlled by the provenance of the Hui-Lu Low Uplift, Lufeng Low Uplift, and Dong-sha Uplift, and has developed a braided river delta sedimentary system. LF14-1A core drilling shows that a large set of braided river delta thick sand bodies are developed in the Wen 5 member and the reservoir physical properties are good, and the average porosity is generally greater than 10% (Figure 10a). The sand body thickness of the Huizhou Sag is relatively thin. The HZ25-3A single well shows that the Wenchang Formation reservoir is mainly composed of thin sand bodies, and the average physical properties of thin sand bodies are low (Figure 10b). Therefore, sand body thickness is one of the important factors affecting reservoir physical properties.

![Figure 9](image_url)

**Figure 9.** Differences in the cementation pattern of sand bodies with different thicknesses. (a) Model figure of thin sand body cementation; (b) Model figure of thick sand body cementation.
5.1.3. Difference in Reservoir Anti-Compaction Ability Caused by Burial Mode

Previous studies on Paleogene reservoirs in the Zhu-1 Depression suggest that primary pores in the middle-deep reservoirs below a depth of 3500 m basically disappear, and secondary dissolved pores develop below a depth of 3500 m [61]. However, exploration in recent years has shown that the primary intergranular pores in the Wen 5 reservoir with burial depth of less than 4000 m are still very developed in the Lufeng Sag. It can be seen from the sandstone thin section that the rock particles mainly show point contact and point-line contact (Figure 5a–d). Research and analysis reveal that early tectonic uplift is one of the key factors for the development of primary pores in deep reservoirs. The tectonic uplift reduces the pressure on the formation, so that the compaction action of the reservoir is correspondingly weakened, and the physical properties of the reservoir are improved. The LF13-7 tectonic belt, the LF16-1 tectonic belt, the LF14-4 tectonic belt, and the HZ25 conversion belt all experienced early uplift during the burial process (Figure 11). Early uplift reduced overburden pressure. Furthermore, the reservoir experienced an early diagenetic stage in the shallow burial environment of the formation. Compaction and cementation have consolidated the rock and formed a set of anti-compaction skeletons [28,62]. Therefore, during the deep burial of the Wenchang Formation in the later stage, due to the increase in rock anti-compaction ability, the amount of reservoir pores lost due to strong compaction was limited. Because of the protection of the anti-compaction skeleton, the primary intergranular pores in the Paleogene reservoirs are still developed (Figure 12a–c). The LF8-1 tectonic belt, XJ30 conversion belt and XJ24 conversion belt mainly experienced continuous rapid burial during burial (Figure 11). The rapid burial makes the overlying pressure increase continuously, resulting in the rapid compaction of pore space and the destruction of primary pores. Casting thin sections show that the compaction action was strong. Rock particles were compacted and deformed, and reservoir properties decreased (Figure 12d–f). Therefore, different burial methods are important reasons for the preservation of primary intergranular pores in the Zhu-1 Depression.
<table>
<thead>
<tr>
<th>Location</th>
<th>LF 13-7 Structural Belt</th>
<th>LF 8-1 Structural Belt</th>
<th>LF 16-1 Structural Belt</th>
<th>LF 14-4 Structural Belt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buried History</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Burial Mode</td>
<td>Early uplift, later burial</td>
<td>Persistent burial</td>
<td>Early uplift, later burial</td>
<td>Early uplift, later burial</td>
</tr>
<tr>
<td>Influence on Reservoir</td>
<td>Favorable</td>
<td>Unfavorable</td>
<td>Favorable</td>
<td>Favorable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Location</th>
<th>XJ 30 Conversion Belt</th>
<th>HZ 25 Conversion Belt</th>
<th>XJ 24 Conversion Belt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buried History</td>
<td></td>
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<tr>
<td>Burial Mode</td>
<td>Persistent burial</td>
<td>Early uplift, later burial</td>
<td>Persistent burial</td>
</tr>
<tr>
<td>Influence on Reservoir</td>
<td>Unfavorable</td>
<td>Favorable</td>
<td>Unfavorable</td>
</tr>
</tbody>
</table>

Figure 11. Burial history map of the Wenchang Formation in different sags of the Zhu-1 Depression.
5.1.4. Difference in Reservoir Anti-Compaction Ability Caused by Geothermal Gradient

The plastic deformation of rocks is related to ground temperature. When the temperature increases, the ductility of rocks increases, thereby reducing the anti-compaction ability of rocks, damaging the reservoir space and decreasing the physical properties of reservoirs. Therefore, temperature is an important factor affecting the compaction action of quartz sandstone [63, 64]. Some scholars believe that the increase in formation temperature makes the mineral more prone to plastic deformation, resulting in the weakening of anti-compaction ability, thereby reducing reservoir physical properties [65]. Furthermore, the increase in geothermal gradient will lead to an increase in reservoir pressure solution strength. Under a high geothermal environment, the solubility of rock minerals in water increases. With an increase in sediments burial depth, when the pressure of overlying strata exceeds the normal pore fluid pressure, the solubility at the particle contact increases, resulting in lattice deformation and dissolution. Studies have shown that the geothermal gradient in the Pearl River Mouth Basin increases as a whole from north to south. The difference in the geothermal gradient is mainly caused by the gradual thinning of crustal thickness toward the centre of the ocean and with closer distance to the internal heat source (earth mantle) of the earth. The Zhu-1 Depression is located near the mainland of Guangdong, where the crustal thickness is relatively thick. The great distance from the heat source (earth mantle) inside the earth is the main reason for the relatively low geothermal gradient [66]. Studies have shown that in the Zhu-1 Depression, the geothermal gradient of the Lufeng Sag is 3.12 °C/100 m, and that of the Huizhou Sag is 3.38 °C/100 m [67]. Overall, the Lufeng Sag is in a relatively low geothermal gradient. Under the background of low ground temperature, the compaction action of the Lufeng Sag is weak. Statistical analysis shows that when the burial depth of the Lufeng Sag is 4100–4200 m, it is mainly point-line and line contact. When the burial depth of the Huizhou Sag is 4100–4200 m, it is mainly line and line-convex. The contact manner of the two vertical particles reflects the difference in the compaction degree (Figure 13). Through the cast thin section, it can be seen that the particles in the Lufeng Sag are mainly point-line contact, and the
pore space is mainly primary pores, showing irregular polygons and triangles. The contact between pores and particles is relatively flat, and there is no obvious harbour-shaped corrosion. The cast thin section of Huizhou Sag shows a strong compaction action, and the particles mainly have concave-convex contact. It can also be seen that the mica particles are compacted, and the primary pores have basically disappeared (Figure 13). Under the same burial depth, the reservoir of the Lufeng Sag has point-line contact, and the reservoir of the Huizhou Sag has concave-convex contact, which shows that the lower geothermal gradient affects the compaction rate of rock and increases the anti-compaction ability of rock, which is beneficial to the preservation of deep primary pores.

Figure 13. Comparison and analysis of compaction under different geothermal gradients in the Zhu-1 Depression.

5.1.5. Difference in Reservoir Dissolution Strength Caused by Organic Acid Content and Dissolution Components

Organic acid dissolution is one of the important factors that improves reservoir quality in the later stage. The occurrence of dissolution depends mainly on the following three conditions [68–71]. First, the abundance of organic matter is high, and the type is good. The thickness of mudstone containing organic matter is relatively large and mature, which is foundation of dissolution fluids. Second, it is necessary to have a suitable migration path to migrate the organic acids generated by the source rock to the reservoir through appropriate migration channels such as faults and sand bodies. Third, there should be more easily accessible particles in the reservoir, mainly including feldspar, rock debris and carbonate cements. The above conditions are the necessary conditions for the occurrence of organic acid dissolution. If all three occur, secondary dissolution pores will develop. Compared with the Lufeng Sag, the secondary dissolution pores of the Wenchang Formation in the Huizhou Sag are the main reservoir space. The development of secondary dissolution pores in the Wenchang Formation in the Huizhou Sag is mainly due to the close proximity hydrocarbon source rock. Organic acids produced by source rocks can be directly migrated to sandstone reservoirs for dissolution. Furthermore, the Wenchang Formation reservoirs in the Huizhou Sag contain more soluble components.
(1) Content of organic acids

The proportion of secondary dissolution pores in sandstone reservoirs in the Wenchang Formation of the Lufeng Sag is less than that in the Huizhou Sag. Owing to the development of a large, braided river delta sedimentary system in the Wenchang Formation of the Lufeng Sag, the area of limnetic facies is small, and the organic matter content is low (Figure 14a). Therefore, the organic acid content produced by mature source rocks is relatively scarce. Compared with the Lufeng Sag, the sedimentary period of the Wenchang Formation in the Huizhou Sag is dominated by limnetic facies, and small braided river delta and fan delta are developed only around the depression (Figure 14b). During the sedimentary period of the Wenchang Formation in the Huizhou Sag, the area of lake facies area was large, and the organic content was high, and the corresponding organic acid content was high. Additionally, because the direct contact area between the Wenchang Formation reservoirs and source rocks is limited in the Lufeng Sag, most of the reservoirs are connected through faults. Therefore, the organic acids generated after the hydrocarbon source rock enters the mature stage need to pass through the migration channel to enter the reservoir, and some H+ is consumed in the migration process [72], resulting in less organic acid content in the reservoir. Consequently, the dissolution is weaker. It can be seen from the organic acid migration section of Well 14 in the Lufeng Sag that there are mainly two combinations of migration paths. First, the organic acid produced by the source rock of Wen 4 is laterally migrated to the reservoir of the ramp zone of the braided river delta plain facies in Wen 5, and the contact area between the hydrocarbon source rock and reservoir is small. Second, the organic acid moves through the fault and other migration channels into the upper reservoir (Figure 15). Some H+ is consumed during the migration process, which results in a decrease in the organic acid content in the sandstone reservoir and the development of secondary dissolution pores. However, through the corrosion profile of the Wenchang Formation in the HZ25 transition zone, it can be seen that the sand body of the Wenchang Formation in the Huizhou Sag directly contacts the hydrocarbon source rock, and the contact area is large. The organic acid directly migrates laterally to the Wen 6 Member reservoir to accumulate (Figure 16), reducing the consumption of H+. A large amount of H+ enters into the reservoir to dissolve easily soluble components such as feldspar and rock debris, thus strengthening the development of secondary dissolution pores in the Wenchang Formation in the Huizhou Sag.

Through the analysis of LF14-1A single well, it is found that there are few oil layers in the Wenchang Formation, which mainly consists of water layers and some dry layers. The thin section under the microscope shows the development of primary intergranular pores and some secondary dissolution pores formed by partial feldspar dissolution (Figure 17a). The dissolution strength is weak, and primary intergranular pores are still the main reservoir space. This further shows that the content of organic acids in the Paleogene Wenchang Formation of the Lufeng Sag is low, resulting in less development of secondary pores. Compared with the Lufeng Sag, well HZ25-2A shows that a large number of oil layers in the Wenchang Formation are developed, which leads to an increase in the content of organic acids in the reservoir and the development of secondary dissolution pores. The thin section under the microscope also shows that the feldspar is strongly dissolved, and the secondary dissolution pores are the main reservoir space (Figure 17b).
Figure 14. Sedimentary facies map of the Wenchang Formation in the Lufeng Sag (a) and Huizhou Sag (b).
Figure 15. Dissolution profile of the Wenchang Formation in the 14th tectonic belt in the Lufeng Sag.

Figure 16. Dissolution profile of the Wenchang Formation in the 25th transition zone of the Huizhou Sag.
Figure 17. Comprehensive histogram of single well LF14-1A (a) and HZ25-2A in the Zhu-1 Depression (b). Q represent quartz; F represent quartz; I represent illite.

(2) Multiple types of dissolution objects

The development of secondary pores is not only related to the organic acid content and migration paths but is also affected by the types of dissolution objects in sandstone reservoirs. Observations through the polarisation microscope and scanning electron microscope show that the dissolution objects of the Wenchang Formation in the Huizhou Sag are more diverse, mainly including feldspar particle, early carbonate cement and rock debris (Figure 18). The diversification of dissolution components is one of the main factors that directly lead to the development of secondary dissolution pores. The type of dissolution object in the Wenchang Formation reservoir of the Lufeng Sag is mostly limited to feldspar particle dissolution. When organic acids migrate to sandstone reservoirs, multiple types of dissolution components will enhance the development of secondary dissolution pores. Therefore, multiple types of dissolution objects are one of the factors influencing the development of secondary pores in the Huizhou Sag.
Figure 18. Microscopic pictures of secondary dissolution pores in the Paleogene reservoir in the Zhu-1 Depression. (a) Feldspar dissolution, and secondary dissolution pore development. Well LF14-1A, 4163.48 m, Wenchang Formation, SE; Q represent quartz; F represent quartz; I represent illite; (b) Feldspar dissolution, and secondary dissolution pore development. Well LF14-1A, 4163.48 m, Wenchang Formation, SE; Q represent quartz; F represent quartz; (c) Feldspar dissolution, and secondary dissolution pore development. Well HZ25-3A, 3861.5 m, Wenchang Formation, SE; (d) Carbonate cementation dissolution, and secondary dissolution pore development. Well LF14-1A, 4157.25 m, Wenchang Formation, plane-polarised light; (e) Carbonate cementation dissolution, and secondary dissolution pore development. Well HZ25-3A, 3712 m, Wenchang Formation, plane-polarised light; (f) Carbonate cementation dissolution, and secondary dissolution pore development. Well HZ26-1A, 3235 m, Wenchang Formation, plane-polarised light; (g) Rock debris dissolution, and secondary dissolution pore development. Well HZ25-3A, 3481 m, Wenchang Formation, plane-polarised light; (h) Rock debris dissolution, and secondary dissolution pore development. Well HZ25-1A, 3712 m, Wenchang Formation, plane-polarised light; (i) Rock debris dissolution, and secondary dissolution pore development. Well HZ25-3A, 3468 m, Wenchang Formation, plane-polarised light.

5.2. Summary of Different Reservoir Models in the Zhu-1 Depression

By analysing the characteristics of reservoirs in the Lufeng Sag and Huizhou Sag in the Zhu-1 Depression, we have concluded the occurrence of two types of high-quality reservoir development models: the preservation model of compaction-resistant primary pores and the dissolution-prone secondary dissolution pore development model (Figures 19 and 20). The primary intergranular pores are mainly developed in Paleogene reservoirs in the Lufeng Sag. The primary intergranular pores can be preserved in the deep layer due to effective resistance to compaction. The high component maturity of quartz sandstone can effectively resist compaction, which is the congenital condition of intergranular pore development. The early sedimentary system of the Wenchang Formation in the Lufeng Sag is mainly braided river delta, with large sets of thick sand bodies developed. Under the action of upper compaction, the dissolution of detrital minerals in sandstone and mudstone and the transformation of clay minerals provide a high concentration of Ca$^{2+}$, Mg$^{2+}$, Fe$^{3+}$, CO$_3^{2-}$ ions. The stratum water carrying CO$_3^{2-}$ precipitates at the contact between sandstone and mudstone, and finally forms calcareous cementation at the top.
and bottom channel of the sand body. Cementation consolidation of rock particles can effectively protect primary intergranular pores. Early strata uplift slowed down the upward pressure. Under the background of shallow burial, the reservoir experienced the early diagenetic stage. Compaction and cementation made the rock consolidate and formed an effective anti-compaction skeleton. The Lufeng Sag is located in a relatively low geothermal environment. Low ground temperature slows down the plasticity of minerals, making them less prone to plastic deformation and increases the rock’s resistance to compaction. Under the action of a variety of comprehensive factors in the Lufeng Sag, primary intergranular pores are still well developed in the Wen 5 reservoir below a depth of 4000 m. However, the dissolution pores are well developed in the adjacent Huizhou Sag. The Wenchang Formation sand body in the Huizhou Sag directly contacts the hydrocarbon source rock and has a large contact area. The organic acids generated by the hydrocarbon source rock directly migrate laterally to the reservoir of the Wen 6 member to accumulate, and the short-distance migration reduces the consumption of H⁺. A large amount of H⁺ enters the reservoir to dissolve feldspar, rock debris and other soluble components. Furthermore, the Wenchang Formation reservoir in the Huizhou Sag contains a variety of soluble substances. Organic acids can dissolve a variety of substances after entering the reservoir, resulting in the development of secondary dissolution pores.

Figure 19. Preservation model of compaction-resistant primary pores in the Lufeng Sag of the Zhu-1 Depression.
Figure 20. Dissolution-prone secondary dissolution pore development model in the Huizhou Sag of the Zhu-1 Depression.

6. Conclusions

(1) The reservoir characteristics of the Paleogene Wenchang Formation in the Lufeng Sag and Huizhou Sag are significantly different. The rock types of Paleogene reservoirs in the Lufeng Sag are mainly lithic quartz sandstone with high quartz and low feldspar. Primary intergranular pores are the main reservoir space. The Paleogene reservoirs in the Huizhou Sag are mainly feldspar lithic sandstone. Secondary dissolution pores are developed, which are the main reservoir space. Overall, the reservoir properties of the Lufeng Sag are better than those of the Huizhou Sag.

(2) The four main controlling factors of deep high-quality reservoir development in the Lufeng sag are summarised. A sandstone reservoir with high quartz content is the congenital condition of primary intergranular pore development in the Lufeng Sag. The top and bottom cementation formed by a large set of thick delta sand bodies in Wen 5 member can inhibit compaction and effectively protect the middle channel sand bodies. An early shallow burial reservoir can form a set of anti-compaction skeletons to effectively reduce the damage of compaction on pore space. The sandstone reservoir slows down compaction action to protect primary intergranular pores under a low geothermal environment.

(3) The development of secondary dissolution pores in the Huizhou Depression benefits from source rock adjacent to the Wenchang Formation Reservoir. Organic acids produced by source rocks can be directly migrated to sandstone reservoirs for dissolution. Furthermore, the Wenchang Formation reservoirs in the Huizhou Sag contain more soluble components. Therefore, secondary dissolution pores are more developed.

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