Microscopic pore structure characteristics and logging response characteristics of different diagenetic facies reservoirs and their impact on the distribution of high quality reservoirs

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Distribution of high quality diagenetic facies is controlled jointly by sedimentary facies, diagenesis and pore structure, and especially throat distribution is the main factor for controlling sandstone reservoir permeability. Reservoir in the hydromica cementation--residual intergranular pore facies and hydromica cementation--feldspar corrosion facies is distributed mainly in semi-deep lacustrine gravity flow composite channel turbidites; fine--tiny throats are developed, the connectedness of pore throats is good, and their percolation capacity is the best; oil and water are of relatively uniform seepage flow, and the oil and gas in pores are produced via throats extremely easily. The reservoir in the chlorite cementation facies and hydromica cementation weak corrosion facies is located in the margin of branch channels and distributed in island shape; the pore throat radius is small but is distributed uniformly, and the percolation capacity of pore throats is medium to bad. Reservoir in the carbonate cementation facies and carbonate + hydromica cementation facies is developed mainly between branch channels; the development degree of the pore structure is low, throats are fine and small, and pore throat connectedness is bad; the oil and gas rich in pores are difficult to pass small throats, and the recovery ratio is low.

[Keywords: Ordos basin; high quality reservoir; diagenetic facies; pore structure; logging response]

Introduction

Diagenetic facies is the comprehensive reflection of the diagenetic environment of sandstones and the diagenetic products formed in this environment, while diagenetic environment is controlled by sedimentary environment. That is, the main research contents of diagenetic facies are the secondary diagenetic characteristics of reservoir rocks in the present stage, including compaction-corrosion fabric, composition and type of cementing matters, pore morphology and distribution characteristics, etc1-3. The study of diagenetic facies assemblage is based on the analysis of sedimentary facies in combination with reservoir development characteristics and physical characteristics, so the analysis of the distribution characteristics of different diagenetic facies can provide reliable geologic bases for prediction and evaluation of favorable reservoir areas1-3. Qingyang region belongs to Ordos basin and is located in the southwest margin of Yishan slope (Figure 1); the main pay formation--C63 reservoir is semi-deep lacustrine turbidite and belongs to a typical reservoir with low porosity--ultra-low porosity and ultra-low permeability1-5. Predecessors have deeply studied the impact of sedimentary characteristics of C63 reservoir and diagenesis on the reservoir physical properties in Qingyang region, but their research on the geophysical response characteristics of diagenetic facies controlling the distribution of high quality reservoirs, the microscopic pore structure of diagenetic facies, etc. is weak6-7. This paper has studied the pore structure characteristics of different types of diagenetic facies of C63 reservoir and analyzed the logging response characteristics and planar distribution of relevant diagenetic facies on the basis of considering sedimentary background and collecting logging data and production test data using the casting...
slice and SEM analysis results in combination with the experimental analyses such as high pressure mercury injection, constant rate mercury injection, etc., thus providing microscopic theory and scientific bases for high efficiency development of waterflooding oilfields.

Cores and casting slice observation indicate that the lithology of C63 reservoir in Qingyang region is mainly lithic feldspar sandstones and secondarily feldspar lithic sandstones (Figure 2). Grain size of sandstones is generally 0.05~0.25 mm, and they have poor grain psephicity, mainly sub-angular shape, good to medium sorting property, and medium to relatively low maturity of rock structure and composition. The content of quartz and feldspar among clastic components is high and respectively 41% and 22.1% on an average. Debris types include metamorphic debris and volcanic debris, with their average content being respectively 2.5% and 5.4%. Content of sedimentary debris is low and averagely 1.6%. The content of mica among other components is high, can reach 24.6% at most and is averagely 7.5%. Interstitial matters are mostly authigenic mineral type cementing matters, including illite, chlorite, carbonate, silica, etc., with their average content being respectively 8.1%, 0.7%, 4% and 1.1%. Grain contact relationships mainly include point-line contact and line contact. Pore type cementation and film-pore type cementation are common. Compaction degree is medium to relatively high.

Figure 1 Structural location of Qingyang region

Figure 2 Type and composition of rocks of C63 reservoir
Materials and Methods

Diagenetic Facies Types and Their Pore Structure Characteristics

Diagenetic facies types

According to the analysis and test data of appraisal and SEM of 384 casting slices, the diagenesis of C63 reservoir in Qingyang region is mainly divided into two types: (1) destructive diagenesis (compaction, cementation) leading to compaction of reservoir; (2) constructive diagenesis enhancing the connectedness of pore throats after corrosion by pore water (corrosion objects mainly including feldspar, debris). Predecessors divided the diagenetic facies of various minerals according to the variation of clay minerals, zeolite minerals, carbonate minerals, autogenic quartz, etc. in the study of the diagenetic facies of Yanchang Fm. in different areas of Ordos basin8,9. This paper divides the diagenetic facies of C63 reservoir into the following 6 types mainly according to sedimentary microfacies development characteristics (generally characterized by the ratio of total sandstone thickness to formation thickness), main diagenesis, pore assemblage and evolution, diagenetic characteristics and difference as well as content of interstitial matters, surface pore ratio, etc. (Table 1).

Carbonate cementation facies

Rock types mainly include ultra-fine--fine grained lithic feldspar sandstones and lithic sandstones, and the carbonate cementing matters such as calcite, ferrocalcite, ferrodolomite, etc. are developed in the facies and account for over 65% of the total quantity of cementing matters in the diagenetic facies (Table 1). The pores are mainly matrix micropores, secondarily residual intergranular pores and solution pores and an extremely small quantity of microfractures (Figure 3b), and the surface pore ratio is 0.45%. The carbonate-filled residual intergranular pores block off the exchange of hydrocarbon fluids (Figure 3a), and the highest loss ratio of intergranular pores can reach 50%. This is also the main cause for leading to low porosity and low permeability tight reservoirs in the research region. The porosity is generally less than 6%, the permeability is less than 0.06mD, the sand bodies are thin and have poor continuity, and the ratio of total sandstone thickness to formation thickness is less than 0.3. The facies belt is the most unfavorable diagenetic facies belt in the region.

Carbonate + hydromica cementation facies

The facies is distributed mainly between branch channels, ultra-fine--fine grained lithic feldspar sandstones are developed, the average content of cementing matters is 13.6%, and the proportion of carbonate cementing matters and hydromica cementing matters is respectively 40.4% and 47.1%. Due to high early compaction degree, primary intergranular pores are filled by matrixes and autogenic clay minerals to a high
degree. In addition, the flexible clastic grains such as mica, argillaceous debris, etc. are easily bent and pseudo-matrixed after compaction, so that the reservoir spaces of the diagenetic facies are mainly micropores in argillaceous matrixes and occasionally feldspar solution pores and lithic solution pores finally. The porosity is less than 7%, the permeability is less than 0.09mD, the heterogeneity between sand beds is strong, and their oil bearing property is bad.

Results

Sand bodies have poor continuity and mainly include ultra-fine grained lithic feldspar sandstones. The ratio of total sandstone thickness to formation thickness is less than 0.35, the physical properties of reservoirs are poor, the porosity is 7%~8%, and the permeability is (0.09~0.15) mD. Affected by alkaline formation fluids, a large quantity of illite minerals cemented in film shape or filling the pores are developed and often associated with clay minerals such as kaolinite etc. (Figures 3d and 3e). This not only reduces pore volume but also divides throats numerous tiny throats and increases ineffective pores. Affected by strong mechanical compaction and pressure solution, only a small quantity of intergranular intercrystalline pores and solution pores are developed in reservoir spaces, and the surface pore ratio is averagely 1.43%.

The rocks are mainly fine grained lithic feldspar sandstones and have fine grains, good sorting property and high debris content, and chlorite cementing matters account for 60%~95% of all cementing matters. The existence of chlorite films in the early stage can effectively inhibit siliceous cementation and carbonate cementation and increase the reservoir resistance to compaction, thus making it possible to reform reservoirs by acid fluids in the late stage\textsuperscript{10,11}. However, with the increase in chlorite film thickness and cementing matter content in the late stage, pore type filling causes the connectedness of effective pores and throats to become poor (Figure 3f), and lots of residual intergranular pores are lost. The reservoir spaces are mainly intergranular pores and solution pores, the average content of intergranular pores is 1.63%, the average surface pore ratio is 2.15%, the physical properties of reservoirs are medium, the porosity is 7%~9%, and the permeability is (0.12~0.18) mD.

Rocks are mainly medium--fine grained lithic feldspar sandstones with high feldspar content. Average content of illite cementing matters is 7.1%, the average surface pore ratio is 2.64%, the porosity is 8%~10%, and the permeability is (0.15~0.23) mD. Affected by acid formation water, the reservoir spaces are mostly secondary pores generated by solution of feldspar, debris, etc. (Figure 3f). Illite cementing matters are filled between intergranular pores, thus reducing pore throat volume and degrading the physical properties of reservoirs. Feldspar corrosion not only occurs in feldspar grains but also will generate intergranular solution pores between grains and connect the residual intergranular pores to increase pore throat volume (Figure 3g). The facies is volume-expanded diagenetic facies and can increase the reservoir space and percolation space of reservoirs, thus making for continuous charging and enrichment of oil and gas.

Hydromica cementation--residual intergranular pore facies

The physical properties of reservoirs are relatively good. Porosity is >10%, the permeability is >0.2mD, the ratio of total sandstone thickness to formation thickness is over 0.45, and the continuous development degree of sand bodies is high. Rocks are mainly medium grained lithic feldspar sandstones and have relatively coarse grains, high content of rigid grains such as quartz etc. and hydromica, and strong compression strength. In addition, the early developed chlorite is rich in Fe and has low idiomorphology, so chlorite films are easily formed to protect clastic grains (Figure 3h) and prevent them from contacting pore water. The development degree of primary intergranular pores is high. Reservoir spaces are mainly cementing matter type residual intergranular pores after compaction, and the surface pore ratio is averagely 3.24%. Affected by strong mechanical compaction, the distribution area of the facies is not large. Pore structure characteristics of different diagenetic facies

The difference in multiple factors such as pore type, pore throat characteristics, etc. during sedimentation and diagenetic evolution leads to complex geologic conditions of low permeability reservoirs and obvious diversity of microscopic pore structures; in addition, the correlation of porosity with permeability is bad; that is, reservoir percolation capacity is not affected by a single factor such as pore size, pore distribution, etc\textsuperscript{12}.
Table 1 Geology and logging response characteristics of all diagenetic facies of C6 reservoir

<table>
<thead>
<tr>
<th>Diagenetic facies types</th>
<th>Lithology</th>
<th>Sedimentary microfacies</th>
<th>Sand ratio</th>
<th>Cement/%</th>
<th>Pore type /%</th>
<th>Surface pore ratio /%</th>
<th>Pore radius /μm</th>
<th>Drainage capillary pressure /MPa</th>
<th>Average throat radius /μm</th>
<th>Main throat radius /μm</th>
<th>Pore-throat radius ratio</th>
<th>Structure percolation coefficient /μm²</th>
<th>Porosity /%</th>
<th>Permeability /mD</th>
<th>Logging response characteristics</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>GR /API RT /Ωm AC /μs/m DEN /g/cm³</td>
</tr>
<tr>
<td>A (1) (2)</td>
<td>III</td>
<td>&lt;0.3</td>
<td>Ka:0.32</td>
<td>Ch:1.02</td>
<td>Sc:1.08</td>
<td>Hy:2.76</td>
<td>Ca:8.49</td>
<td>0.45</td>
<td>120.3</td>
<td>2.68</td>
<td>0.25</td>
<td>0.16~0.26</td>
<td>697</td>
<td>&lt;0.005</td>
<td>&lt;7</td>
</tr>
<tr>
<td>B (3)</td>
<td>III</td>
<td>&lt;0.33</td>
<td>Ka:1.12</td>
<td>Ch:0.75</td>
<td>Sc:1.34</td>
<td>Hy:6.42</td>
<td>Ca:5.48</td>
<td>0.68</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>/</td>
<td>&lt;0.005</td>
<td>&lt;7</td>
<td>&lt;0.09</td>
</tr>
<tr>
<td>C (4) (5)</td>
<td>I (3)</td>
<td>0.35~0.3</td>
<td>Ka:1.85</td>
<td>Ch:0.38</td>
<td>Sc:1.08</td>
<td>Hy:9.68</td>
<td>Ca:2.68</td>
<td>1.43</td>
<td>128</td>
<td>2.34</td>
<td>0.318</td>
<td>0.17~0.34</td>
<td>518</td>
<td>0.01</td>
<td>7~8</td>
</tr>
<tr>
<td>D (5)</td>
<td>III</td>
<td>0.45~0.36</td>
<td>Ka:1.5</td>
<td>Ch:6.45</td>
<td>Sc:1.06</td>
<td>Hy:3.19</td>
<td>Ca:2.99</td>
<td>2.15</td>
<td>130.2</td>
<td>2.05</td>
<td>0.67</td>
<td>0.56~1.05</td>
<td>290</td>
<td>0.02</td>
<td>7~9</td>
</tr>
<tr>
<td>E (6)</td>
<td>I</td>
<td>0.5~0.4</td>
<td>Ka:0.86</td>
<td>Ch:1.44</td>
<td>Si:1.6</td>
<td>Hy:7.06</td>
<td>Ca:3.06</td>
<td>2.64</td>
<td>132.4</td>
<td>1.51</td>
<td>0.89</td>
<td>0.3~1.3</td>
<td>212</td>
<td>0.06</td>
<td>8~10</td>
</tr>
<tr>
<td>F (7)</td>
<td>II</td>
<td>&gt;0.45</td>
<td>Ka:0.5</td>
<td>Ch:2.5</td>
<td>Sc:1.89</td>
<td>Hy:5.35</td>
<td>Ca:3.46</td>
<td>3.24</td>
<td>138.1</td>
<td>1.62</td>
<td>1.174</td>
<td>0.4~2.15</td>
<td>186</td>
<td>0.16</td>
<td>&gt;10</td>
</tr>
</tbody>
</table>

Qualitative evaluation and quantitative analysis of microscopic pore structures of different diagenetic facies are of much guidance significance to high efficiency development of waterflooding oilfields. The main pore radius in the hydromica cementation--residual intergranular pore facies is 110~190μm (Table 1), and the volume of the pores of >150μm radius accounts for over 35% of the total pore volume. Throats are mainly fine throats and occasionally medium throats (Figures 4a and 4b), and the throat radius is 1.174 μm on an average and 0.4~2.15 μm in general; the cumulative contribution rate of the throats of 0.7~2.1μm radius to permeability is up to over 90% (Figure 5a) and they are main percolation passages. Final mercury injection saturation is up to 91.5%. According to high pressure mercury injection results, the mercury injection threshold pressure is low, the platform scope is wide and partial to the lower left of the capillary pressure curve, and there are many large pore throats.

The proportion of intergranular pores in the hydromica cementation--feldspar corrosion facies is about 22.7%, feldspar solution pores + lithic solution pores account for 75.7% of the total surface pore ratio (Table 1), the pore radius is large and is distributed uniformly, and the proportion of large pores increases. Average throat radius is 0.89 μm, tiny--fine throats predominate, and their distribution shows obvious dual-peak shape. The main throat radius is 0.3~1.3 μm, and the cumulative contribution rate of the throats of >0.5 μm radius to permeability can reach over 95% (Figure 5b). Capillary pressure curve is partial relatively to the lower left wide platform and the drainage capillary pressure is medium.
The average radius of intergranular pores in the chlorite cementation facies is 130.2 μm, the pores of 110–145 μm radius account for 76% of all pores, and the proportion of large pores is reduced. Throats are distributed in single-peak shape and include mainly tiny throats and a small quantity of micro-throats. The throat radius is 0.67 μm on an average and 0.56–1.05 μm in general. Throats of 0.17–0.34 μm radius are main percolation spaces. The capillary pressure curve is partial to the upper right narrow platform (Figure 5c).

The proportion of the intercrystalline pores and solution pores in the reservoir of hydromica cementation weak corrosion facies account for 50%–60% of the total surface pore ratio, and the proportion of large pores is reduced. Average throat radius is 0.318 μm, and the throats include mainly micro-throats and a small quantity of tiny throats and are distributed in dual-peak shape. The throats of 0.17–0.34 μm radius are the main percolation spaces of the facies, the cumulative contribution rate of the throats of >0.18 μm radius to permeability is up to over 95%, and the capillary pressure curve platform is narrow (Figure 5d).

The reservoir spaces in the carbonate cementation facies are mainly intercrystalline micropores, and the average pore radius is 120.32 μm. Micro-throats are developed and distributed mainly in single-peak shape. The throat radius is 0.25 μm on an average and 0.16–0.26 μm in general, and the cumulative contribution rate of the throats of >0.12 μm radius to permeability can reach over 95%. The mercury injection threshold pressure of the facies is the highest (Figure 5e), mercury can hardly enter the facies, the sorting property is poor, the final mercury injection quantity is low, and the average mercury injection saturation is only 45%.

According to Figures 4a and 4b, with the variation of pore types of different diagenetic facies, the pore radius is approximate and the pore distribution range is basically similar, but the contribution capacity of the reservoir of different diagenetic facies to permeability is provided obviously by the large throats distributed on a relatively concentrated basis. Especially when the throat radius is distributed in dual-peak shape, due to wide distribution range of throat radius, the contribution of throats to permeability is relatively dispersive. In comparison with contribution to permeability and peak value, the mercury injection saturation difference and peak value always lag behind relatively; in addition, the contribution of throat radius to permeability corresponding with the highest mercury injection quantity is not the largest (Figure 5). This indicates that the contribution of small throats to permeability is low and large throats make a large contribution to permeability in spite of their small volume. A larger percent of large throats shows an obvious difference in percolation capacity. This reflects that pore size is not the main microscopic pore structure factor for affecting sandstone reservoir percolation capacity and throat radius is the main factor for controlling sandstone reservoir permeability without regard to other factors. Therefore, the reservoir of the hydromica cementation–residual intergranular pore facies has the largest percolation capacity, the reservoir of the hydromica cementation–feldspar corrosion pore facies has the second largest percolation capacity, and the reservoir of the carbonate cementation facies has the smallest percolation capacity.

Distribution characteristics of pore-throat radius ratio

The heterogeneity of pore structures of low permeability reservoirs is affected by pore-throat radius ratio (Figure 4c). When heterogeneity is strong (i.e. pore-throat radius ratio is large), small throats surround large pores, and discharge of fluids in pores is blocked; in case of water displacing oil, continuous phases are easily damaged and thus broken, percolation resistance is increased, and both the flowability of oil and gas and the saturation of movable fluids are reduced. In case of weaker heterogeneity of pore structures (i.e. smaller pore-throat radius ratio), large pores are easily surrounded by large throats; when fluids in pores are discharged, percolation resistance is small, oil and gas are easily discharged continuously via these large throats, and the saturation of movable fluids is high.  

Fine--tiny throats are developed in the hydromica cementation–residual intergranular pore facies and hydromica cementation–feldspar corrosion facies. The effective pore-throat radius ratio in the former facies is the lowest and averagely 186 (Table 1), the distribution range is small and the distribution frequency is high (Figure 4c). The pore-throat radius ratio in the latter facies is large and averagely 212. The difference between the pores and throats in the two diagenetic facies is the smallest; that is, a single pore is connected by multiple large throats, the permeability is good, and the oil and gas in pores are produced via throats extremely easily. The pore-throat radius ratio in the chlorite
cementation facies is larger than that in the two facies (Figure 4c) and is averagely 212 (Table 1) and its frequency distribution is approximately symmetrical normal distribution. Micro-throats predominate, but the pore throat radius distribution is uniform, and the pore throats have good connectedness and also relatively good percolation capacity.

The pore-throat radius ratio in the hydromica cementation weak corrosion facies and carbonate cementation facies is the largest (Figure 4c) and respectively 518 and 697 on an average (Table 1). The frequency distribution of the pore-throat radius ratio is approximately symmetrical normal distribution, but due to fine and small throats, a single pore is connected mostly by few small throats, the connectedness of pores and throats is poor, the oil and gas rich in pores are difficult to pass small throats, and the recovery ratio is low.

Discussion

Predecessors qualitatively characterized the connectedness of pore throats according to the parameters such as drainage capillary pressure, maximum mercury injection saturation, mercury ejection efficiency, etc. in general. This paper has properly modified the concept structure percolation coefficient summarized by predecessors to comprehensively characterize the configuration relation of pores with throats and their connectedness. The formula is below (1):

$$\varepsilon = R_0 \sqrt{\frac{100K}{W_e}}$$

Where: $\varepsilon$ is structure percolation coefficient, $\mu$m$^2$; $R_0$ is median pore throat radius, $\mu$m; $K$ is gas logging permeability, mD; $W_e$ is mercury ejection efficiency, %. It can be seen that the structure percolation coefficient is directly proportional to median pore throat radius and the square root of permeability and inversely proportional to the square root of mercury ejection efficiency; that is, the larger the median pore throat radius, the larger the rock permeability and the lower the mercury ejection efficiency, the larger the structure percolation coefficient, the better the pore throat connectedness, and the more favorable the pore structure of reservoir rocks for flowing of fluids.

As mentioned previously, the hydromica cementation--residual intergranular pore facies has the largest effective throat radius, the lowest pore-throat radius ratio, good sorting property of pore throats, and low drainage capillary pressure, and the mercury injection rate curve is in single-peak shape (Figure 5a), so the structure percolation coefficient is the largest (averagely 0.16 $\mu$m$^2$), and the reservoir capacity and percolation capacity of the reservoir are the best.

The pore throats in the hydromica cementation--feldspar corrosion facies have relatively poor sorting property, and the mercury injection rate curve shows dual-peak shape, single-peak shape or unobvious peak shape (Figure 5b). The development degree of large pore throats in the facies is lower than that in the hydromica cementation--residual intergranular pore facies. The connectedness of pore throats is common, and the structure percolation coefficient is obviously reduced (averagely 0.06$\mu$m$^2$). The structure percolation coefficient of the chlorite cementation facies, hydromica cementation weak corrosion facies and carbonate cementation facies is respectively 0.02$\mu$m$^2$, 0.01$\mu$m$^2$ and 0.005$\mu$m$^2$.

The pore throat radius is small and has a wide distribution range, and the mercury injection rate curve shows obvious dual-peak shape and equivalent peak value (Figures 5c, 5d and 5e). The mercury injection rate from the minimum pore throat radius to the maximum one in the three facies is more uniform than that in the former two diagenetic facies. In addition, the pore structure development degree is low and the percolation capacity is also the smallest.

Impact of pore structure on reservoir percolation characteristics

Low permeability reservoirs have poor physical properties and are easily affected by pore structure; large throats control reservoir percolation capacity; the larger the pore structure, the larger the ratio of permeability to porosity, and the more favorable the reservoirs for fluid flowing. The reservoir rocks with strong heterogeneity of pore structure are characterized by high degree of mutual interference between oil and water, high saturation of bound water, narrow scope of oil-water co-percolation area, and obvious weak hydrophilicity. The scope of co-percolation area becomes narrow gradually and has a large difference from dominant diagenetic facies to subordinate diagenetic facies (Table 2). Affected by the flowing differential pressure of fluids, water phase permeability is increased gradually with the increase in the content of fluids (water) preferentially occupying pores. The complex pore structure of low permeability reservoirs easily leads to breaking of oil continuity and thus occurrence of liquid resistance effect. Charging of oil and gas is difficult in small throat-connected pore spaces (e.g. hydromica cementation weak corrosion facies reservoirs mainly with intercrystalline micropores), and the saturation of
bound water is high. Large pore throat spaces (e.g. hydromica cementation–residual intergranular pore facies) with low drainage capillary pressure and good connectedness are favorable areas for charging of oil and gas.

Table 2 Percolation characteristic parameters of different diagenetic facies of C63 reservoir

<table>
<thead>
<tr>
<th>Diagenetic facies types</th>
<th>Permeability (mD)</th>
<th>Porosity (%)</th>
<th>Bound water</th>
<th>Intersection point</th>
<th>Residual oil</th>
<th>Co-percolation area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydromica cementation--residual intergranular pore facies</td>
<td>0.252</td>
<td>10.5</td>
<td>37.8</td>
<td>0.007</td>
<td>59.3</td>
<td>0.148</td>
</tr>
<tr>
<td>Hydromica cementation--feldspar corrosion facies Chlorite cementation facies</td>
<td>0.167</td>
<td>9.8</td>
<td>37.7</td>
<td>0.005</td>
<td>60.6</td>
<td>0.087</td>
</tr>
<tr>
<td>Hydromica cementation weak corrosion facies</td>
<td>0.126</td>
<td>8.9</td>
<td>41.5</td>
<td>0.005</td>
<td>60.1</td>
<td>0.064</td>
</tr>
<tr>
<td>Hydromica cementation weak corrosion facies</td>
<td>0.093</td>
<td>8.8</td>
<td>55.1</td>
<td>0.0021</td>
<td>59.7</td>
<td>0.051</td>
</tr>
</tbody>
</table>

Logging Response Characteristics of Different Diagenetic Facies and Distribution Characteristics of High Quality Reservoirs

Through the analysis of the longitudinal and transverse distribution law of various diagenetic facies, the diagenetic facies of reservoirs can be evaluated, and the distribution of high quality reservoirs can be finally determined. Firstly analyze the logging response characteristics of relevant diagenetic facies and build a logging interpretation template based on the diagenetic facies interpretation result of coring wells in the study of diagenetic facies belt distribution; finally plot the planar distribution map of diagenetic facies according to sedimentary facies, pore evolution degree and sand body distribution law.

Logging response characteristics of different diagenetic facies

This paper has established the logging response template of different diagenetic facies (Table 1) based on the logging interpretation result of porosity and permeability of reservoirs and the results of core analysis, casting slice appraisal and SEM test of coring wells and by comparing the results with the logging curves including GR, AC, RT, DEN, etc.

Affected by calcite cementation, the porosity of carbonate cementation facies is extremely low, and logging response characteristics show two-low and two-high (Figure 6), i.e. low GR, low AC, high RT and high DEN; AC is less than 220 μs/m, GR is 65–95 API, and DEN is larger than 2.6 g/cm³ in general. If reservoirs are oil reservoirs, the high resistivity characteristic of the reservoirs of the facies is not remarkable due to being affected by fluid properties.

Hydromica cementation–weak corrosion facies reservoirs have high GR, low DEN, low neutron porosity and a large difference between neutron porosity and density porosity (Figure 6) due to being affected by pore filling type and pad type occurrence of authigenic minerals such as illite etc.

The response characteristics of chlorite cementation facies reservoirs on conventional logging curves show three-high and one-large (Figure 6); i.e. due to being affected by silty sandy mudstones, argillaceous siltstones, etc., the reservoirs of the facies have medium to high GR ranging from 80 to 122 API, AC ranging from 217 to 242 μs/m, DEN ranging from 2.0 to 2.4 g/cm³, and a large difference between neutron porosity and density porosity.
Figure 6 Diagenetic facies analysis of single wells of C63 reservoir in Qingyang region

The clay minerals such as illite etc. in hydromica cementation--feldspar corrosion facies reservoirs occur in the form of pore filling. Affected by corrosion of unstable components such as feldspar etc., the neutron porosity is 9.3%, the difference between neutron porosity and density porosity is small, the GR is 85~104 API, the AC is 207~230 μs/m, the DEN is 1.71~2.4 g/cm³, and the RT is around 130~160 Ωm (Figure 6).

Hydromica cementation--residual intergranular pore facies is developed mainly in gravity flow composite channel turbidite sands. Due to good physical properties of reservoirs and well-developed residual intergranular pores, the density of reservoirs is also low and their logging response characteristics also show three-low, one-high (Figure 6), i.e. low GR, low AC, low DEN and high RT, and a small difference between neutron porosity and density porosity.

On the whole, C63 reservoir has high development degree of hydromica cementation--feldspar corrosion facies and hydromica cementation--residual intergranular pore facies and good distribution of favorable diagenetic facies belts and is affected strongly by acid formation water, so C63 reservoir is the favorable exploration interval in the research region.

Distribution characteristics of diagenetic facies and prediction of high quality reservoirs

The reservoir property of reservoirs is affected by sedimentary environment and also has a close relation to diagenesis. The impact of sedimentary environment on reservoir physical properties and diagenesis is comprehensively considered in the division and study of diagenetic facies of reservoirs in this paper, so effective reservoirs can be analyzed and predicted effectively according to diagenetic facies. According to the logging response characteristics of diagenetic facies, the diagenetic facies types of over 400 wells in the research region have been identified. Taking the planar distribution of sedimentary facies and sand bodies as the base map, the planar distribution map of diagenetic facies has been worked out (Figure 7). The result matches well with the actual production performance (Figure 8), thus further indicating the reasonableness of the diagenetic facies classification scheme.
C6 reservoir has the highest development degree of hydromica cementation--feldspar corrosion facies and carbonate + hydromica cementation facies on plane (Figure 7). Hydromica cementation--feldspar corrosion facies reservoir with good physical properties is developed mainly in semi-deep lacustrine gravity flow composite channel turbidites with large sand body thickness and relatively large grain size. The reservoir belongs to a favorable diagenetic facies belts, and is distributed mainly in the southwest, northwest and central part of the research region. In terms of production, the reservoir shows that the injection water line advances uniformly along large-proportion fine pore throats and medium pore throats, the sweep area of waterflooding is large, the average daily oil production is high, and the stable production period with low water cut is long. The reservoir is the main pay formation for oilfield development. The carbonate + hydromica cementation facies is developed in between branch channels with <5m sand body thickness and small grain size (Figure 7), has poor physical properties of reservoirs, and is distributed mostly in the central part and northeast. In addition, the carbonate + hydromica cementation facies is distributed alternately with the hydromica cementation--feldspar corrosion facies.

The hydromica cementation--residual intergranular pore facies is developed mainly in the thick sand beds of semi-deep lacustrine turbidite multi-stage superposition branch channels and distributed with small area in Chicheng Township (Figure 7) and belongs to one of high quality reservoirs. Oil and water are of relatively uniform seepage flow, the single-well productivity is high in the early stage but the water cut increases quickly, the stable production period is short (Figure 8), and the production difficulty is the lowest.

Chlorite cementation facies is located in the margin of semi-deep lacustrine turbidite branch channels and has medium physical properties of reservoirs but is distributed to a limited extent and developed sporadically only in Malianyaoxian belt (Figure 7). In spite of uniform swept area of water displacing oil, the proportion of small pore throats in the facies is large, so it is difficult to displace out the oil in these small pore throats by oil injection, the overall percolation efficiency of the reservoir is bad, oil and water are produced together after water breakthrough, the water production is large (Figure 8), and the ultimate oil displacing effect and recovery ratio are low.

The hydromica cementation--weak corrosion facies is distributed mostly in island shape (Figure 7) and has poor physical properties of reservoirs and the lowest single-well productivity; in addition, the productivity decline rate is quick; in case of water breakthrough, wells are water flooded quickly and there is almost no stable production time (Figure 8). The carbonate cementation facies has the worst physical properties of reservoirs and is developed sporadically only in the east.
Conclusion

The main sandstones of C63 reservoir in Qingyang region are lithic feldspar sandstones with medium to relatively low structure maturity and low component maturity. According to sedimentary microfacies development characteristics, main diageneses, pore assemblage and evolution, diagenesis characteristics and difference, etc. as well as the content of interstitial matters, surface pore ratio, etc., totally 6 diagenetic facies have been divided below: arbonate cementation facies, carbonate + hydromica cementation facies, hydromica cementation weak corrosion facies, chlorite cementation facies, hydromica cementation--feldspar corrosion facies and hydromica cementation--residual intergranular pore facies. Their pore structure becomes good successively.

Logging response characteristics of different types of diagenetic facies have been established. Diagenetic facies division scheme matches well with the reservoir oil productivity. The distribution of high quality reservoirs is controlled by both sedimentary facies and diagenetic facies. Vertically, the development degree of hydromica cementation weak corrosion facies in the bottom of C63 reservoir is relatively high, and hydromica cementation--feldspar corrosion facies and hydromica cementation--residual intergranular pore facies deposited in branch channels are developed in the middle upper part. On plane, the development degree of hydromica cementation--feldspar corrosion facies and hydromica cementation--residual intergranular pore facies is high, and they are affected strongly by acid formation water and are favorable diagenetic facies belt distribution areas and main pay formations for oilfield development. Pore structure development degree of the carbonate cementation facies and carbonate + hydromica cementation facies is low, the oil and gas rich in pores are difficult to pass small throats, and the recovery ratio is low.

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