Architectural Units and Groundwater Resource Quantity Evaluation of Cretaceous Sandstones in the Ordos Basin, China

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Abstract: Sandstone is a common lithology in a number of groundwater reservoirs. Studying the skeleton sandstone architectural units, therefore, lays the basis for characterizing aquifer systems, groundwater quality, and resource evaluation. This comprehensive analysis of Cretaceous aquiferous sandstones in the Ordos basin, China, shows that there exists a basin-scale skeleton sandstone in the Luohe Formation which contains 11 isolated barrier beds, 12 small skeleton sandstone bodies in Huanhe Formation, and 3 in the Luohandong Formation. The spatial structure and superimposed relationship as well as the medium properties of these skeleton sandstones and isolated barrier beds can be shown by 3D visualization models. Simultaneously, resource quantity can be evaluated with the 3D inquiry functions. The comparison between property models and structural models indicates that the salinity of groundwater of the Luohe Formation has a close connection with the locations of isolated barrier beds that contain abundant gypsum. Through quantitative calculation, groundwater resource of the Cretaceous Luohe and Luohandong formations is estimated to be 1.6×10^{12} m³, and the total groundwater resource of the Cretaceous system in the Ordos basin is more than 2×10^{12} m³.

Key words: skeleton sandstone, reservoir architecture, groundwater, Cretaceous, Ordos basin

1 Introduction

The Ordos basin, located in northwestern China (Fig. 1a), is an important energy resource base for China, containing petroleum, natural gas, sandstone-type uranium, and geothermal resources (Li Sitian et al., 1992; He Zixin, 2003; Chen et al., 2004; Jiao et al., 2005a; Tuo et al., 2007; Zhao et al., 2014). The basin also has abundant groundwater resource (Hou Guangcai and Zhang Maosheng, 2004; Chen et al., 2013). With an average altitude of 1300 m, the basin surface is characterized by loess and desert (Fig. 1b). With an annual precipitation of 250 to 550 mm, the Ordos basin is in an arid to semiarid environment. The Yellow River is the main surface drainage (Figs. 1c, 1d). Past prospecting indicates that the Cretaceous sandstone in Ordos basin is not only the main domain of groundwater resource storage and circulation but also a high quality groundwater reservoir. From the contour map of groundwater table (Fig. 1d), we can identify that the Cretaceous formations contain five groundwater subsystems that have a close relationship with surface drainage (Xie Yuan et al., 2003; Hou Guangcai and Zhang Maosheng, 2004; Wang Deqian, et al., 2005). Therefore, characterizing the spatial configuration and internal structure of Cretaceous sandstones is very important to the research of groundwater system structure and groundwater resource evaluation. In previous studies of the Ordos basin, researchers have investigated lithology, sedimentary facies, thickness and pore structure of sandstone aquifers (Xie Yuan et al., 2003, 2010, 2012; Lu Qi, et al., 2004; Deng Guoshi et al., 2008; Tao Zhengping et al., 2008), but there have been few systematic research relating groundwater reservoir heterogeneity and internal structure, water quality assessment, and aquiferous sandstone volume estimation.

In fact, sandstone heterogeneity is a ubiquitous geologic
phenomenon, which is embodied by sedimentary interfaces and variations of sediment granularity and components as well as diagenesis (Miall, 1991; Jiao et al., 2005b). The research on spatial distribution characteristics of isolated barrier beds is the key to studying sandstone heterogeneity and the genesis of natural resources such as oil, gas, groundwater, and sandstone-type uranium deposit (Eggenhuisen et al., 2010; Frlomena et al., 2010; Morad et al., 2010; Taggart et al., 2010). 3D geological modelling is a good technology to analyze and visualize aquifer structure (Yan Huiwu et al., 2004; Raiber et al., 2012; Shi et al., 2015).
This paper presents the study of aquiferous sandstone formations of the Cretaceous system in the Ordos basin. Through building 3D structural and property models for the Cretaceous skeleton sandstones (Jiao Yangquan et al., 2006), this paper explains heterogeneity in groundwater quality, calculates the volume of aquiferous sandstone using 3D spatial inquiry functions, and evaluates the groundwater resource quantity. The approaches used in this study have generality in understanding aquifer structure at basin scale and may be used to quantify groundwater resource.

2 Structure of the Ordos Basin

The Ordos basin, covering an area of \(37.5 \times 10^4\) km\(^2\), consists of a depo-center and several peripheral sub-basins (Fig. 2). The depo-center, with its west margin inclining to the east steeply and east margin inclining to the west gently, has the shape of a dustpan. The central part of the basin has little fracture damage, and the peripheral parts are consist of several Tertiary fault basins. The main fault basins include Hetao-Jilantai basin in the north, the Yinchuan basin in the northwest and the Fenwei basin in the south. The main faults include thrust faults in the southwest margin, east margin faults and the basin-controlling faults (Fig. 2).

The Cretaceous system in the Ordos basin has an average thickness of 776m with the thickest exceeding 1300m, mainly distributed in the middle and west of the basin center. The strata are considerably asymmetrical. Their thickness in the west margin generally exceeds 800m. The lower Cretaceous strata only exist locally in the Hetao-Jilantai fault basin in the north of Ordos basin.

The Cretaceous system of the Ordos basin consists of three lithologic units. They are coarse clastic Luohe Formation, fine clastic Huanhe Formation and coarse-thin clastic Luohandong-Jingchuan Formation of lower Cretaceous (Fig. 3). The Cretaceous skeleton sandstone refers to those with a thickness greater than 15m and lateral dimension greater than 5000m. The skeleton sandstone inside the coarse clastic formation and the fine clastic formation constitutes the main groundwater reservoirs.

3 Discussions

3.1 Structure Analysis of the Cretaceous Skeleton Sandstone

Two aspects of the structure analysis of Cretaceous skeleton sandstone were performed in order to unveil the sandstone heterogeneity. The first is the external structure analysis, aimed at demonstrating spatial location and configuration. The second is the internal structure analysis, aimed at investigating the argillaceous isolated barrier beds inside the sandstone.

3.1.1 Research methods and processes

The main information used in the structure analysis of
Cretaceous skeleton sandstone is obtained from outcrops and log data from oil and gas boreholes. Resistivity log, spontaneous potential and gamma log are used to identify sandstone and isolated barrier beds. The results are shown by vertical lithological sequence (Fig. 3). Secondly, important interfaces and marker beds are identified and used in the correlation of strata, including sandstone and isolated barrier beds. Some intersecting skeleton profiles of at basin scale are chosen for systematic strata and sandstone correlation (Fig. 4). Thirdly, the spatial distributional characteristics and inner structure of skeleton sandstone are analyzed through lithological statistical analysis and plane cartographic analysis.

3.1.2 Cretaceous skeleton sandstone and internal structure characteristics

The correlation results of nine netlike skeleton profiles and 678 drilling holes reveal that there exists a large-scale skeleton sandstone in the Luohe Formation, which contains 11 argillaceous isolated barrier beds. There are 12 skeleton sandstones in the Huanhe Formation, and 3 in the Luohandong Formation. To avoid confusion, Cretaceous skeleton sandstones are systematically named as follows (Fig. 4): LH-S for Luohe sandstone, HH-S for Huanhe sandstone, and LHD-S for Luohandong sandstone. LH-N represents Luohe isolated barrier beds, and small alphabets (a, b, c….) represents finer units of sandstone or isolated barrier beds.
As shown in Fig. 5, the Luohe skeleton sandstone is widespread in a thick layer, with an average thickness of 313 m, and a width and length of 100 km and 320 km, respectively. Generally, the west and the south parts of the Luohe Formation are thicker than the east and the north parts. The average thickness at the east and north borders is about 100 m, but that around Wuqi county and Zhidan county in west part of Ordos basin is more than 300 m (Fig. 6). The average buried depth of the Luohe Formation ranges from 500 m to 695 m, and the deepest buried depth is up to 1494 m. The average altitude ranges from 676 m to 862 m. The Luohe skeleton sandstone formed in alluvial and aeolian environment while the isolated barrier beds formed in arid lakes (Cheng Soutian et al., 2000; Jiang et al., 2001, 2004).

Eleven (11) argillaceous isolated barrier beds inside the Luohe skeleton sandstone, which develop mainly in the middle and south of Ordos basin, spread discontinuously in thin layers with an average thickness of 6 m (Fig. 6). Formed in arid lakes, these barrier beds are composed of mudstone and siltstone with abundant gypsum. With a porosity from 6% to 9% and permeability less than $5 \times 10^{-15}$ m$^2$ ($5 \text{md}$), they are considered aquitards.

Formed in lakes and deltas, the Huanhe Formation is
comprised of fine sediments (Cheng Soutian et al., 2000; Jiang et al., 2001, 2004). As shown in Figure 7, lacustrine mudstone and thin distributary mouth bar sandstone develop in delta systems, but distributary channel sandstone and subaqueous distributary channel sandstone are limited. The small scale but large number of distributary channels constitutes the skeleton sandstone and form the main groundwater reservoir of the Huanhe Formation. Twelve (12) skeleton sandstones are located in the middle and south of the Ordos basin with an average thickness of 117 m, average width of 10 km and average length of 30 km (Fig. 8).

Similar to the Luohe Formation, the Luohandong Formation (Fig. 9) also develops large-scale aeolian...
Fig. 7. Outcrop of delta front deposits of the Huanhe Formation in Dushitu River of Etuoke county, Ordos basin.

Fig. 8. Thickness contours of skeleton sandstones of the Huanhe Formation, Ordos basin.
sandstone (Cheng Soutian et al., 2000; Jiang et al., 2001, 2004) and thus forms an important aquifer. The contrasting characteristics of the strata reveals that there are three sandstones in the Luohandong Formation, with an average thickness of 114 m, average width of 28 km, and average length of 43 km. Compared with the Luohe Formation, the Luohandong sandstone has shallower buried depth ranging from 202 m to 231 m. The maximum buried depth is 735 m. The altitude ranges from 1087 m to 1127 m. The strata mainly distribute in the western part of the Ordos basin. The skeleton sandstone mainly distributes in the east of the Pingliang district and the Sanyanjing district (Fig. 10).

3.2 3D Modeling and Visualization of Skeleton Sandstone Structure

Constructing and analyzing 2D profiles and thickness contour maps are important to the research on groundwater systems. However, they cannot reveal the spatial configuration and internal structure of skeleton sandstone exactly and successively. The 3D visualization modeling technology overcomes these limitations (Hindle, 1997, 1999; Bekele et al., 1999; Mao et al., 2012).

Systemic correlation of skeleton sandstones and isolated barrier beds is the key to 3D modeling of sandstone internal structure. Using the Luohe Formation to illustrate the point, the information used in 3D modeling come from correlation data of skeleton sandstone and isolated barrier beds. Interpolating these data allows us to build the bottom, top, and side surface of skeleton sandstone to form model units. By integrating model units, we could observe and analyze the spatial configuration and internal structure of sandstone from different angles, as shown in Fig. 11.

Similarly, we used 22 interface model units to demonstrate 11 isolated barrier beds inside the Luohe skeleton sandstone. By integrating model units of skeleton sandstone and isolated barrier beds, we could build volume model which, along with a large number of sedimentary profiles derived using 3D inquiry function, can reveal the internal structure and heterogeneity of sandstone (Fig. 12).

The 3D visualization modeling technology can be used not only to reveal spatial structure of groundwater reservoir, but also in groundwater system research, 3D numerical simulation and groundwater resource evaluation.

3.3 3D Modeling and Visualization of Skeleton Sandstone Medium Properties

Because skeleton sandstones are saturated with groundwater and exploration showed that groundwater chemistry changes spatially (Hou Guangcai and Zhang Maosheng, 2004), we could use the 3D visualization modeling technology to build property models of groundwater, such as total dissolved solids. Our model units indicate clearly that a high salinity area (>3g/l) exists around Huanxian County in the south of the Ordos basin and low salinity is widespread in the north of the Ordos basin (Fig. 13).

Compared with the corresponding structure model units of the Luohe skeleton sandstone, it can be seen that high salinity is closely associated with isolated barrier beds inside the skeleton sandstone. The areas where isolated barrier beds develop coincide with those where high salinity develops (Fig. 13). The reason for this
phenomenon may be that isolated barrier beds usually form in arid lake and have abundant content of gypsum. Therefore, the places where isolated barrier beds develop contain higher concentrations of salt and therefore poor quality of groundwater.

3.4 Application of Skeleton Sandstone Structure Model Units—Calculation of Groundwater Resource Quantity

Calculation of groundwater reservoir volume is significant to the evaluation of groundwater resource quantity. Because of its predictability and 3D inquiry functions, 3D visualization models can be used to calculate the volume of skeleton sandstone and isolated barrier beds. With the parameter of porosity and aquiferous coefficient, the groundwater resource quantity can be calculated. The results of these calculations for the Cretaceous system of the Ordos basin are shown in Table 1.

On the basis of the sandstone volume, the groundwater resource quantity is calculated as follows:

\[
Q = V \times \phi \times \varepsilon \\
V = V_s - V_g
\]

where \( Q \) represents groundwater resource quantity, \( V \) is the valid volume of sandstone, \( V_s \) is the saturated sandstone volume, \( V_g \) is the saturated isolated barrier beds volume, \( \phi \) is the porosity of sandstone, and \( \varepsilon \) is the aquiferous coefficient of sandstone. Using \( \phi=24\% \) for the Luohe Formation, \( \phi=28\% \) for the Luohandong Formation, and \( \varepsilon=0.3 \) (Lu et al., 2004), the groundwater resource quantity of the Luohe and Luohandong formations can be calculated as follows:

\[
Q_{\text{Luohe}} = (2.18 \times 10^{13} \text{ m}^3 - 1.21 \times 10^{11} \text{ m}^3) \times 24\% \times 0.3 = 1.56 \times 10^{12} \text{ m}^3
\]

\[
Q_{\text{Luohandong}} = (2.65 \times 10^{11} \text{ m}^3 + 1.01 \times 10^{11} \text{ m}^3 + 8.33 \times 10^{10} \text{ m}^3) \times 28\% \times 0.3 = 3.78 \times 10^{10} \text{ m}^3
\]

\[
Q_{\text{total}} = Q_{\text{Luohe}} + Q_{\text{Luohandong}} = 1.61 \times 10^{12} \text{ m}^3
\]

Our calculations presented above are consistent with Fig. 10. Thickness contour map of the Luohandong skeleton sandstone, Ordos basin
some previous studies. Table 2 compares the results from various sources.

If the groundwater resource quantity of the Huanhe sandstone shown in Figure 8 and elastic storativity of deep groundwater in the Luohe Formation and Luohandong Formation are considered, the total groundwater resource quantity of the Cretaceous system in the Ordos basin exceeds 2×10^{12} m^3.

### Table 1 Volume calculation results of the Luohe and Luohandong sandstone and isolated barrier beds in the main body of the Ordos basin

<table>
<thead>
<tr>
<th>Strata</th>
<th>Sandstone</th>
<th>Volume above water table (m^3)</th>
<th>Volume below water table (m^3)</th>
<th>Total volume (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luohe Formation</td>
<td>LH-S</td>
<td>4.14×10^{11}</td>
<td>2.18×10^{13}</td>
<td>2.22×10^{13}</td>
</tr>
<tr>
<td></td>
<td>LHD-S-a</td>
<td>4.18×10^{10}</td>
<td>2.65×10^{11}</td>
<td>2.69×10^{11}</td>
</tr>
<tr>
<td></td>
<td>LHD-S-b</td>
<td>1.22×10^{11}</td>
<td>1.01×10^{11}</td>
<td>2.23×10^{11}</td>
</tr>
<tr>
<td></td>
<td>LHD-S-c</td>
<td>1.86×10^{10}</td>
<td>8.33×10^{10}</td>
<td>1.02×10^{11}</td>
</tr>
<tr>
<td>Luohandong Formation</td>
<td>LH-N-a</td>
<td>6.01×10^{10}</td>
<td></td>
<td>3.76×10^{10}</td>
</tr>
<tr>
<td></td>
<td>LH-N-b</td>
<td>2.77×10^{10}</td>
<td></td>
<td>6.21×10^{10}</td>
</tr>
<tr>
<td></td>
<td>LH-N-c</td>
<td>3.68×10^{10}</td>
<td></td>
<td>2.84×10^{9}</td>
</tr>
<tr>
<td></td>
<td>LH-N-d</td>
<td>9.56×10^{9}</td>
<td></td>
<td>2.21×10^{9}</td>
</tr>
<tr>
<td></td>
<td>LH-N-e</td>
<td>9.78×10^{9}</td>
<td></td>
<td>6.74×10^{9}</td>
</tr>
<tr>
<td></td>
<td>LH-N-f</td>
<td>2.12×10^{8}</td>
<td></td>
<td>1.21×10^{11}</td>
</tr>
</tbody>
</table>

### Table 2 Groundwater resources quantity of Cretaceous in the Ordos basin

<table>
<thead>
<tr>
<th>Calculator</th>
<th>Calculation methods</th>
<th>Strata</th>
<th>Groundwater resource quantity (×10^{12} m^3)</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jiao et al., 2006</td>
<td>Sandstone contrast and 3D visualization modeling</td>
<td>Luohe Formation</td>
<td>1.56</td>
<td>Without considering elastic storativity</td>
</tr>
<tr>
<td>Sun et al., 2004</td>
<td>Macroscopic compute</td>
<td>Luohe Formation</td>
<td>1.613594</td>
<td>Include elastic groundwater resource quantity</td>
</tr>
<tr>
<td>Lu et al., 2004</td>
<td>Microcosmic statistic</td>
<td>Cretaceous system</td>
<td>1.1–1.6</td>
<td>Without considering elastic storativity</td>
</tr>
</tbody>
</table>

### 4 Conclusions

The comprehensive analysis of Cretaceous aquiferous sandstones in the Ordos basin shows that there exists a basin-scale skeleton sandstone in the Luohe formation which contains 11 isolated barrier beds, 12 small skeleton sandstones in the Huanhe Formation, and 3 in the Luohandong Formation.

The Luohe skeleton sandstone is widespread in a thick...
layer. Generally the sandstones in the west and the south parts are thicker than in the east and the north parts. Eleven (11) argillaceous isolated barrier beds inside skeleton sandstone, which develop mainly in the middle and south of the Ordos basin, spread discontinuously in thin layers. The Huanhe skeleton sandstone, which is characterized by small scale and large number, develop in the middle and south of the Ordos basin. The Luohandong skeleton sandstone, whose scale is between the Luohe and Huanhe formations, mainly distribute in the east of the Pingliang district and the Sanyanjing district.

3D visualization modeling technology can reveal the spatial configuration, developing scale and superimposing relationship of skeleton sandstone and isolated barrier beds successively. Moreover, the 3D
visualization modeling technology can be used to build property models of sandstone. Comparison between property models and structural models of skeleton sandstone identifies locations of high salinity groundwater in the Luohe Formation, which is likely caused by the dissolution of gypsum contained in argillaceous isolated barrier beds.

Valid volume of aquiferous sandstone can be calculated by using 3D sandstone structure models. With the data of porosity and aquiferous coefficient, the groundwater resource quantity can be calculated too. The results reveal that groundwater resource quantity of the Luohe and Luohandong formations of the Cretaceous system is $1.6 \times 10^{12} \text{ m}^3$. If the groundwater resource quantity of the Huanhe Formation and elastic storativity of confined water are considered, the total groundwater resource quantity of the Cretaceous system in the Ordos basin exceed $2 \times 10^{12} \text{ m}^3$.

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