Journal of Earth Science, 2017 online *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-016-0935-2

A Comprehensive Porosity Prediction Model for the Upper Paleozoic Tight Sandstone Reservoir in the Daniudi Gas Field, Ordos Basin

Longwei Qiu*[1], **Shengchao Yang***[1,2], **Ningning Xu**[1], **Qingsong Gao**[3], **Xiangjin Zhang**[4], **Xugang Liu**[3], **Donghui Wang**[3]
1. *School of Geosciences, China University of Petroleum, Qingdao 266580, China*
2. *State Key Laboratory for Mineral Deposits Research, School of Earth Sciences and Engineering, Nanjing University, Nanjing 210046, China*
3. *Exploration and Development Institute, North-China Branch Company, SINOPEC, Zhengzhou 450006, China*
4. *Tianjin Fanglian Technology Development Co., Ltd., Tianjin 300280, China*

ABSTRACT: This paper investigated theporosity controlling factors for tight sandstone reservoir in the DaniudiGas field, Ordos Basin based on an intergrated petrographic, petrophsical and geostatistical analyses,and proposed a comprehensive prediction model for reservoir porosity. Compaction was found to be a key factor for causing reservoir densification.The degree of sandstone compaction appears to be affected by grain sizes and sorting. Under normal compaction conditions (e.g. cement content less than 6%, and with no dissolution), the variation in reservoir porosity with burial depth can be well correlated with grain compositions, grain sizes, and sorting. Based on qualitative examination of the controlling factors for reservoir porosities, geostatistics wereused to quantify the effects of various geological parameters on reservoir porosities. A statistical model for comprehensive prediction of porosity was then established, on the assumption that the present reservoir porosity directly relates to both normal compaction and diagenesis.This model is easy to use,and has been validated with measured porosity data. The porosity controlling factors and the comprehensive porosity prediction can be used to quantify effects of the main controlling factors and their interaction on reservoirproperty evolution, and may provide a reference model for log interpretation.

KEYWORDS: tight sandstone reservoir, controlling factors, porosity,Daniudigas field, Ordos Basin

0 INTRODUCTION

As an important part of unconventional natural gas, tight sandstone gas is attracting attention of more and more petroleum and geological researchers (Wei et al, 2016; Hu et al, 2015; Hu et al, 2013; Fu et al, 2012; Zou et al, 2012). Tight sandstone reservoirs have typical features of tight lithology, low porosity and low permeability (Guo et al, 2010; Spencer, 1989). Nowadays, controlling factors of tight sandstone reservoir properties have been studied well, and reservoir properties were jointly influenced by three major aspects, sedimentation, diagenesis and structure respectively (Zhang et al, 2013;Zhang et al, 2010a; Zhang et al, 2010b; Liu et al, 2008;Zhou et al, 2008;Tang et al, 2007).The quality of reservoirswas largely characterized by sedimentation control, compaction dominance, cementation enhancement, and dissolution improvement (Cao et al, 2012).Pore development mechanism of tight sandstone and itsinfluence factors vary greatly from regions and horizons (Zhang, 2008). Now that porosity is a crucial factor dictating development of high quality reservoirs or "sweet spots" in tight sandstone (Liu et al, 2013), whichever factor plays the predominant role, its impact on reservoir would eventually reflect to porosity alteration, therefore porosity is the basis for correct evaluation and effective prediction of tightsandstone reservoirs.

Regarding factors influencing Upper Paleozoic reservoir properties in Daniudigas field, Ordos Basin, some scholars thought that sedimentary factor prevails (Yang et al, 2010;Yin and Ying, 2005), while others argued that diagenesis plays a pivotal role (Xu et al, 2011). In addition, previous studies on influencingfactors of tight sandstone reservoirproperties in thestudy area were mainly qualitative analyses, lacking quant-itative studies on the influence degree of various factors on physical properties. In order to define controlling effect and influence degree of each factor on properties of tightsandstonereservoir, taking Upper Paleozoic tightsandstone reservoir in Daniudigas field, Ordos Basin for example, the authors conducted a quantitative/semi-quantitative analysis of reservoir controlling factors including sedimentation and diagenesis.The key point of this paper is to discuss porosity evolution mechanism subjected to compaction by establishing normal compaction curves of rock as a function of lithology, grain size and sorting; and mathematical methods were used to quantify in-

---

*Corresponding author: qiulwsd@163.com; yangsc_2012@hotmail.com

Manuscript received May22, 2016.
Manuscript accepted February12, 2016.

Qiu, L.W., Yang, S.C., Xu, N.N., et al., 2017. A Comprehensive Porosity Prediction Model for the Upper Paleozoic Tight Sandstone Reservoir in the Daniudi Gas Field, Ordos Basin.*Journal of Earth Science*. doi: 10.1007/s12583-016-0935-2

fluence degree of each controlling factor on reservoir poro-sity, so as to build a comprehensive porosity prediction modelunder various key factors.

1 GEOLOGICAL BACKGROUND

Daniudigas field lies in the northeastern Yishanramp in Ordos Basin, at a junction area between Yulin City, Shanxi Province and Ordos City, Inner MongoliaMunicipality, cove-ring an exploration area of about 2,003km^2(Zhang, 2014; Du et al, 2013;Jiang et al, 2012). Regionally, it is a gentle monocline high in the northeast and low in the southwest(Fig. 1).The Upper Paleozoic depositional systems of the study area are marine facies, marine-continental transition-continental facies (Qiu et al, 2013). The Upper Carboniferous Taiyuan Formation is mainly developed littoral deposit, the Lower PermianShanxi Formation is mainly developed braided river delta deposit, and the Lower Permian Lower Shihezi Formation is dominated by braided river deposit (Hou and Liu, 2012). Main gas-bearing intervals are reservoir beds of CarboniferousTaiyuan Formation, Permian Shanxi Formation and Lower Shihezi Formation (Luo et al, 2007). In reservoir petrological characteristics, quartz is the highest content, but varies over a wide range, i.e., 74–97% of the total clast, averaging 88.9%.Feldspar is universally low and generally not more than 20%. Lithic fragment is 3.5–58%, averaging 19.55%, dominated by sedimentary rock fragments and shallow parametamorphic rock fragments, as well as minor amount of magmatic rock fragm- ents.Cements include kaolinite, illite, calcite, quartz, siderite and dolomite (Qiu et al, 2013). Besides, minor amounts of mica chips and heavy minerals are observable, with contents gener- ally less than 5%. Data of molded thin sections and scanning electron microscopy (SEM) indicate that reservoir space type is diverse, dominated by intergranular pores, intercrystal pores, and intragranular dissolution pores, fewer primary pores in addition to minor microfissures (Qiu et al, 2013).

2 METHOD AND RESULTS

Properties of tight sandstone reservoir are influenced by many factors, and factors influencing reservoir porosity differ greatly from regions and horizons (Zhang, 2008). Understan-ding controlling effect of each factor is a prerequisite of effecti-ve prediction of porosity. Based on existing data, this paper primarily analyzed porosity controlling factors of the Upper Paleozoic tight sandstone reservoir in Daniudi gas field in terms of sedimentation and diagenesis.

2.1 Sedimentary Factors

Sedimentary facies macroscopically control sand body's origin type, thickness, scale and spatial distribution, and micro-scopically dictate petrological characteristics such as clastic particle size, sorting, psephicity, contact mode and components of interstitial material and their contents (Zhang et al, 2013;Zhou et al, 2008;Tang et al, 2007).

Macroscopically, reservoir properties data of different sedimentary facies in the study area indicate that, variations in reservoir properties were small within each sedimentary micro-facies, only mouth bar and mid-channel bar had slightly better physical properties (Table 1), and favorable sedimentary facies features were insignificantly manifested.

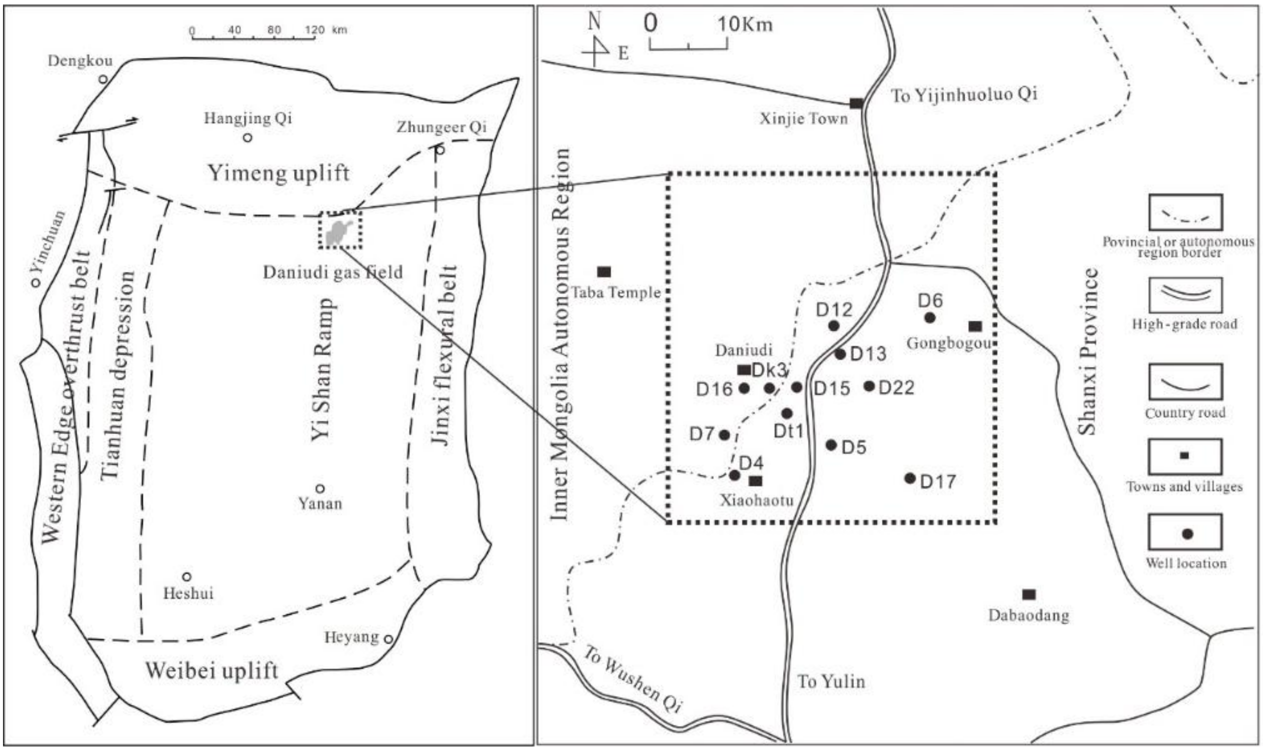

Figure 1. Tectonic units of Ordos Basin and location of the Daniudi gas field (modified from Xu et al, 2011; Hao et al, 2006).

Table 1 Reservoir properties of different sedimentary microfacies of Upper PaleozonicDaniudi gas field, Ordos Basin.

Sedimentary microfacies	Braided channel	Mouth bar	Underwater braided channel	Mid-channel bar
N	877	121	687	594
Φ(%)	5.99	7.49	6.4	7.18
K ($\times 10^{-3} \mu m^2$)	0.475	0.508	0.448	0.508

Notes: N- number of data points; Φ- average porosity; K- average permeability.

Microscopically, studies over the relationships between grain size and sorting coefficient versus reservoir propertiesindicate that, the coarser the grain size of rock, the better the physical properties (Fig. 2a);and reservoir porosity was the best at sorting coefficient of 1.6–2.0 and tended to get worse significantly at sorting coefficient greater than 2.0(Fig. 2b).Given the porosity controlling effect of sedimentary micro-facies is insignificant while controlling effects of rock grain size and sorting are stronger, this study focuses on reservoir porosity controlling effects of microscopical parameters including rock grain size and sorting.

2.2 Diagenesis Factors

Clastic reservoir researches reveal that, the availability of reservoir is a depositional problem, there is a reservoir where there is a sand body, but reservoir quality is morediagenesis-dependent (Zhang et al, 2010). Having knowledge about effect of diagenesis on reservoir porosity is important to defining for-mation of a favorable reservoir. For development of the Upper Paleozoic tight sandstone reservoir in Daniudi gas field, constr-uctive diagenesis consists of dissolution and fracturing, and dis-ruptive diagenesis is made up of compaction and cementation.

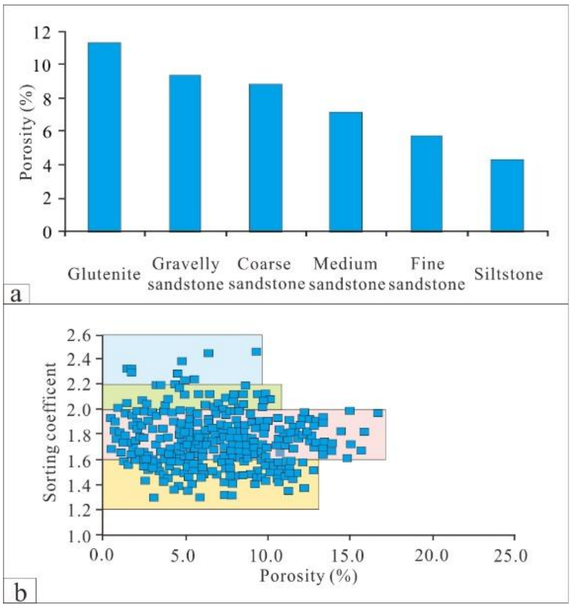

Figure 2. Relationship between porosity and rock properties in the Upper Paleozoic reservoir of Daniudi gas field, Ordos Basin.

a. Histogram of porosity versus grain size of the rock in Lower Shihezi Formation, Ordos Basin; b. Sorting–porosity cross plot for Upper Paleozoic rock in Daniudi gas field, Ordos Basin.

2.2.1 Compaction

Compaction phenomenon is relatively pervasive in tight sandstone reservoirs, microscopic qualitative studies show that the reservoir particles are in an ascending order of compaction extent as compaction-deformed plastic particles, directional aligned major axes of clastic particles, skeleton particles with line contact or asperity contact (Fig. 3a), and rigid particles fractured under pressure (Fig. 3b). Quantitatively, apparent compaction rate can be used to characterize compaction strength.

Apparent compaction rate=(primary porosity –intergr-anular volume)/primary porosity×100%

where, intergranular volume=intergranular porosity + cement (Houseknecht, 1987), and primary porosity was calcu-lated using Trask sorting coefficient method (Scherer, 1987),

$$\text{Primary porosity} = 20.91 + (22.9/S_o)$$

In which S_o is Trask sorting coefficient, $S_o = (P_{25}/P_{75})^{0.5}$. P_{25} and P_{75} are particle diameters corresponding to 25 % and 75 % at grain size probability cumulative distribution curve (Scherer, 1987), and grain size data were all obtained from microscopic inspection of rock thin sections, particle diameter statistics were aided by image analysis software.

As calculated, compaction extent of the Carboniferous-Permian tight sandstone reservoir in Daniudi gas field was quite uneven, with apparent compaction rate being 17.4–97 %, averaging 71.5 %. And the rate of Taiyuan Formation was 25–91.6 %, averaging 77.9 %. Shanxi Formation was 17.4–92.6 %, averaging 63.4 %，and that of Lower Shihezi Formation was 26–97 %, averaging 72.8 %. According to compaction extent classification (Hu et al, 2007; Zhang, 2014), the study area was regarded to have moderate-to-strong overall compaction.

Compaction is an important factor of reservoir tightness, and to find causes of such variations, it is necessary to further study compaction mechanism. Studies indicate that, a number of factors influence compaction, such as rock type, rigid particle content, particle size, sorting coefficient, cement content, abnormal fluid pressure, burial mode and acting time (Wei et al, 2016;Wilkinson and Haszeldine, 2011; Xiao et al, 2011; Shou et al, 2006; Warren and Pulham, 2001). Manyscholars use normal compaction curves they built to conduct mechanical compaction correction of porosity evolution process, or utilized the compaction curves in combination with porosity envelopes to judge development of abnormal porosity zone, but most of them did not consider petrophysical properties (lithology, grain size, sortability, etc.), except that some scholars conducted such discussions (Zhang et al, 2014;Cao et al, 2013; Zhang et al, 2011; Zhang et al, 2004) or simulated compac- tion mechanism (Xi et al, 2015;Cao et al, 2011; Liu et al, 2006;).

In order to take petrological characteristic variation into full account and discuss compaction mechanism more precisely, the authors established normal compaction curves in terms of three petrological parameters, namely, lithology, grain size and sorting. To eliminate the effects of cementation and dissolution as much as possible, data points corresponding to cement content less than 6 % (reservoir porosity is less affected under such condition) and undeveloped dissolution were selected to calculate normal compaction curves. As can be known from particle sorting coefficient versus porosity cross plot (Fig. 2b), sorting coefficient of 1.6–2.0 is more favorable to preservation of reservoir porosity; therefore, data points at sorting coefficient of 1.6–2.0 were selected to establish normal compaction curves as a function of lithology and grain size.As can be known from pore decreasing rate (Δ*Φ*) of sandstone at the same depth interval under normal compaction condition (Fig. 4), compaction resistance of quartz sandstone was stronger than that of litharenite, and the coarser the grain size of rock, the stronger the compaction resistance. In addition,normal compaction curves were established for sandstones as a function of grain size and sorting coefficient, and it is found that, given the same burial depth, the coarser the grain size, the better the petrophysical properties (Fig. 5a), while sandstones of different sorting coefficients had relatively prominent difference in normal compaction curves (Fig. 5b). Therefore, if considered from perspectives of grain size and sorting coefficient only, the variational patterns shown are still similar, even though error increases somewhat. In light of research operability, porosity evolution could be well handled just from perspectives of grain size and sorting coefficient.

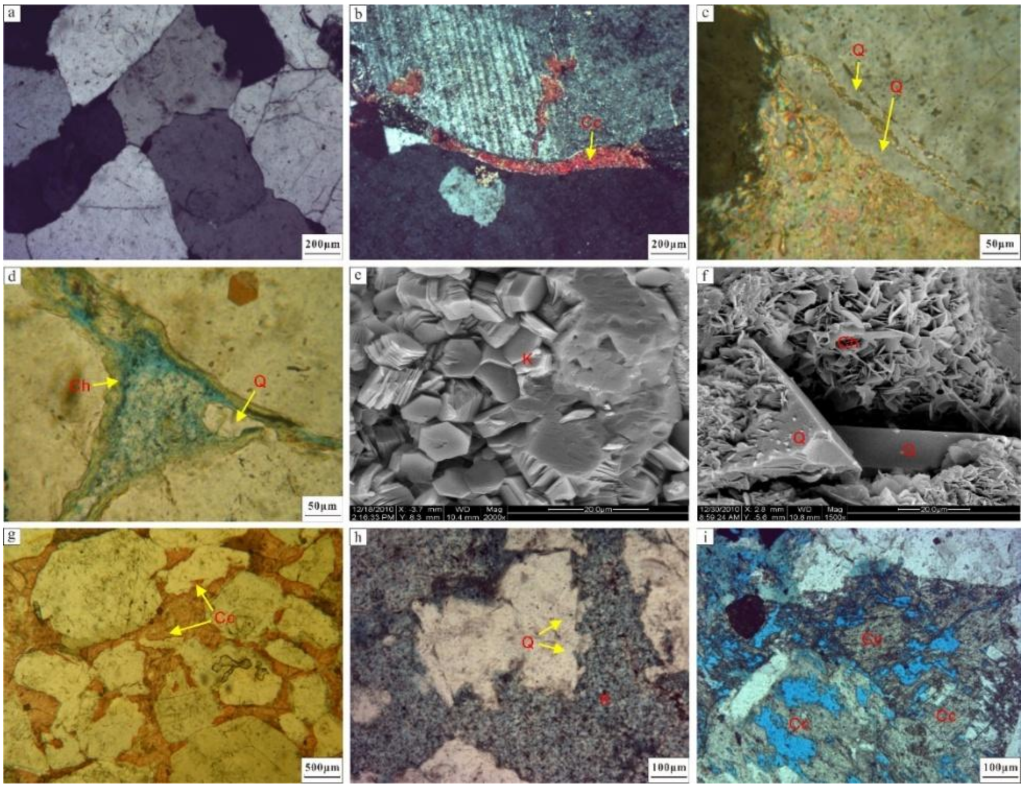

Figure 3. Diagenesis types of the Upper Paleozoic reservoir in Daniudi gas field, Ordos Basin.

(a) Closely-compacted particles in asperity contact, Da-18 Well, 2780.3m, C3t2, ×50(+); (b) compaction-ruptured quartz particles, Da-8 Well, 2715.75m, C3t2, ×50(+), Cc-carbonate cement; (c) two phase enlargement edge of quartz (Q), Da-28 well, 2549.35m, P1x1, ×200; (d) authigenic chlorite film (ch) growing around quartz particle surface, authigenic quartz particles developed between particles (Q), Da-28 Well, 2490.45m, P1x1, ×200(-); (e) authigenic kaolinite appears pseudohexagonal flaky, with intercrystal pores developed, DK-13 Well, 2681.0m, P1x2, ×2000 (SEM); (f) intergranular pores filled with flaky chlorite and authigenic quartz particles, Da-69 Well, 2539.28m, P1x3, ×1500 (SEM); (g) Cc-calcite cement , metasomatic clastic particles, Da-9 Well, 2671.4m, C3t2, ×20(-); (h) enlargement edge dissolution of quartz (Q), DK-13 Well, 2682.13m, P1x3, ×100(-); (i) Cc-carbonate cement dissolution , Da-8 Well, 2719.4m, C3t2, ×100(-).

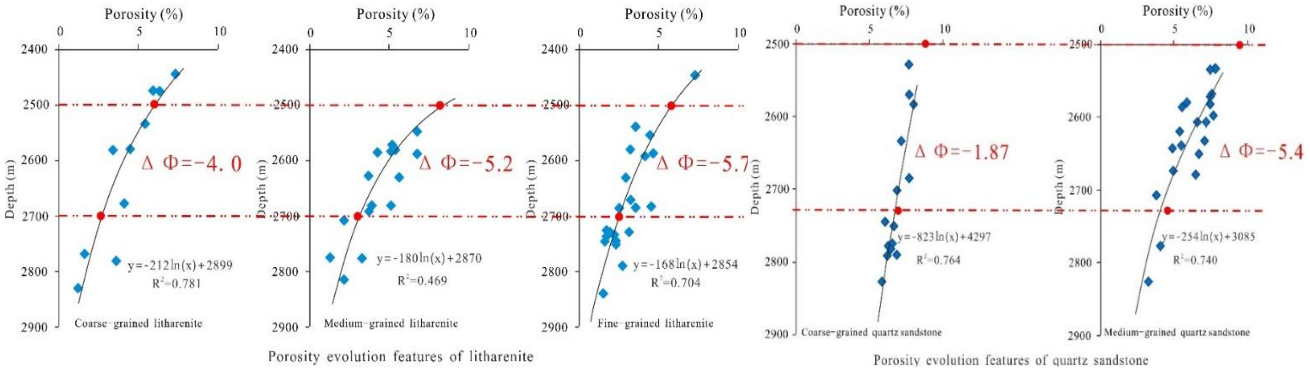

Figure 4. Porosity evolution curves of different types of Upper Paleozoic rocks inDaniudigasfield,Ordos Basin(sorting coefficient 1.6–2,cement content ≤6 %) (modified from Zhang, 2014).

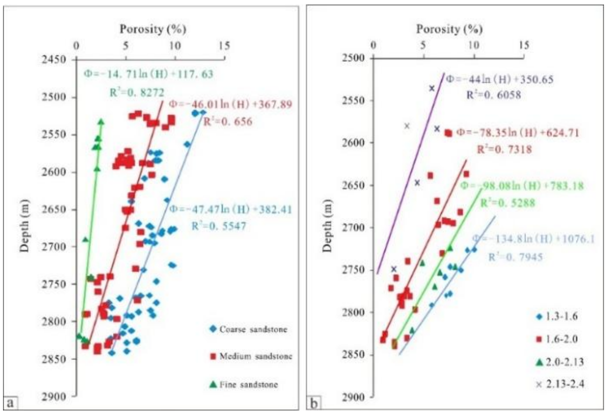

Figure 5. Porosity evolution curves of Upper Paleozoic formation of Daniudigasfield,Ordos Basin in different depositional settings (modified from Zhang, 2014) (a) Evolution plots of porosity versus burial depth for reservoirs with different grain size fractions; (b) Evolution plots of porosity versus burial depth for reservoirs with different sorting coefficients.

Lithofabric features have much impact on compaction, and reservoir porosity is influenced by grain size, sorting coefficient and burial depth under normal simple burial condition. Therefore, by calculating weighting factors of grain size and sorting coefficient with respect to porosity, we can obtain a calculation formula of porosity Φ_1 under normal burial compaction condition (calculated through grey relational analysis, influence coefficients of grain size and sorting with respect to porosity were 0.50142 and 0.49858 respectively, with detailed description of the method shown below):

$$\Phi_1 = 0.50142 \times \begin{cases} -14.7\ln(H) + 117.63 \ \ (fs) \\ -46.01\ln(H) + 367.89 \ \ (ms) \\ -47.47\ln(H) + 382.41 \ \ (cs) \end{cases}$$

$$+0.49858 \times \begin{cases} -134.8\ln(H) + 1076.1 \ \ (s1) \\ -78.35\ln(H) + 624.71 \ \ (s2) \\ -98.08\ln(H) + 783.18 \ \ (s3) \\ -44\ln(H) + 350.65 \ \ (s4) \end{cases}$$

Here, fs means fine sandstone; ms means medium sandstone; cs means coarse sandstone; s1, s2, s3 and s4 represent sorting value “1.3–1.6”, “1.6–2.0”, “2.0–2.1”, “2.1–2.4” respectively.

2.2.2 Cementation

Types of cementation presented in the study area mainly include siliceous cementation, carbonate cementation and clay mineral cementation. In quantity, siliceous and carbonate cements were the most abundant and had multiple phases (Fig. 3c), followed by clay mineral, and other authigenic minerals were of lower content. In occurrence, siliceous cement mainly occurred in the form of secondary enlargement edge (Fig. 3c), with developed authigenic quartz particles being observed too (Figs. 3d and 3f). Authigenic kaolinite had generally good crystal form, filling intergranular pores in pseudohexagonal flakes (Fig. 3e). It was common to see chlorite coating distributed over particle rims (Fig. 3d), and it was also observed that minor amount of foliated chlorite filled in the intergranular pores (Fig. 3f). Carbonate cement has double effects on reservoir properties: on one hand, cements deposited among particles directly occupy intergranular pores, enabling worse reservoir properties; and on the other hand, due to uneven distribution, cements formed in early stage can serve as skeleton particles having certain compaction resistance, which alleviate compaction effect and are likely to provide material basis for dissolution in late stage, thereby exerting certain pore-preserving effect (Lin et al, 2011;Xu et al, 2011; Zhang et al, 2008).

2.2.3 Metasomatism

In the Upper Paleozoic tight sandstone reservoir of Daniudigas field, common metasomatic processes mainly occurred among quartz, carbonate and clay minerals, such as calcite-metasomatizedclastic particles (Fig. 3g) and ferrocalcite-metasomatizedcalcite. Besides, as well as clay mineral-metasomatizedquartzsecondary enlargement edge, ferrocalcite–metasomatizedcryptocrystallinesilicalite clast, and calcite–metasomatizedclay mineral (Tang et al, 2007).

2.2.4 Dissolution

Multiple dissolution occurred in tight sandstone reservoir of the study area due to diagenetic environment alteration, and the secondary pores formed could improve reservoir properties well. What commonly seen are secondary enlargement edgedissolution of quartz (Fig. 3h), dissolution of quartzparticles and lithic fragmentparticles, and dissolution of carbonateparticles (Fig. 3i); among which, quartz dissolution and lithic fragmentdissolution were predominant in the area, while carbonateparticledissolution was less common. As occurring dissolution is mainly dissolution of quartzparticles and secondary enlargement edge of quartz (Qiu et al, 2015), it’s found in data points with relatively developed dissolution that secondary plane porosity of dissolution has certain positive correlation with quartz content(Fig. 6). On the other hand, alteration of aluminosilicatemineral is a process of increasing pores. For example, feldsparkaolinization and illitization is a volume-decreasing process and will form additional pore space (Zhang, 2007; Huang et al, 2009), therefore, such alterations have constructive effects on properties of tightsandstonereservoir. Various types of dissolution pores improved poreconnectivity effectively, so dissolution is an important way improvingreservoir properties in the context of tightening.

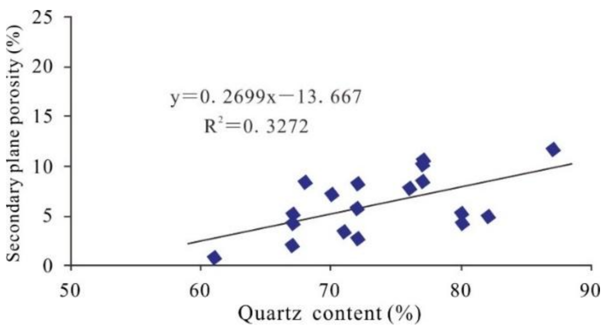

Figure 6. Relationship between quartz content and secondary plane porosity in the dissolution zone of Upper Paleozoic in Daniudigasfield,Ordos Basin (modified from Zhang, 2014).

In summary of the above diagenesis analysis, the Upper Paleozoic reservoir of Daniudigas field underwent intense diagenetic alteration, where compaction and cementation are main causes of porosity reduction, while dissolution and partial alteration improved reservoir properties to some extent.

3 DISCUSSION

3.1 Influence degree of each factor on porosity

Qualitative analysis of each factor’s influence on physical properties is a common way discussing main controlling factors of physical properties, however, influence degree of each factor on reservoir properties is still less studied, lacking quantitativedata to calculate the degree. Based on analysis of property controlling factors of the Upper Paleozoic tight sandstone reservoir in Daniudi gas field, this paper quantifies the influence degree of each parameter on reservoir porosity. Comprehensive evaluation of various influence factors yields a comprehensive calculation formula about porosity:$\Phi = \sum_i^n a_i X_i$, where, Φ is the ultimately calculated porosity of the reservoir, n is the number of total reservoir parameters selected, a_i is weighting factor of a selected parameter, X_i is relational expression between a selected parameter and porosity (Zhang, 2014). Weighting factor is an indicator of influence degree of a selected parameter on reservoir properties, and can be determined in a number of ways, such as factor analysis (Lüet al, 2006), analytic hierarchy process (Wang et al, 2003), and grey relational analysis (Liu et al, 2005; Chen et al, 2014). Grey relational analysis is a classicalmethod, relatively objective and easy to operate. Thus, grey relational analysis was employed to solve for weighting factor of each property influence factor of tightsandstonereservoir as per the following computation principle (Liu et al, 2005):

$$\mathrm{X}^{(0)} = \begin{bmatrix} x_1^{(0)}(0) & x_1^{(0)}(1) & \cdots & x_1^{(0)}(m) \\ x_2^{(0)}(0) & x_2^{(0)}(1) & \cdots & x_2^{(0)}(m) \\ \vdots & \vdots & \cdots & \vdots \\ x_n^{(0)}(0) & x_n^{(0)}(1) & \cdots & x_n^{(0)}(m) \end{bmatrix} \quad (1)$$

$$\mathrm{X}_t^{(1)}(i) = \mathrm{X}_t^{(0)}(i) / \mathrm{X}_1^{(0)}(i),\ t = 1, 2\cdots, n; i = 1, 2\cdots, m \quad (2)$$

Here $X_n(m)$ represents the nth data point, and each data point has $m$factorparameters.△max and △min are absolute extrema of the difference between each subfactor and the principalfactor at the same observation time point.

$$\xi_{i,0} = \frac{\Delta\min + \rho\Delta\max}{\Delta_t(i,0) + \rho\Delta\max},\ i = 1, 2\cdots, m \quad (3)$$

where, ρ is grey relational resolution factor used to adjust magnitude of numerical difference between influence factors, ranging between 0 and 1 (Liu et al, 2005), the smaller the ρ, the greater the resolving power, its value is normally set as 0.5.

$$r_{i,0} = \frac{1}{n}\sum_{t=1}^{n}\xi_{i,0} \quad (4)$$

$$a_i = r_i \Big/ \sum_{i=1}^{m} r_{i,0} \quad (5)$$

As factors of a system have different physical meanings and original variable series has different dimensions, all data have to be preliminarily nondimensionalized to guarantee comparability among parameters. Common nondimensionalization methods include initial value, maximum value and mean method (Liu et al, 2005). In this paper, nondimensionalization is done using initial value method. Various selected parameters (1) were initialized using Eq. (2). Then relational coefficients were calculated using Eq. (3), grey relational grades were calculated using Eq. (4), and finally, weighting factors of each parameter were calculated using Eq. (5).

Based on geological data configuration, sixrelatively independent major parameters were selected to reflect primary geological information and diagenetic alterationinformation influencing reservoir properties in a relatively comprehensive way. Specifically, we selected parameters representative of sedimentary environment-median grain size and sorting coefficient, parameters representative of reservoir lithological characteristics-quartz content and clay mineral content, parameter representative of diagenesis-cement content, and parameter representative of compaction degree-burial depth. With porosity as principal factor (principal series), median grain size, sorting coefficient, quartz content, clay mineral content, burial depth and cement content serve as subfactors. According to a porosity calculation formula under multi-factor comprehensivecontrol, present porosity Φ was obtained:

$\Phi = a$×(relational formula between grain size and porosity)+b×(relational formula between sorting coefficient and porosity)+c×(relational formula between depth and porosity)+d×(relational formula between quartz content and porosity)+e×(relational formula between clay mineral content and porosity)+f×(relational formula between cementation and porosity)

In which, a, b, c, d, e and f are weighting factors to solve for (Table 2).

Substituting weighting factors into the above formula yields porosity:

Φ=0.17264×(relational formula between grain size and porosity)+0.17167×(relational formula between sorting coefficient and porosity)+0.16063×(relational formula between depth and porosity)+0.17599×(relational formula between quartz content and porosity)+0.14462×(relational formula between clay mineral content and porosity)+0.17445×(relational formula between cementation and porosity)

$$\Delta_{\max} = \max_i \max_t \left| X_t^{(1)}(i) - X_t^{(1)}(0) \right|$$
$$\Delta_{\min} = \min_i \min_t \left| X_t^{(1)}(i) - X_t^{(1)}(0) \right|$$

Quantitative computation of influence degree of each factor on porosity enabled reservoir porosity solving to be operable. Nonetheless, more important objective of controlling factor study is to predict favorable reservoir. Therefore, it is necessary to establish a porosityprediction model based on controlling factor study.

3.2 Comprehensive Porosity Prediction for tight sandstone reservoir

During geohistorical period, reservoir properties were subjected to extremely complex influence of various geologic factors, it is impossible to recover reservoir property evolution process in a completely precise way. During discussion in this paper, pores are regarded as superposition of two portions, one portion is pores preserved under normal compaction condition, and the other portion is pores contributed by diagenesis to the reservoir, so that a quantitative porosity prediction model was established. To make the prediction model brief and operable, following assumptions were thus set as follow:

(1) The present porosity is deemed as algebraic sum of normal compactionporosity and diagenesiscontribution to porosity;

(2)In contribution to porosity, cement and authigenicclay mineral occupy pore volume leading to reduced porosity, so their contributions were negative values; dissolution is able to improve porosity, thus its contribution is positive value; sorting coefficient and grain size are parameters concerning normal co-mpaction curve, used to solve for normal compaction porosity;

(3) Dissolution is hard to quantify, and as there is certain positive correlation between quartz content and percentage of secondary dissolution pores and quartz dissolution is the main type of dissolution, the weighting factor of quartz content was used to replace dissolution weighting factor, and their relational expression was used to approximately solve for dissolution pore percent.

Under the above predetermined conditions, simply by calculating weighting factors of parameters concerning normal compaction porosity Φ_1 (depth, sorting coefficient, and grain size), parameter having pore enlargement effect (dissolution) and parameters having pore decreasing effect (clay mineral content, and cement) with respect to porosity, one can obtain comprehensive calculation formula of porosity Φ:

$$\Phi = c\times\Phi_1 + d\times(\Phi_1 + \Phi_{\text{dissolution}}) + \mathrm{e}\times(\Phi_1 - \Phi_{\text{clay}}) + f\times(\Phi_1 - \Phi_{\text{cementation}})$$

where, $\Phi_{\text{dissolution}}$ is percent of dissolution enlarged pores, Φ_{clay} is percent of pores occupied by authigenic clay mineral, and $\Phi_{\text{cementation}}$ is percent of cement-occupied pores.

With the latter four parameters in Table 2 as an entirety, percent of each parameter was calculated, which was the very weighting factor of each factor, and grain size and sortingcoefficient were thus calculated, too, i.e., 0.50142 and 0.49858 respectively. Therefore, the porosity calculation formula for the Upper Paleozoic reservoir at Daniudi is as follows:

Table 2 Comprehensive quantitative evaluation data of the Upper Paleozoic tight sandstone reservoir in Daniudi gas field, Ordos Basin.

Well No.	M value (mm)	Sorting coefficient	Clay mineral content (%)	Depth (m)	Cement content (%)	Quartz content (%)
Da-2 Well	1.00000	1.00000	1.00000	1.00000	1.00000	1.00000
Da-14 Well	0.97386	0.79610	0.52653	0.74097	0.94791	0.73461
Da-14 Well	0.75511	0.88461	0.97906	0.97511	0.65250	0.97825
Da-14 Well	0.99818	0.92225	0.98921	0.91013	0.84751	0.85276
Da-14 Well	0.85303	0.89494	0.90943	0.91654	0.63424	0.96697
Da-3 Well	0.93500	0.95685	0.81497	0.99242	0.70528	0.98405
Da-3 Well	0.85439	0.84915	0.80154	0.88065	0.99777	0.82865
Da-3 Well	0.50246	0.73336	0.89950	0.72106	0.68846	0.68631
Da-3 Well	0.98014	0.81076	0.74447	0.89721	0.71543	0.95017
Da-3 Well	0.94288	0.89850	0.85942	0.98927	0.70975	0.91365
Da-3 Well	0.92639	0.74670	0.66841	0.82482	0.63929	0.88578
Da-3 Well	0.86959	0.94462	0.86507	0.90842	0.82148	0.86594
Da-3 Well	0.81142	0.74227	0.70328	0.76854	0.72411	0.83070
Da-3 Well	0.99841	0.86191	0.68123	0.79040	0.60534	0.83029
Da-3 Well	0.55510	0.86864	0.75451	0.91312	0.69059	0.97695
Da-3 Well	0.86037	0.87308	0.89090	0.78652	0.49778	0.75492
Da-3 Well	0.75826	0.69394	0.69155	0.66091	0.33333	0.69329
Datan-1 Well	0.69159	0.94861	0.87488	0.87007	0.94211	0.84272
Datan-1 Well	0.79227	0.89096	0.80384	0.92864	0.64204	0.82555
Datan-1 Well	0.77879	0.77187	0.60253	0.81997	0.73541	0.80304
Datan-1 Well	0.80173	0.67204	0.62789	0.70696	0.53417	0.67904
Datan-1 Well	0.74249	0.65452	0.61750	0.69386	0.52102	0.67014
Datan-1 Well	0.74890	0.67058	0.63144	0.71166	0.55711	0.68660
Datan-1 Well	0.96548	0.89315	0.76430	0.97972	0.69219	0.93911
Datan-1 Well	0.61550	0.70440	0.62719	0.76545	0.61407	0.80527
Datan-1 Well	0.76576	0.67209	0.65357	0.74025	0.54242	0.71656
Grey relational grade	0.82604	0.82138	0.76855	0.84203	0.69197	0.83467
Weighting factor	0.17264	0.17167	0.16063	0.17599	0.14462	0.17445

$\Phi = 0.26840\times\Phi_1 + 0.26605\times(\Phi_1 + \Phi_{\text{dissolution}}) + 0.24498\times(\Phi_1-\Phi_{\text{clay}})+0.22057\times(\Phi_1-\Phi_{\text{cementation}})$,
that is, $\Phi = \Phi_1 + 0.26605\times\Phi_{\text{dissolution}} - 0.24498\times\Phi_{\text{clay}} - 0.22057\times\Phi_{\text{cementation}}$;where$\Phi_1$ is normal compaction porosity, and substituting expression of Φ_1 into algebraic expression of Φ, we get:

$$\Phi = 0.50142\times\begin{cases}-14.7\ln(H)+117.63 \quad (fs)\\ -46.01\ln(H)+367.89 \quad (ms)\\ -47.47\ln(H)+382.41 \quad (cs)\end{cases}$$

$$+0.49858\times\begin{cases}-134.8\ln(H)+1076.1 \quad (s1)\\ -78.35\ln(H)+624.71 \quad (s2)\\ -98.08\ln(H)+783.18 \quad (s3)\\ -44\ln(H)+350.65 \quad (s4)\end{cases}$$

$$+0.26605\times\Phi_{\text{dissolution}}-0.24498\times\Phi_{\text{clay}}-0.22057\times\Phi_{\text{cementation}}$$

Here, fs means fine sandstone; ms means medium sandstone; cs means coarse sandstone; s1, s2, s3 and s4 represent sorting value “1.3–1.6”, “1.6–2.0”, “2.0–2.1”, “2.1– 2.4” respectively.

In the study area, Member 1 of the lower Permian Shanxi Formation (Shan-1 member in short) has many data points and complete reservoir parameterdata, reservoir property parameters of Shan-1 member were substituted into the calculation formula, and comparison between the calculated result and measured porosity shows that most errors were less than 15% and only about 25% of data points had error over 15%, that is, 75% of the data can be corresponded to each other(Table 3). Therefore, the porosity calculation formula eventually obtained under multi-factor comprehensive control hascertain reference value.

4 CONCLUSION

(1)The Upper Paleozoic tight sandstone reservoir in Daniudigas field, Ordos Basin has many property controlling factors, in which compaction and cementation are main causes of porosity reduction, while dissolution and partial alteration improved reservoir properties to some extent.Compaction is a key factor of reservoir tightness and its variability is mainly manifested in grain size fraction and sorting. Under normal compaction condition (cement content less than 6% and with no dissolution), change of porosity with burial depth was well correlated with rock composition, grain size fraction and sorting.

(2) Influence degree of each factor on reservoir porosity was quantified by grey relational analysis, grey relational grade and weighting factor of each parameter(median grain size, sorting coefficient, clay mineral content, depth, cement content, and quartz content) with respect to reservoir porosity were calculated, and present porosity was deemed as superposition of normal compactionporosity and contribution of diagenetic alteration to porosity, so as to obtain reservoir porosity calculation formula under multi-factor control:

$$\Phi = 0.50142\times\begin{cases}-14.7\ln(H)+117.63 \quad (fs)\\ -46.01\ln(H)+367.89 \quad (ms)\\ -47.47\ln(H)+382.41 \quad (cs)\end{cases}$$

$$+0.49858\times\begin{cases}-134.8\ln(H)+1076.1 \quad (s1)\\ -78.35\ln(H)+624.71 \quad (s2)\\ -98.08\ln(H)+783.18 \quad (s3)\\ -44\ln(H)+350.65 \quad (s4)\end{cases}$$

$$+0.26605\times\Phi_{\text{dissolution}}-0.24498\times\Phi_{\text{clay}}-0.22057\times\Phi_{\text{cementation}}$$

fs means fine sandstone; ms means medium sandstone; cs means coarse sandstone; s1, s2, s3 and s4 represent sorting value “1.3–1.6”, “1.6–2.0”, “2.0–2.1”, “2.1– 2.4” respectively.

(3) Such qualitative analysis through precise quantitative analysis helps quantifythe influences of main controlling fact-ors of reservoir properties and their interaction on reservoir properties, and can provide reference for geological log interpretation model and plays a guiding role in analysis and prediction of reservoir “sweet spots”.

ACKNOWLEDGMENTS

This study was supported by the China National Key Research Project (No. 2011ZX05009-002), Joint KeyPetrochemical Project Funded by National Natural Science Foundation of China (No. U1262203) andProject of Graduate Innovation Program in China University of Petroleum (East China) (No.YCX20150007). The authors thank Research Institute of Expl- oration and Development, North-ChinaBranch Company, SINOPEC, for some data preparation.The final publication is available at Springer via http://dx.doi.org/10.1007/s12583-016-0935-2.

REFERENCES CITED

Cao, Y.C., Xi, K.L., Wang, Y.Z., et al., 2013. Quantitative Research on Porosity Evolution of Reservoirs in Member 4 of Paleogene Shahejie Formation in Hexiwu Tectonic Zone of Langgu Sag, Jizhong Depression. *Journal of Palaeogeograhy*, 15(5): 593–604 (in Chinese with English Abstract)

Cao, Y.C., Xi, K.L., Wang, J., et al., 2011. Preliminary Discussion of Simulation Experiments on the Mechanical Compaction and Physical Property Evolution of Sandstones. *Geoscience*, 25(6): 1152–1158 (in Chinese with English Abstract)

Cao, Y.C., Yuan, G.H., Wang, Y.Z., et al., 2012. Genetic Mechanisms of Low Permeabillity Reservoirs of Qingshuihe Formation in Beisantai area, Junggar Basin. *Acta Petrolei Sinica*, 33(5): 758–771 (in Chinese with English Abstract)

Chen, S.Y., Bi, M.W., Liu, H.M., et al., 2014. Quantitative Prediction Model for the Dongying Delta-Fluxoturbidite Depositonal System in the Middle E_S^3 Period. *Acta Sedimentological Sinica*, 32(5): 921–929 (in Chinese with English Abstract)

Du, W., Jiang, Z.X., Zhang, Y., et al., 2013. Sequence Stratigraph and Sedimentary Facies in the Lower Member of the Permian Shanxi Formation, Northeastern Ordos Basin, China. *Journal of Earth Science*, 24(1): 75–88Fu, H.J., Tang, D.Z., Xu, H., et al., 2012. Characteristics of Tight Sandstone Reservoir and Accumulation Process of Gas Pool. *Fault-Block Oil & Gas Field*, 19(1): 47–50 (in Chinese with English Abstract)

Guo, Z.H., Zhao, Y.C., 2010. Logging Evaluation of Tight Sandstone Gas Reservoir in He-2 Member of Daniudi Gas Field. *Natural Gas Geoscience*, 21(1): 87–94 (in Chinese with English Abstract)

Hao, S.M., Hui, K.Y., Li, L., 2006. Reservoiring features of Daniudi low-permeability gas field in Ordos basin and its exploration and development technologies. *Oil & Gas Geology*, 27(6): 762–768 (in Chinese with English Abstract)Hou, R.Y., Liu, Z.Q., 2012. Reservoir Evaluation and Development Strategies of Low-Permeability Tight Reservoir in Daniudi Gas Field in the Ordos Basin. *Oil & Gas Geology*, 33(1): 118–128 (in Chinese with English Abstract)

Table 3 Checking table of porosity for the Upper Paleozoic tight sandstone reservoir in Daniudigasfield,Ordos Basin.

Well No.	Median grain size (mm)	Sorting coefficient	Clay mineral (%)	Depth (m)	Cement content (%)	Quartz content (%)	Description	Primary porosity (%)	Calculated porosity (%)	Error (%)
Da-14 Well	0.480	1.97	7	2791.38	1	88	Coarse-grained quartz sandstone	6.3	6.91	10.6
Da-3 Well	0.400	1.90	6	2775.81	0	74	Medium-grained litharenite	6.2	6.88	11.0
Da-3 Well	0.480	2.19	12	2776.54	5	85	Coarse-grained lithic quartz sandstone	4.6	5.07	10.3
Da-3 Well	0.400	1.72	14	2790.7	0	89	Coarse-grained lithic quartz sandstone	5.1	5.51	8.1
Da-3 Well	0.450	1.97	12	2791.96	0	89	Coarse-grained lithic quartz sandstone	5.6	5.96	6.4
Da-3 Well	0.690	1.80	5	2795.55	3	70	Over coarse-grained feldsparthiclitharenite	6.3	5.53	12.2
Da-3 Well	0.550	1.75	9	2806.09	3	88	Coarse-grained lithic quartz sandstone	4.9	5.50	12.3
Da-3 Well	0.320	1.60	9	2819.16	0.5	73	Medium-grained litharenite	4.1	4.55	11.0
Da-3 Well	0.570	1.63	2	2822.86	1	85	Coarse-grained lithic quartz sandstone	7.5	6.90	8.0
Da-3 Well	0.500	1.61	10	2824.3	2	80	Coarse-grained litharenite	6.1	4.31	29.3
Da-3 Well	0.670	1.84	6	2826.62	1.5	89	Gravelly over Coarse-grained lithic quartz sandstone	6.1	5.98	2.0
Da-3 Well	0.500	1.92	8	2827.2	1.5	84	Gravelly coarse-grained lithic quartz sandstone	5.1	5.11	0.2
Da-3 Well	0.680	2.47	0	2829.67	1	85	Gravelly over coarse-grained lithic quartz sandstone	9.2	7.17	22.1
Datan-1 Well	0.330	2.00	3	2745.92	2	70	Gravelly medium- and coarse-grained litharenite	8.1	7.87	2.8
Datan-1 Well	0.325	2.38	1	2739.25	0.5	66	Gravelly medium-grained litharenite	10.1	8.63	14.6
Datan-1 Well	0.400	2.11	10	2741.28	2	58	Coarse-grained litharenite	4.8	5.45	13.5
Datan-1 Well	0.380	2.16	0	2742.91	1.5	71	Gravelly coarse- and medium-grained litharenite	12.8	8.89	30.6
Datan-1 Well	0.360	2.20	0	2743.3	2	77	Gravelly coarse-grained litharenite	13.4	9.20	31.4
Datan-1 Well	0.515	1.84	0	2744.56	6	81	Gravelly coarse-grained litharenite	11.5	8.56	25.6
Datan-1 Well	0.285	1.70	0	2746.84	2	66	Medium-grained litharenite	9.6	8.29	13.7
Datan-1 Well	0.400	1.86	7	2786.46	1	57	Gravelly coarse-grained litharenite	6.3	4.84	23.1
Datan-1 Well	0.300	1.88	0	2787.47	1	57	Medium-grained litharenite	7.0	6.53	6.8
Datan-1 Well	0.400	1.76	1	2789.03	1	74	Coarse-grained litharenite	8.6	7.45	13.3
Datan-1 Well	0.370	1.81	0	2790.02	2	72	Coarse- and medium-grained litharenite	8.4	7.30	13.1
Datan-1 Well	0.350	1.68	0	2791.1	2.5	74	Medium-grained litharenite	7.7	7.30	5.2
Datan-1 Well	0.400	1.76	1	2835.14	0	73	Medium-grained litharenite	5.5	6.11	11.1
Datan-1 Well	0.400	2.12	0	2835.67	0	74	Medium-coarse-grained litharenite	7.9	6.41	18.9
Datan-1 Well	0.400	1.89	5	2838.71	0	65	Coarse-grained litharenite	5.1	4.44	13.0
Datan-1 Well	0.300	1.82	0	2840.41	0	61	Medium-grained litharenite	5.0	5.32	6.4
Datan-1 Well	0.250	1.50	6	2841.19	0	56	Medium-grained litharenite	3.2	3.47	8.4
Datan-1 Well	0.500	1.64	10	2841.54	0	57	Coarse-grained litharenite	3.6	2.55	29.2

Houseknecht, D.W., 1987. Assessing the Relative Importance of Compaction Processes and Cementation to Reduction of Porosity in Sandstones. *AAPG Bulletin*, 71(6): 633–642.

Hu, H.Y., Peng, S.M., Lu, C.H., et al., 2007. Diagenetic Reservoir Facies and Reservoir Space Evolution of the Quantou Formationof Lower Cretaceous in Xinli Oilfield, Jilin Province. *Journal of Palaeogeograhy*, 9(1): 97–106 (in Chinese with EnglishAbstract)

Hu, H.Y., Zeng, Z.P., Liu, J.Z., 2015. Key Elements Controlling Oil Accumulation within the Tight Sandstones. *Journal of EarthScience*, 26(3): 328–342

Hu, L.N., Zhao, J.Z., 2013. A Discussion on the Determination Way to Effective Thickness of TIGHT SANDSTONES GAS POOLS. *NaturalGas Geoscience*, 24(1): 69–77 (in Chinese with English Abstract)

Huang, S.J., Huang, K.K., Feng, W.L., et al., 2009. Mass Exchange among Feldspar, Kaolinite and Illite and Their Influences onSecondary Porosity Formation in Clastic Diagenesis: A Case Study of the Upper Paleozoic Ordos Basin and Triassic XujiaheFormation, Western Sichuan Sag. *Geochimica*, 38(5): 498–506 (in Chinese with English Abstract)

Jiang, Z.X., Xu, J., Wang, G.T., 2012. The Discovery and Significance of a Sedimentary Hiatus within the Carboniferous TaiyuanFormation, Northeastern Ordos Basin, China. *AAPG Bulletin*, 96(7): 1173–1195

Lin, C.M., Zhang, X., Zhou, J., et al., 2011. Diagenesis Characteristics of the Reservoir Sandstones in Lower Shihezi formation fromDaniudi Gas Field, Ordos Basin. *Advances in Earth Science*, 26(2): 212–223. (in Chinese with English Abstract)

Liu, C., Zhang, Q., Pang, G.Y., et al., 2013. Quantitative Prediction of Porosity of Tight Sandstone Reservoir: A Case Study ofChang-8 Member Pay Set in Jiyuan Area, Ordros Basin. *Lithologic Reservoir*, 25(5): 70–75 (in Chinese with English Abstract)

Liu, J.Y., Ma, Z.X., Sun, S.Y., 2008. Present Research Situation and Prospects of Tight Gas-Bearing Sandstone. *Natural GasGeoscience*, 19(3): 316–319 (in Chinese with EnglishAbstract)

Liu, J.Y., Peng, Z.C., Guo, X.B., 2005. Application of Grey Relational Analysis to Reservoir Evaluation: A Case Study of Bei 2 Area,Saertu Oilfield, Daqing. *Petroleum Geology and Recovery Efficiency*, 12(2): 13–15 (in Chinese with English Abstract)

Liu, G.Y, Jin, Z.J., Zhang, L.P., 2006. Simulation Study on Diagenetic Compaction of Clastic Rock. *Acta Sedimentolog- ical Sinica*,24(3): 407–413 (in Chinese with English Abstract)

Luo, Y.M., Liu, W.X., Tan, X.Q., et al., 2007. Diagenesis Evaluation on the Upper Palaeozoic Reservoirs in Daniudi Gas Field,Ordos basin. *Petroleum Geology & Experiment*, 29(4): 384–390 (in Chinese with English Abstract)

Lv, H.H., Ren, M.D., Liu, J.C., et al., 2006. Applicantion of Q-model principal factor analysis and clustering method in evaluationon sandstone reservoirs of the Neogene in Huatugou Oilfield, Qaidam Basin. *Acta Scientiarum Naturalium UniversitatisPekinensis*, 42(6): 740–745 (in Chinese with English Abstract)

Qiu, L.W., Xu, N.N., Zhou, Y.Y., et al., 2015. Dissolution of Quartz in Tight Sandstones of the Daniudi Area, Ordos Basin, and Its Influence on High Quality Reservoirs. *Bulletin of Mineralogy, Petrology and Geochemistry*, 34(1): 38–44 (in Chinese withEnglish Abstract)

Qiu, L.W., Zhou, Y.Y., Gao, Q.S., et al., 2013. Study of Porosity Structure Features of and Its Influences on Carboniferous andPermian Tight Sandstone Reservoir Rock in Daniudi gas field, Ordos Basin and Their Influence Factors. *Petroleum Geology and Recovery Efficiency*, 20(6): 15–18 (in Chinese with English Abstract)

Scherer, M., 1987. Parameters Influencing Porosity in Sandstone, a Model for Sandstone Porosity Prediction.*AAPG Bulletin*, 71(5): 485–491.

Shou, J.F., Zhang, H.L., Shen, Y., et al., 2006. Diagenetic Compaction Mechanisms of Sandstone Reservoirs in China Oil andGas-Bearing Basins. *Acta Petrologica Sinica*, 22(8): 2165–2170 (in Chinese with English Abstract)

Spencer, C.W., 1989. Review of Characteristics of Low-Permeability Gas Reservoirs in Western United States. *AAPG Bulletin*, 73(5): 613–629.

Tang, H.F., Peng, S.M., Zhao, Y.C., et al., 2007. Analysis on Main Controlling Factors of Physical Properties of Tight Sandstone Reservoir. *Journal of Xi'an Shiyou University (Natural Science Edition)*, 22(1): 59–63 (in Chinese with English Abstract)

Wang, J.D., Liu, J.Y., Yu, R.T., et al., 2003. Application of Analytic Hierarchy Process to Reservoir Evaluating. *Journal of DaqingPetroleum Institute*, 27(3): 12–14 (in Chinese with English Abstract)

Warren, E.A., Pulham, A.J., 2001. Anomalous Porosity and Permeability Preservation in Deeply Buried Tertiary and MesozoicSandstones in the Cusiana Field, Llanos Foothills, Colombia. *Journal of Sedimentary Research*, 71(1): 2–14

Wei, W., Zhu, X.M., Meng, Y.L., et al., 2016. Porosity Model and Its Application in Tight Gas Sandstone Reservoir in the Southern Part of West Depression, Liaohe Basin, China. *Journal of Petroleum Science and Engineering*, 24–37

Wilkinson, M., Haszeldine, R.S., 2011. Oil Charge Preserves Exceptional Porosity in Deeply Buried, Overpressured, Sandstones:Central North Sea, UK. *Journal of the Geological Society*, 168(6): 1285–1295

Xi, K.L., Cao, Y.C., Wang, Y.Z., et al., 2015. Factors Influencing Physical Property Evolution in Sandstone Mechanical Compaction: The Evidence from Diagenetic Simulation Experiments. *Petroleum Science*, 12: 391–405

Xiao, L.H., Gao, Y.T., Tian, W.Z., et al., 2011. The Retardation Compaction in Clastic Rocks by Overpressure and the Prediction Model for Porosity. *Bulletin of Mineralogy, Petrology and Geochemistry*, 30(4):400–406 (in Chinese with English Abstract)

Xu, S.M., Lin, C.M., Wang, X.F., et al., 2011. Reservoir Diagenesis of He 2-3 Member of the Lower Shihezi Formation in DaniudiGas Field, Ordos Basin and its effect on reservoir physical properties. *Geoscience*, 25(5): 909–916 (in Chinese with English Abstract)

Yang, Y., Jiang, Z.X., Zhang, X.L., et al., 2010. Controlling Factors of and Lithofacies Interpretation for Tight Reservoirs in He-3Member of Daniudi Gas Field. *Journal of Northwest University (Natural Science Edition)*, 40(4): 699–702 (in Chinese withEnglish Abstract)

Yin, X., Ying, W.M., 2005. Reservoir Evaluation for the Low Porosity and Permeability Sandstone of Upper Paleozoic in theDaniudi Gas Field, Ordos Basin. *Mineral Petrol*, 25(2): 104–109 (in Chinese with English Abstract)

Zhang, H.L., Zhang, R.H., Yang, H.J., et al., 2014. Characterization and Evaluation of Ultra-Deep Fracture-Pore Tight Sandstone Reservoirs: A Case Study of Cretaceous Bashijiqike Formation in Kelasu Tectonic Zone in Kuqa Foreland Basin, Tarim, NWChina. *Petroleum Exploration and Development*, 41(2): 158–167 (in Chinese with English Abstract)

Zhang, J.Z., Chen, S.J., Xiao, Y., et al., 2013. Characteristics of the Chang-8 Tight Sandstone Reservoirs and Their Genesis inHuaqing Area, Ordos Basin. *Oil & Gas Geology*, 34(5): 679–684 (in Chinese with English

Abstract)

Zhang, Q., Zhu, X.M., Zhong, D.K., et al., 2004. Reservoir Characteristics of the Paleogene Clastic Rock in Dongying Sag,Shandong Province and Their Controlling Factors. *Journal of Palaeogeograhy*, 6(4): 493–502 (in Chinese with EnglishAbstract)

Zhang, R.H., Yao, G.S., Shou, J.F., et al., 2011. An Integrated Porosity Forecast Model of Deposition, Diagenesis and Structure.*Petroleum Exploration and Development*, 38(2): 145–151 (in Chinese with English Abstract)

Zhang, S.N., 2008.Tight Sandstone Gas Reservoirs: Their Origin and Discussion. *Oil & Gas Geology*, 29(1): 1–10 (in Chinese withEnglish Abstract)

Zhang, S.N., Ding, X.Q., 2010. Characteristics and Origin of Tight Sandstone Reservoirs of Yanchang Formation in Southern OrdosBasin, China. *Journal of Chendu University of Technology (Science & Technology Edition)*, 37(4): 386-394 (in Chinese with English Abstract)

Zhang, S.W., 2007. “Water–Depleting Effect” in Diagenetic Stage and Its Petroleum Geological Significance. *Acta SedimentologicalSinica*, 25(5): 701–707 (in Chinese with English Abstract)

Zhang, X.F., Hou, M.C., Chen, A.Q., 2010. Features and Main Controlling Factors of Tight Sandstone Reservoirs in the LowerShihezi Formation in the Northeastern Ordos Basin. *Natural Gas Industry*, 30(11): 34–38 (in Chinese with English Abstract)

Zhang, X.J, 2014. Quantitative Analysis of the Diagenetic Evolution of the Carboniferous-Permian Tight Sandstone in Daniudi Gas Field. Master thesis. China University of Petroleum (East China), Shandong, 10–56 (in Chinese with English Abstract)

Zhou, K., Peng, J., Geng, M., 2008. Analysis on Main Controlling Factors of Physical Properties of Tight Sandstone Reservoir inCentral-Southern Sichuan Transition Zone. *Fault-Block Oil & Gas Field*, 15(2): 8–11 (in Chinese with English Abstract)

Zou, C.N., Zhu, R.K., Liu, K.Y., et al., 2012. Tight Gas Sandstone Reservoirs in China: Charactersitics and Recognition Criteria.*Journal of Petroleum Science and Engineering*, 82–91