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Research Article

Reservoir effectiveness evaluation based on comprehensive reservoir quality evaluation indexes of well logging: A case study on the Permian Qixia Fm in the western Sichuan Basin☆,☆☆

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Abstract

In the western Sichuan Basin, the Permian Qixia Fm grained dolomite reservoirs are currently the new focus of natural gas exploration and development. The Qixia Fm is characterized by developed dissolved vugs and fractures, low matrix porosity and strong heterogeneity, so evaluation faults tend to occur if reservoir effectiveness is evaluated by means of the traditional porosity evaluation, and the consequently the predicted gas well productivity is more deviated from the actual measurement. In this paper, the characteristics of Qixia Fm reservoirs in this area were firstly analyzed. Then, the method and criterion of the effectiveness evaluation of Qixia Fm reservoirs in the western Sichuan Basin were established by means of numerical simulation and special logging data processing. And the following research results were obtained. First, surface porosity of matrix pores and secondary dissolved vugs calculated based on the special processing of conventional logging and electric imaging logging can be used to evaluate the reservoir properties of reservoirs. Second, deep and shallow dual lateral logging in combination with electric imaging logging and Stoneley wave energy data can be used to evaluate the filtration capacity of reservoirs. Third, the criterion of effective Qixia Fm reservoirs is established, including storage coefficient $\geq$0.6, deep lateral resistivity <5000 Ω·m, surface porosity >0.6%, Stoneley wave attenuation $\geq$10% and comprehensive reservoir evaluation index $\geq$0.25, and the evaluation criterion can well characterize reservoir quality and gas well productivity. The field application results of this evaluation method and evaluation criterion indicate that the coincidence rate of reservoir effectiveness has increased from 70% to over 90%. Thus, the technical difficulties related to the heterogeneous carbonate reservoir effectiveness evaluation are basically solved. Besides, they provide a basis for the determination of production test layer selection, completion engineering and development scheme so as to cut down the natural gas exploration and development cost.

Keywords: Sichuan Basin; Western; Permian; Qixia Fm; Reservoir; Logging; Comprehensive reservoir quality evaluation index; Adaptability; Effectiveness; Filtration capacity

In recent years, encouraging progress has been made in natural gas exploration of the Permian strata in the Shuangyushi, Daxingchang and Jiulongshan regions, western Sichuan Basin. Many wells revealed a high industrial gas rate from the Permian Makou and Qixia formations [1]. This indicates good potential of exploration and development in the Permian. Thus, the Qixia Formation is considered to be one of the most realistic replacement formation in the Sichuan Basin. Cores recovered from wells show that, the Qixia Fm reservoirs in the Western Sichuan Basin are characterized by a good

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development of dissolved pores-vugs and fractures, low matrix porosity and strong heterogeneity, and reservoirs vary greatly in lithology and type across regions, making reservoir effectiveness and well productivity respond differently to acoustic, electric and nuclear loggings. Accordingly, traditional porosity logging method failed to evaluate the reservoir effectiveness in several wells (e.g. Hanshen 1, Longgang 70 and Dashen 001-X4), with the predicted gas well productivity lower or higher than the actual value. Is there any new logging-based evaluation method that can address the technological problems? In this paper, the characteristics of the Qixia Fm reservoirs in western Sichuan Basin were analyzed; then, the method and the criterion for the integrated evaluation of pores, vugs and fractures in the Qixia Formation were established through numerical modeling and fine processing of special well logging data.

1. Reservoir characteristics and adaptability of traditional methods

1.1. Basic reservoir characteristics

The Permian Maokou Fm hydrothermal dolomite and Qixia Fm grained dolomite reservoirs were formed in the Shuangyushi, Daxingchang and Jiulongshan regions, western Sichuan Basin, under the effect of the penecontemporaneous exposure dissolution, shallow burial dolomitization, later stage thermal water sedimentation and hydrothermal reformation, and tectonic disruption. Cores recovered from wells reveal that the Qixia Fm reservoirs have three major characteristics (Fig. 1).

1.1.1. Variable lithology

Dolomitization degree of reservoir varies greatly over the regions. Lithology is dominated by dolomite in the Shuangyushi and Daxingchang regions and by limestone in the Jiulongshan region.

1.1.2. Low reservoir porosity

In the northern region, the porosity of dolomite reservoirs varies in a large range, with an average of 3.15%. In the southern region, the porosity ranges from 1% to 3%, with an average of 2.06%. The porosity of limestone reservoirs is 0.5–2.0% in the northern and southern regions, averaging at 1.12% (Fig. 1).

1.1.3. Complex fracture-vug system

The majority of dissolved pores and vugs were formed as a result of further dissolution of preexisting pores. Dissolution occurred along fractures often led to the formation of a variety of dissolved vugs. Fractures include tectonic fractures and dissolved fractures. Dissolved fracture is more conducive to reservoir effectiveness. Fractures and dissolved pores-vugs along fractures together constitute the fracture-dissolved vug system [2].

1.2. Adaptability of traditional methods

1.2.1. The unified porosity-based evaluation criterion is inapplicable to the effectiveness evaluation of reservoirs with complex lithology

Comprehensive studies suggest that the lower porosity limit for the Permian dolomite reservoirs is about 2%. Core-based analysis of reservoir physical properties reveals that, dolomite reservoirs exhibit better physical properties than limestone reservoirs. For example, Well Shuangyu 001-1 produced 83.7 × 10^4 m^3/d gas from No.2 and No.3 dolomite reservoirs of the Qixia Formation, of which the neutron porosity averages at 4%; and Well Longtan 1 produced 105.6 × 10^4 m^3/d gas from No.5 and No.6 limestone reservoirs of the Qixia Formation, of which the neutron porosity averages at 2%. Thus, it is inappropriate to apply a unified porosity evaluation criterion in evaluating the quality of the Qixia Fm reservoirs with complex lithologies.

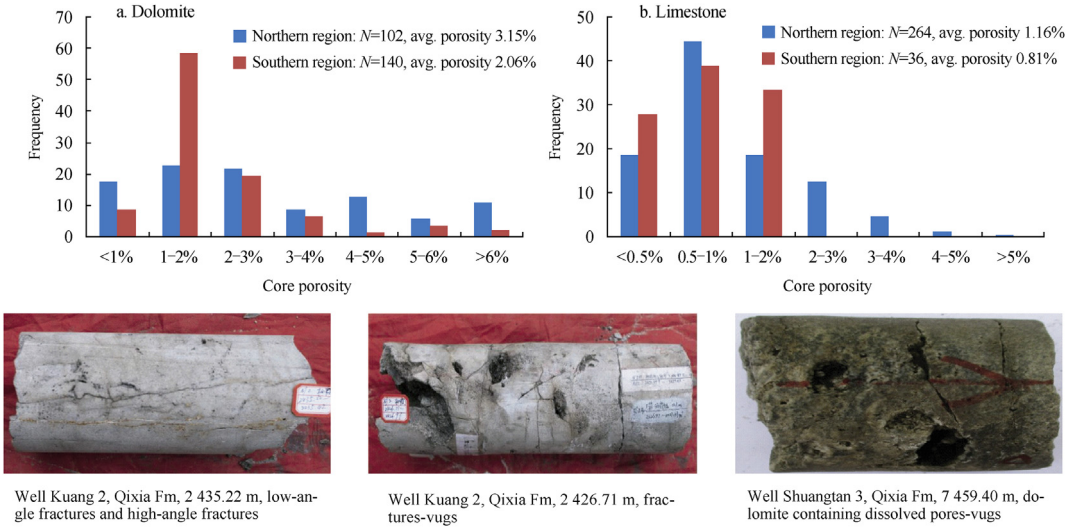

Fig. 1. Characteristics of the Permian Qixia Fm reservoir in the western Sichuan Basin. Note: *N* refers to the number of samples.