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Research Advances

A Quantitative Method for Evaluating Fault Vertical Opening and Sealing Properties during Hydrocarbon-Charging Periods

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Objective

Faults are the main channel of hydrocarbon vertical migration in a faulted basin (Jiang et al., 2018). It is helpful to guide the exploration by accurately evaluating the opening and sealing characteristics of faults at different depths. However, the fault vertical opening and sealing properties cannot at present be evaluated quantitatively. Taking the Raoyang Sag in the Bohai Bay Basin as an example, based on the stress analysis of the fault zone, this research analyzes the factors influencing the opening and sealing characteristics of fault zones and proposes a quantitative method for evaluating fault vertical opening and sealing properties during hydrocarbon-charging periods.

Methods

Factors influencing the opening and sealing characteristics of fault zones

The main source rocks of the Raoyang Sag occur in the 3rd and the lower 1st of the Shahejie Formation, while the oils predominantly accumulate in the 2nd and the upper 1st of the Shahejie Formation, Dongying Formation and Neogene strata (Jiang et al., 2017). The vertical distribution of oils is characterized by the comb pattern, the oil layers being separated by multiple caprocks. Hence, the fault vertical opening and sealing properties play an important role in controlling vertical hydrocarbon distribution.

The fractures in fault zones are the real channels of hydrocarbon migration along faults. The connectivity of these fractures depends on the balance between the external compressive stress and the internal resistance stress in the vertical direction of the fault plane during hydrocarbon-charging periods. When the compressive stress is greater than the resistance stress, fractures are squeezed and the fault is vertically sealed. The compressive stress is derived from the gravitational force of the overlying strata and the regional compressive stress. The calculation of the gravitational force of the overlying strata should be based on the characteristics of paleo-strata sedimentary thickness during hydrocarbon-charging periods. The regional compressive stress can be obtained from the numerical simulation results of paleo-stress fields in the study area by previous researchers (Wang and Dai, 2012). The resistance stress is derived from the resistance stress of the fault rock skeleton and the pore fluids in fault rock fractures. The resistance stress of the fault rock skeleton depends on the lithology of the fault rock. Brittle rock usually has a higher resistance to compressive stress and is beneficial to fracture development. In contrast, plastic rock is beneficial to fault sealing. The fault rock is derived from broken pieces of fault plates. Therefore, the lithological composition of the fault rocks can be estimated by the average lithological composition of the caprock of the upper and lower walls of the fault, then the resistance stress of the fault rock skeleton can be quantified by multiplying the lithological composition of the fault rocks by the compressive strength of a single lithology. Mudstone can retain maximum fluid pressure in the caprock during its geological history. According to the model of "oil-gas transfer station" formed by fault-sandbody, this pressure can represent the resistance stress of the pore fluids in fault rock fractures at the moment of fault vertical opening. The pressure can be calculated using the empirical formula of acoustic time values (Guo and Qu, 1997).

Quantitative evaluation for the fault vertical opening and sealing properties

Based on the above influencing factors, we present equations for evaluating fault vertical opening and sealing properties (Fig. 1). They are as follows:

$$S = \frac{F_1 + F_2}{F_3 + F_4} \tag{1}$$

$$F_1 = \rho \mathrm{gh} \cdot \cos\theta \tag{2}$$

$$F_1 = \rho \mathrm{gh} \cdot \cos\theta \tag{3}$$

$$F_3 = \sum_{i=1}^{n} \sigma_i \cdot \frac{1}{2} \cdot \left(\frac{\sum_{j=1}^{m} h_j}{H} + \frac{\sum_{k=1}^{o} h_k}{H'} \right) \tag{4}$$

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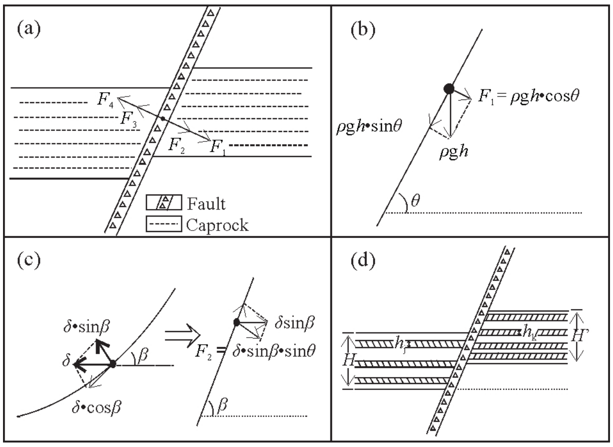

Fig. 1. Mechanical analysis of influencing factors of fault vertical opening and sealing.
(a) The S depends on the balance between the external compressive stress and the internal resistance stress in the vertical direction of the fault plane; (b) deconstruction of the gravity of overlying strata; (c) deconstruction of the regional compressive stress; (d) the calculating principle of the lithological composition of the fault rocks.

$$F_4 = \frac{1}{10}\bullet\left(\rho_0\bullet H_0 - \frac{\rho_0-\rho_w}{C}\bullet\ln\frac{\Delta t}{\Delta t_0}\right) \tag{5}$$

The meaning of each symbol of formulas is shown in the Appendix 1.

Results

This work evaluated the vertical connectivity in the Dongying Formation caprock of thirteen faults in the Raoyang Sag using the new method. It can be found that the S values of sealing faults are all greater than 0.95, while the S values of opening faults are all less than 0.95 (Fig. 2). This indicates that the threshold of the S value for controlling fault vertical connectivity in the Raoyang Sag is 0.95. The evaluation based on the formula conforms well to the actual opening and sealing characteristics of the faults.

Conclusions

By analyzing the balance between the external compressive stress and internal resistance stress in the vertical direction of the fault plane, a quantitative equation is established for evaluating fault vertical opening and sealing properties during hydrocarbon-charging periods. The results show that the evaluation is consistent with actual fault vertical connectivity. Hence, this method can be used to effectively evaluate fault vertical opening and sealing properties during hydrocarbon-charging periods and help to predict the oil-enrichment layers.

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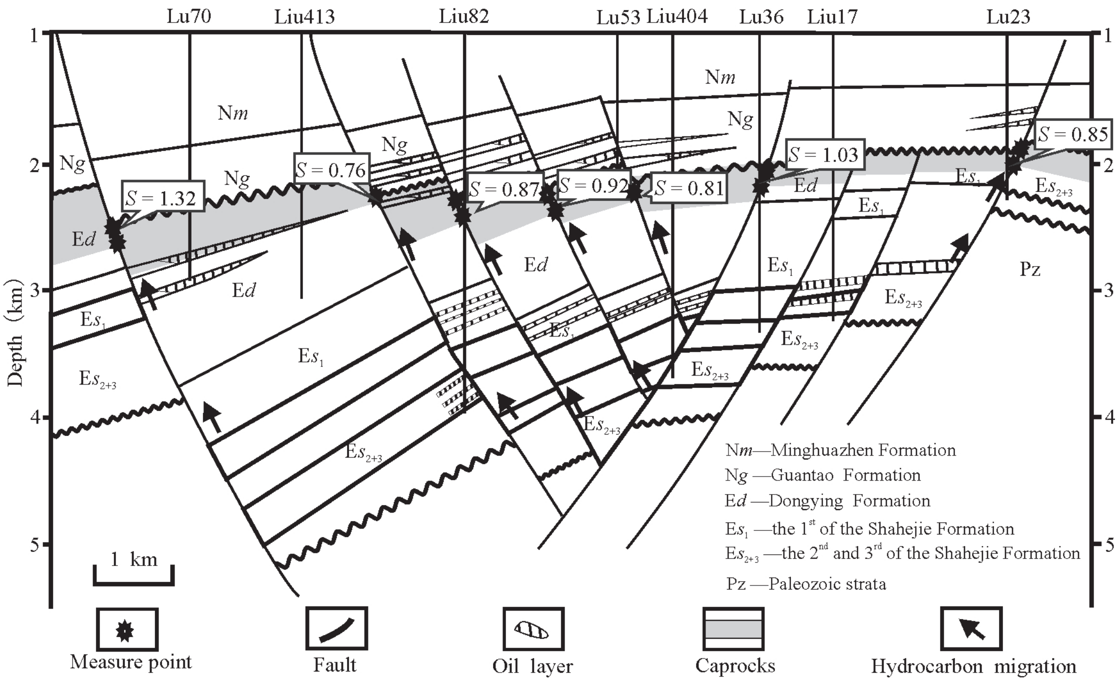

Fig. 2. Relationship between the evaluation of fault opening and sealing characteristics of the Dongying Formation caprocks and the hydrocarbon distribution in the Raoyang Sag.

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Appendix 1 Nomenclature of formulas

S	Evaluation coefficient of fault opening and sealing properties, and it is more favorable for the fault vertical sealing when the S value is larger
F_1	Gravity of the overlying strata
F_2	Regional compressive stress
F_3	Resistance stress of fault rock skeleton
F_4	Resistance stress of the pore fluids in the vertical direction of the fault plane
ρ	Average density of the overlying strata
g	Gravitational acceleration
h	Depth of the measuring point during the hydrocarbon charging period
δ	Original regional compressive stress
θ	Dip angle of the fault
β	Angle between fault strike and principal compressive stress
σ_i	Compressive strength of a single lithology
i	Sequence number of the single lithology
n	Total number of lithology
H and H'	Thickness of the two plate caprocks
j and k	Sequence number of single lithologic layers in the two fault plates
m and o	Total numbers of layers with the single lithology in the two fault plates
h_j and h_k	Thickness of layers with the single lithology
ρ_o and ρ_w	Density of the current overlying strata and the formation water, respectively
H_0	Current depth of the measuring points
C	Gradient of the semi logarithmic value of the acoustic time
Δt and Δt_0	Acoustic time values of the depth of H_0 and the ground surface