A new method of metamorphicrock buried hill fracture reservoir modeling

GU Shaohua\textsuperscript{a,b}, LIU Yuetian\textsuperscript{a,b}, HAN Longyu\textsuperscript{a,b}, JIANG Bin\textsuperscript{c, a*}

\textsuperscript{a}Key Laboratory for Petroleum Engineering of the Ministry of Education, Fuxue road 18, Beijing, 102249, China
\textsuperscript{b}College of Petroleum Engineering, China University of Petroleum, Fuxue road 18, Beijing, 102249, China
\textsuperscript{c}China Offshore Oil Research Center, China National Offshore Oil Corporation, Beijing, 100010, China

Abstract

Metamorphicrock buried hill reservoir is a type of complex fracture reservoirs and hard to characterize. The paper proposes a new method for buried hill modeling, to establish double porosity model, including fracture and matrix. In matrix modeling process, metamorphic lithology theory is used to characterize the complicated distribution of lithology for phase modeling, and matrix model with porosity and permeability under the control of lithology phase condition is completed by random simulation modeling. The data of lithology come from well logging in buried hill reservoir. In fracture modeling, the feature of strong anisotropy of permeability in formation is considered and a new method of fracture modeling is applied to characterize the fracture system. Then the method is used in history matching of real reservoir simulation to test the reliability, and the result shows the model by new method are closer to real reservoir than model by common method.

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1. Introduction

Metamorphic rock buried hill reservoir has complex geological features and distinctive cause of formation, totally different with sedimentary reservoir. This type of reservoirs is widely distributed in Bohai Bay areas, eastern China, especially Liaohe depression. Many scholars researched and attained valuable achievements about geological features of buried hill. The Archean metamorphic rock series

\* Corresponding author: LIU Yuetian. Tel.: 0086-10-89732260
E-mail address: cc0012@126.com.
spread around Liaohe Basin, forming the oldest crystalline basement [1-2]. Parts of the bedrock are affected by numerous active magma movements, so that metamorphism continued and formation formed with various types of rock interspersed. Several tectonic moments occurred in this area over the past millions of years. The geological impacts led sustained cyclical fault activity, and influenced greatly on the late drape structure of buried hills [3-6]. Fault and complex micro-cracks shaped in fault movements became the main path of hydrocarbon migration during accumulation process. Because of large scale fault throw formed in strong geological movement, metamorphic rock of buried hill can be close to generating rocks, and then they obtained oil and gas supply. These hydrocarbons from generating rock migrated along the fault surface or fracture into metamorphic rock [7-8]. Above the reservoir, overlying mudstone sealed hydrocarbons effectively as caprock, so the buried hill structure can compose a trap. After metamorphism process, different types of lithology, such as amphibolite rock and diabase, emerged and some of them abundant with melanocratic mineral. These rocks compose of isolated layer and protect the preservation of hydrocarbons inside trap. That’s the origin of metamorphic rock buried hill reservoir.

**Nomenclature**

| Symbol | Description                                      |
|--------|--------------------------------------------------|
| \( \varphi_f \) | Fracture porosity, %                             |
| \( R_{mf} \) | Resistivity of mud filtrate, \( \Omega \cdot m \) |
| \( R_{LLD} \) | Deep lateral resistivity, \( \Omega \cdot m \)    |
| \( R_{LLS} \) | Shallow lateral resistivity, \( \Omega \cdot m \)  |
| \( M_f \) | Bond index                                       |
| \( R_{mf1} \) | Mud filtrate resistivity on the ground, \( \Omega \cdot m \) |
| \( R_{mf2} \) | Mud filtrate resistivity in reservoir, \( \Omega \cdot m \) |
| \( t_1 \) | Measuring point temperature, °C                 |
| \( t_2 \) | Formation temperature, °C                       |
| \( D \) | Midpoint of pay zone, m                         |
| \( K_f \) | Fracture permeability, \( 10^{-3} \mu m^2 \)     |
| \( d \) | Fracture aperture, \( \mu m \)                  |
| \( C_b \) | Conductivity of surrounding rock, \( 1/\Omega \cdot m \) |
| \( C_{LLS} \) | Shallow lateral conductivity, \( 1/\Omega \cdot m \) |
| \( C_{LLD} \) | Deep lateral conductivity, \( 1/\Omega \cdot m \)  |
| \( C_m \) | Mud filtrate conductivity in reservoir, \( 1/\Omega \cdot m \) |
| \( X \) | Discriminant coefficient                        |

2. Buried hill reservoir modeling

2.1. General situation of target area

Sheng601 reservoir (Fig.1) is a typical metamorphic rock buried hill reservoir, and it has many
characteristics: Sheng601 has many faults, which divide the formation into many blocks; Fractures by tectonization and metamorphism distributed unevenly inside buried hill reservoir; The reservoir is a new bed-generating and old bed-storing oil and gas reservoirs, in other words, the trap formed before oil generated. Oil and gas migrated from low to high parts along the fracture in the reservoir; Palosome of this reservoir rock has layered characteristics, after regional metamorphism, which was largely preserved layered characteristics, according to seismic interpretation; the boundary between two adjacent layers is not absolutely closed for a large number of high-angle cracks existing in the internal layers.

Fig.1. Structural chart of sheng601 reservoir (left)
Fig.2. Lithological profile of sheng 601 buried hill reservoir from well interpration (right)

2.2. Buried hill lithology phase model and matrix property model

Main idea of phased modeling is the same sedimentary microfacies or lithology phase in same layer have similar geological property, including porosity, permeability. Based on the phase by characteristics of microfacies and depositional, geological modeling can be built. The multi-step modeling approach can make use of experience and knowledge of geologists to reduce randomness in stochastic modeling.

In metamorphic rock reservoir, lithology is an effective way as phased conditions for phased modeling. Several kinds of metamorphic rocks were found in Liaohe depression region by drilling cores, including metamorphic rocks from regional metamorphite, such as gneiss, granulite, leptite, amphibolite. There are some metamorphic rocks from migmatization, such as granitization granit, chorismite. Other kinds of metamorphic rocks from dynamometamorphism were found as well. Rock dike inserted into metamorphic rock buried hill were in varied forms, including lamprophyre, diabase, and intermediate-acidic volcanic rocks. Fig.2 shows lithological profile of sheng 601 buried hill reservoir.

Lithology rock mechanics test verified that: under same tectonic stress, rock with more melanocratic minerals would be more plastic and harder to crack, so they usually are not storage space for oil; On the contrary, the rocks with less melanocratic mineral are crisp and easy to crack, they are always the oil-bearing formation. According to drilling core analysis data, rock were classified by how much melanocratic mineral it has and acquire a sequence table from most to least, as Table.1. The rock rank higher in this table is not easy to crack, called “superior lithology”, and this theory named “lithology superior theory”.
Table 1. Metamorphic buried hills of the lithologic sequence

| Sequence | Lithology                     |
|----------|-------------------------------|
| 1        | Leptite                       |
| 2        | granulite                     |
| 3        | granitization granite         |
| 4        | intermediate-acidic volcanic rocks |
| 5        | gneiss                        |
| 6        | diabase                       |
| 7        | amphibolite                   |

Fig.3. (a) Lithology of drilling core in sheng601 bureid hill reservoir (b) Lithological model of sheng 601 buried hill reservoir (c)Porosity modeling of sheng 601 by phased control

On basis of mud logging data, main lithology of sheng601 are mixed granitization granit, gneiss, diabase, etc. lithology. The order of melanocratic mineral from most to least is: diabase, gneiss, granitization granit, some samples of rock in Fig.3a. According to lithology superior theory, the possibility of Oil bearing rock in sheng601 from most to least follows the same order above. Sequential
indicator simulation was selected for lithological modeling, and outcome as Fig.3b. The properties of matrix are controlled by lithology. Different rocks have different permeability and porosity, so the data need to be discrete according to lithology phase. By sequential Gaussian simulation [9], porosity modeling of sheng601 is built and visualized as Fig.3c.

2.3. Buried hill fracture model

2.3.1. The processing of fracture parameters

Buried hill reservoir is a typical fractured reservoir, both fracture and matrix system have significant influence to oil production, therefore they both need to be taken into consideration. Fractures in metamorphic rock buried hill reservoirs are main channels for permeation of oil and gas. When the fracture aperture is greater than 0.01mm, it shows great penetration ability in loss of drilling mud. Drilling mud filtrate into formation and forms invaded zones, so dual laterolog can fit this situation to interpret fracture porosity. According to the formula (1), fracture porosity can be calculated by following formula.

\[
\phi_f = \frac{1}{\sqrt{R_{mf} \left( \frac{1}{R_{LLS}} - \frac{1}{R_{LLD}} \right)}}
\]

Resistivity of mud filtrate \( R_{mf} \) value can be determined by this way: in the early stage of drilling, calibration value from log heading is suit; during the late stage of drilling, free mud system is usually chose as drilling fluid in order to protect reservoir, so the resistivity of mud resistivity is equal to resistivity of mud, it means \( R_{mf} = R_m \). Then measurements of the mud on the ground resistivity converted to liquid under reservoir conditions by using the following formula.

\[
R_{ml2} = \left( \frac{t_1 + 21.5}{t_2 + 21.5} \right) \times R_{ml1}
\]

According to research on metamorphic rocks of Liaohe depression, relationship between permeability and porosity is as follows.

\[
t_2 = 0.0256D + 19.68
\]

\[
K_f = 33.8 \times \phi_f \times d^2
\]

Fracture aperture may be determined by core samples from sheng601 reservoir. At present, fracture aperture can be calculated by dual lateral resistivity model proposed by A·M·Sibbit [10]. He did a lot of experiments and found the ties between dual lateral conductivity and fracture aperture. The first thing is to discriminate the inclination of fracture, for vertically fracture is \( X > 0.1 \); for skew crack is \( 0 < X < 0.1 \); for horizontal crack is \( X < 0 \).

\[
X = \frac{R_{nd} - R_{lls}}{\sqrt{R_{nd} \times R_{lls}}}
\]

If the fracture inclination is high angle, the model is

\[
d = \frac{C_{lls} - C_{ld}}{4C_m} \times 10^4
\]

If the fracture inclination is low angle, the model is
The data of sheng601 reservoir was processed by above method, permeability of buried hill is range from $1 \sim 1000 \times 10^{-3}$ um².

2.3.2. Fracture anisotropic permeability modeling

$$d = \frac{C_{11s} - C_{10}}{1.2C_{ab}} \times 10^4$$ (7)

As fracture is the main reason for anisotropy in reservoir, how to characterize fractures is the key to study anisotropy. Zhang Jichang and Liu Yuetian[11] proposed an anisotropic fracture modeling in 2006. It is assumed that the reservoir has one set of parallel cracks. Fracture azimuth is $\beta$, and fracture inclination is $\alpha$, the permeability is parallel to fracture is $k$. Earth is put as reference frame to establish a 3-D Cartesian coordinate system. The first one coordinate axis is assumed point to east, and the second point to north and the third point upward. There are three Unit coordinates vector $e_1, e_2, e_3$, in accordance to the coordinate axis. Then we establish a Cartesian coordinate system with fracture in reservoir for reference frame. The intersection line of fracture and horizontal plane was selected as one coordinate axis, in accordance to Unit coordinates vector $J_2$. Another axis is vertical to intersection line above, which corresponds to unit coordinate vector $J_1$. The third axis is vertical to the plane composed by $J_1$ and $J_2$, in accordance to Unit coordinates vector $J_3$, As Fig.4 shows.

The formula to calculate permeability of fracture anisotropy is as follows, and the derivation process of the formulas can reference [11].

$$\bar{K}_s = k \begin{pmatrix} \cos^2 \alpha \cdot \cos^2 \beta + \sin^2 \beta & \sin^2 \alpha \cdot \cos \beta \cdot \sin \beta & \cos \alpha \cdot \sin \alpha \cdot \cos \beta \\ \sin^2 \alpha \cdot \cos \beta \cdot \sin \beta & \cos^2 \alpha \cdot \sin^2 \beta + \cos^2 \beta & -\cos \alpha \cdot \sin \alpha \cdot \sin \beta \\ \cos \alpha \cdot \sin \alpha \cdot \cos \beta & -\cos \alpha \cdot \sin \alpha \cdot \sin \beta & \sin^2 \alpha \end{pmatrix}$$ (8)

In sheng601 reservoir, main permeability orientation point to north by east by approximately 45 degrees. Based on formula (8), anisotropy permeability can be calculated as formula (9).
Fig. 5. (a) X direction permeability of sheng601 anisotropic permeability modeling (b) Z direction permeability of sheng601 anisotropic permeability modeling

\[
\bar{K}_x = 2k \begin{pmatrix}
\cos^2 \alpha + 1 & 0 & 0 \\
0 & \cos^2 \alpha + 1 & 0 \\
0 & 0 & 2\sin^2 \alpha \\
\end{pmatrix}
\]  

(9)

Using the data of anisotropy permeability, anisotropic permeability reservoir model is built by sequential Gaussian simulation method [9]. The result in shows x (Fig. 5a) and z (Fig. 5b) direction of permeability have different values.

3. Verification by numerical reservoir simulation

In order to test the new method of modeling, it should be compared with model by common method, result as Fig. 6. In numerical reservoir simulation, wells in two models both run at bottom hole pressure data from sheng601 reservoir. The curves of liquid production total by new method model (Fig. 6a) and common method model (Fig. 6b), the new method curve is close to well history means it matches the reservoir better, the common method curve is far above the well history, the reason is fracture system without phase control are over-growth in reservoir modeling, which causes more storage space and more pay zones for liquid supply.

Fig. 6. (a) Permeability modeling of sheng601 reservoir using new method and (b) using common method
4. Conclusion

Metamorphic rock buried hill reservoir has complex geological features and distinctive cause of formation, totally different with sedimentary reservoir. So the method of modeling should also be different. Some geological features of metamorphic rock buried hill reservoir need to be taken into consideration, including non-homogeneous lithology and anisotropic permeability.

Buried hill reservoir’s rock is affected by metamorphism, forming formation with various of lithology distributed cross each other. Lithology phase control for matrix phase-control modeling of matrix property is a practice way based on superior lithology theory.

In fracture modeling process, anisotropic fracture parameters are characterized in data processing, including fracture aperture, inclination and azimuth. Due to this work, anisotropic fracture permeability algorithm can be applied to realize the accurately anisotropy fracture modeling in reservoir.

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