Predicting the present-day in situ stress distribution within the Yanchang Formation Chang 7 shale oil reservoir of Ordos Basin, central China

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Abstract
The Yanchang Formation Chang 7 oil-bearing layer of the Ordos Basin is important in China for producing shale oil. The present-day in situ stress state is of practical implications for the exploration and development of shale oil; however, few studies are focused on stress distributions within the Chang 7 reservoir. In this study, the present-day in situ stress distribution within the Chang 7 reservoir was predicted using the combined spring model based on well logs and measured stress data. The results indicate that stress magnitudes increase with burial depth within the Chang 7 reservoir. Overall, the horizontal maximum principal stress ($S_{hmax}$), horizontal minimum principal stress ($S_{hmin}$) and vertical stress ($S_v$) follow the relationship of $S_v \geq S_{hmax} > S_{hmin}$, indicating a dominant normal faulting stress regime within the Chang 7 reservoir of Ordos Basin. Laterally, high stress values are mainly distributed in the northwestern parts of the studied region, while low stress values are found in the southeastern parts. Factors influencing stress distributions are also analyzed. Stress magnitudes within the Chang 7 reservoir show a positive linear relationship with burial depth. A larger value of Young’s modulus results in higher stress magnitudes, and the differential horizontal stress becomes higher when the rock Young’s modulus grows larger.

Keywords Present-day in situ stress · Chang 7 shale oil reservoir · Influencing factor · Ordos Basin · Stress distribution prediction · Yanchang Formation

1 Introduction

With the continued development of hydrocarbon theories and recent exploration practices, the global oil and gas industry has gotten into the period of unconventional hydrocarbon resources. The unconventional shale oil and gas, tight oil and gas, gas hydrates and coalbed methane have shown great potential under the present-day economic and technological conditions, and their production has changed the global energy consumption structure (Jia et al. 2012; Zou et al. 2013; Vedachalam et al. 2015). Among those unconventional resources, shale oil is defined as a kind of non-gaseous hydrocarbon with great exploration and development potential, which is generally accumulated in mudstone and shale layers in multiple states (Zhang et al. 2012, 2015; Zou et al. 2013).

In the past several years, commercial development of shale oil was successfully obtained in many countries of the world, e.g., the USA, Canada and Australia (Zhou et al. 2019). In China, shale oil resources are abundant, and they are widely distributed in the Mesozoic-Cenozoic continental...
basins, including the Songliao Basin, Junggar Basin, Ordos Basin, Qiangtang Basin, Bohai Bay Basin and Qaidam Basin (Yang et al. 2013, 2018; Zhang et al. 2015; Sun 2017; Zhou et al. 2017). In the Ordos Basin, shale oil resources are largely accumulated in the Yanchang Formation Chang 7 oil-bearing layer, and the estimated amount is more than 10 × 10^8 tons (Yang et al. 2013).

Generally, shale oil resources are dispersed over large areas, have lower concentrations and require well stimulation or additional extraction technology (Zou et al. 2013). Hydraulic fracturing is an important approach for shale oil development. During hydraulic fracturing operations in unconventional hydrocarbon reservoirs, the present-day in situ stress state is a critical factor that should be taken into account (Bell 1996; Tingay et al. 2009; Schmitt et al. 2012; Ju et al. 2018). In addition, knowledge of present-day stress field indicates important effects on wellbore stability and reservoir management (Zoback et al. 2003; Binh et al. 2007; Tingay et al. 2009; Rajabi et al. 2016; Ju et al. 2017, 2019). Hence, a better understanding of the present-day in situ stress state will definitely help the exploration and development of shale oil resources. However, few previous studies are carried out focusing on the present-day stress state in the Yanchang Formation Chang 7 oil-bearing layer, which limits the further exploration and development of shale oil in the Ordos Basin.

The objective of this study is to predict the present-day in situ stress distribution within the Yanchang Formation Chang 7 shale oil reservoir and analyze the influencing factors. The results are expected to bring new geological references for shale oil production in the Ordos Basin.

2 Geological setting

The Ordos Basin is the second-largest sedimentary basin in China, which has experienced a complex geological history. The present-day geomorphology indicates that the central part of the Ordos Basin is relatively stable, whereas the margins have undergone strong tectonic activities, resulting in structural complexity (Fig. 1; Zeng and Li 2009; Yang et al. 2012; Lyu et al. 2016; Ju et al. 2020). Within the Ordos Basin, large volumes of unconventional petroleum resources are accumulated in the Upper Triassic Yanchang Formation (Zeng and Li 2009; Ju et al. 2015; Zhang et al. 2015; Cui et al. 2019). The Yanchang Formation are generated in a lake-delta sedimentary system, and it can be divided into ten oil-bearing layers, known as the Chang 10 to Chang 1 oil-bearing layer from bottom to top, based on sedimentary cycle, rock associations, log characteristics and oil-bearing properties of the deposits (Fig. 2; Yang et al. 2012, 2016). The development of the Ordos lake basin gets its peak during the deposition of Chang 7 oil-bearing layer, and mudstone and shale layers of deep and semi-deep lake facies are widely distributed (Fu et al. 2015; Zhang et al. 2015; Yang et al. 2016). In addition, the Chang 7 oil-bearing layer can be further divided into the Chang 71, Chang 72 and Chang 73 sublayers.

Generally, based on the differences in sedimentary structure, rock composition and TOC content, mudstones and shales in the Yanchang Formation Chang 7 oil-bearing layer of Ordos Basin can be divided into two types: black shales and dark mudstones (Fu et al. 2015; Yang et al. 2016). Laterally, the Chang 7 shale is widely distributed with variable thickness (Cui et al. 2019), and shale oil within the Chang 7 oil-bearing layer is mainly distributed in the Dingbian–Ansai–Huangling–Changwu–Pingliang–Huanxian regions (Fig. 3; Fu et al. 2015; Yang et al. 2016). Vertically, black shales are mainly in the Chang 71 sublayer, whereas dark mudstones are widely distributed in all three sublayers. The development scale of mudstones and/or shales greatly varies in different areas.

3 In situ stress tensor

The present-day in situ stress state can be described by the stress tensor, which includes the orientation and magnitudes of three orthogonal principal stresses (Engelder 1993). In general, the stress tensor may be reduced to four components, namely the magnitudes of horizontal maximum principal stress (S_{Hmax}), horizontal minimum principal stress (S_{hmin}) and vertical stress (S_v), and the orientation of horizontal stresses (Bell 1996; Zoback et al. 2003; Ju et al. 2017).

In addition, based on the relative magnitudes of S_{Hmax}, S_{hmin} and S_v, three stress regimes are divided (Anderson 1951; Fig. 4):

(i) normal faulting stress regime (S_v > S_{Hmax} > S_{hmin}),
(ii) strike-slip faulting stress regime (S_{hmax} > S_v > S_{hmin}),
and
(iii) thrust faulting stress regime (S_{Hmax} > S_{hmin} > S_v).

4 Methodology

4.1 Rock mechanics

Knowledge of rock mechanics is critical for accurately predicting the present-day in situ stress distribution (Brooke-Barnett et al. 2015; Ju et al. 2017). Generally, rock mechanics experiment is an important and accurate approach to obtain the mechanics parameters (e.g., Young’s modulus, Poisson’s ratio), and the measured mechanics properties are static ones; however, this approach has its limitations: (i)
The collection of core samples is not continuous, resulting in the discrete rock mechanics parameters along with burial depth; (ii) it is money- and time-consuming. Dynamic velocity-based mechanics properties are easy to calculate based on well logs (Eqs. 1 and 2; Binh et al. 2007; Fjaer et al. 2008; Brooke-Barnett et al. 2015), and more importantly, they are continuous along with burial depth. Hence, continuous static mechanics parameters can be obtained from dynamic data by building the relationship between them.

Dynamic Poisson's ratio:

$$\mu_d = \frac{2 - \left(\frac{v_p}{v_s}\right)^2}{2 \left(1 - \left(\frac{v_p}{v_s}\right)^2\right)}$$  \hspace{1cm} (1)
Dynamic Young’s modulus:

\[ E_d = \frac{\rho v_p^2 (3v_p^2 - 4v_s^2)}{v_p^2 - v_s^2} \]  

where \( v_p \) and \( v_s \) are the compressional and shear wave velocity, respectively, \( \rho \) is the density from bulk density logs, \( E_d \) is the dynamic Young’s modulus, and \( \mu_d \) is the dynamic Poisson’s ratio.

4.2 Method for predicting stress distribution

In general, the \( S_v \) is the simplest to calculate based on Eq. 3, which is the integration of rock densities from the surface to a particular depth (Zoback et al. 2003; Brooke-Barnett et al. 2015; Ju et al. 2017).

\[ S_v = \int_0^h \rho(h)g dh \]  

where \( S_v \) is the vertical stress, \( g \) is the gravitational acceleration, \( \rho(h) \) is the density of the overburden rock as a function of burial depth, and \( h \) indicates the burial depth from the surface to a particular depth.

In most regions including the Ordos Basin, density logs are not acquired from the ground level. Hence, in this study, an extrapolation method was used here and a stress gradient of approximately 23 kPa/m was identified in the open hole section to determine the \( S_v \) magnitude.

For horizontal stresses, there are various models to calculate their magnitudes, which are generally categorized into the uniaxial strain mode and anisotropic mode (Table 1). The uniaxial strain mode assumes that horizontal stress is caused by the weight of overlying strata; hence, the \( S_{Hmax} \) and \( S_{Hmin} \) are the same in magnitude. However, the above assumption does not match the measured results of in situ stresses in most sedimentary basins (Yin et al. 2017).

In this study, the combined spring model (Thiercelin and Plumb 1994; Li and Zhang 1997; Table 1), a commonly used anisotropic mode, was selected to analyze horizontal in situ stresses within the Yanchang Formation Chang 7 shale oil reservoir of Ordos Basin. The combined spring model has two main advantages: (i) The strata are regarded as anisotropic, and (ii) the effects of both Young’s modulus and Poisson’s ratio are taken into account.

4.3 Pore pressure calculation

Pore pressure is an important parameter for calculating horizontal stresses as obviously seen from the models listed in Table 1. Pore pressure can be divided into types of abnormally low pressure, normal pressure, abnormally high pressure and ultrahigh pressure based on pressure coefficient and/or pressure gradient (Du et al. 1995; Table 2).

Eaton’s method (Eaton 1972) for pore pressure prediction can be made from either velocity or resistivity measurements in the well. The following equation (Eq. 4) indicates the empirical equation from the sonic compressional transit time.

\[ P_o = S_v - (S_v - P) \left( \frac{\Delta t_n}{\Delta t} \right)^n \]  

where \( P_o \) is the pore pressure, \( S_v \) is the vertical stress, \( \Delta t_n \) is the sonic transit time, and \( \Delta t \) is the actual transit time.
where $P_0$ is pore pressure, $S_v$ is the vertical stress, $P$ is the hydrostatic pore pressure, $\Delta t_n$ is the sonic transit time or slowness at the normal pressure, $\Delta t$ is the sonic transit time obtained from logs, and $n$ is an exponent.

5 Parameters for stress distribution prediction

5.1 Relationships between static and dynamic mechanics parameters

Based on measurements from rock mechanics experiments and calculations from well logs (Table 3), the relationships between static and dynamic Poisson’s ratio and Young’s modulus are shown as Eqs. 5 and 6, respectively.
For homogeneous and isotropic (Eaton (1969) Biot coefficient) is introduced Anderson et al. Obtained from hydraulic fracturing 

For low porosity and low permeability layers with microfractures Newberry et al. (1985)

Table 1  Empirical models for calculating in situ stress magnitude

| Model name             | Empirical model expression          | Characteristics                                      | References       |
|------------------------|-------------------------------------|-----------------------------------------------------|------------------|
| **Uniaxial strain mode** |                                     |                                                     |                  |
| Dinnik model           | $S_{\text{Hmax}} = S_{\text{hmin}} = \frac{1}{1-\mu} S_v$ | For homogeneous and isotropic layers without pore pressure | Dinnik (1925)    |
| Matthews and Kelly model | $S_{\text{Hmax}} = S_{\text{hmin}} = K(S_v - P_o) + P_o$ | Obtained from hydraulic fracturing with pore pressure, but $K$ is hard to determine | Matthews and Kelly (1967) |
| Eaton model            | $S_{\text{Hmax}} = S_{\text{hmin}} = \frac{1}{1-\mu} (S_v - P_o) + a P_o$ | For low porosity and low permeability layers with microfractures | Anderson et al. (1973) |
| Anderson model         | $S_{\text{Hmax}} = S_{\text{hmin}} = \frac{1}{1-\mu} (S_v - P_o) + a P_o$ | For low porosity and low permeability layers with microfractures | Newberry et al. (1985) |
| Newberry model         | $S_{\text{Hmax}} = S_{\text{hmin}} = \frac{1}{1-\mu} (S_v - a P_o) + P_o$ | For low porosity and low permeability layers with microfractures | Newberry et al. (1985) |

$S_{\text{Hmax}}$, horizontal maximum principal stress; $S_{\text{hmin}}$, horizontal minimum principal stress; $S_v$, vertical stress; $\alpha$, Biot coefficient; $\mu$, Poisson’s ratio; $K$, skeleton stress coefficient; $P_o$, pore pressure; $\beta_1$ and $\beta_2$, coefficients reflecting the horizontal maximum and minimum tectonic stress, respectively; $\varepsilon_{\text{ch}}$ and $\varepsilon_{\text{c}}$, rock strain in the direction of the horizontal maximum and minimum principal stress, respectively; $E$, Young’s modulus; $K_H$ and $K_T$, tectonic stress coefficient in the horizontal maximum and minimum principal stress direction, respectively; $\Delta T$, formation temperature variation; $\alpha$, rock linear expansion coefficient; $\Delta S_H$ and $\Delta S_T$, in situ stress additional quantity in the horizontal maximum and minimum principal stress direction, respectively; $\gamma$, a coefficient that is relevant with Biot coefficient and Poisson’s ratio.

Table 2  The classification of pore pressure (after Du et al. 1995)

| Types                      | Pressure coefficient, kPa | Pressure gradient, kPa/m |
|----------------------------|---------------------------|-------------------------|
| Abnormally low pressure    | <0.96                     | <9.28                   |
| Normal pressure            | 0.96–1.06                 | 9.28–10.41              |
| Abnormally high pressure   | 1.06–1.38                 | 10.41–13.58             |
| Ultrahigh pressure         | >1.38                     | >13.58                  |

$\mu_s = 1.5809 \mu_d - 0.0880$ (5)

$E_s = 0.1316 E_d + 19.5700$ (6)

where $E_d$ and $E_s$ are the dynamic and static Young’s modulus, respectively, and $\mu_d$ and $\mu_s$ are the dynamic and static Poisson’s ratio, respectively.

5.2 Model calibration

The $\varepsilon_H$ and $\varepsilon_s$ for the Chang 7 reservoir in the combined spring model are calibrated with measured data derived from extended leak-off tests (XLOTs) (Table 4) based on Eqs. 7 and 8 (Bredehoeft et al. 1976; White et al. 2002; Zoback et al. 2003; Ju et al. 2017).

$S_{\text{hmin}} = P_c$ (7)

$S_{\text{Hmax}} = 3 S_{\text{hmin}} - P_l - P_o$ (8)

where $S_{\text{Hmax}}$ and $S_{\text{hmin}}$ are the horizontal maximum and minimum stress, respectively, $P_s$ is the shut-in pressure, $P_o$ is the pore pressure, and $P_l$ is the reopening pressure at which closed fractures begin to reopen during repeated pressurization.

Therefore, the average $\varepsilon_H$ and $\varepsilon_s$ for the Chang 7 reservoir can be calculated based on Eqs. 7 and 8, combined spring.
model and those measured stress data in Table 4, and the magnitudes are $\varepsilon_H = 0.5717$ and $\varepsilon_h = 0.2811$, respectively.

### 5.3 Pore pressure within the Chang 7 reservoir

Based on measured pore pressure data from Li et al. (2013) and Duan et al. (2014), the average pressure coefficient within the Chang 7 reservoir ranges between 0.70 and 0.83. Therefore, currently, the Yanchang Formation Chang 7 shale oil reservoir of Ordos Basin experiences the abnormally low pressure.

### 6 Stress distribution within the Chang 7 shale reservoir

#### 6.1 Vertical distribution of present-day in situ stresses

Based on the combined spring model for Chang 7 reservoir in this study, error analysis is carried out in this study, and results indicate that the errors between measured and predicted $S_{H\text{max}}$ and $S_{h\text{min}}$ are generally less than 15% with the majority lower than 10% (Table 4).
Therefore, the one-dimensional mechanical earth model can be conducted for the Chang 7 shale reservoir and the vertical distribution of present-day in situ stresses is predicted (Fig. 5). Generally, within the Yanchang Formation Chang 7 shale oil reservoir of Ordos Basin, the $S_{max}$, $S_{min}$ and $S_v$ magnitudes all increase with burial depth. Overall, they follow the relationship $S_v \geq S_{max} \geq S_{min}$, indicating a dominant normal faulting stress regime (Fig. 5). The results are consistent with those actual stress measurements in the southwestern parts of the studied region (Wang et al. 2014).

6.2 Lateral distribution of present-day in situ stresses

In this study, totally, the vertical distribution of stress magnitudes in the Chang 7 shale reservoir was conducted and analyzed in 101 wells. In the following, the study area is divided into 93 x 100 grids, and the average stress magnitude of $S_{max}$, $S_{min}$ and $S_v$ for each grid is interpolated using the Kriging method based on stress values from adjacent wells. Therefore, the lateral distribution of present-day stresses within the Yanchang Formation Chang 7, Chang 7 and Chang 7 sublayer can be obtained and analyzed (Figs. 6, 7 and 8).

The $S_{max}$ magnitude varies in the interval of 26–46 MPa, 27–46 MPa and 24–47 MPa within the Chang 7, Chang 7 and Chang 7 sublayer, respectively (Figs. 6, 7 and 8). The $S_{min}$ magnitude ranges 21–38 MPa, 22–40 MPa and 21–43 MPa in the Chang 7, Chang 7 and Chang 7 sublayer, respectively (Figs. 6, 7 and 8). The $S_v$ magnitude indicates 22–62 MPa, 24–64 MPa and 24–64 MPa within the Chang 7, Chang 7 and Chang 7 sublayer, respectively (Figs. 6, 7 and 8). Generally, stress distributions in all three sublayers of Yanchang Formation Chang 7 shale oil reservoir indicate similar characteristics with higher and lower stress values located in the northwestern and southeastern regions of the studied region (Figs. 6, 7 and 8).
7 Discussions

7.1 Factors influencing stress distribution

The factor of burial depth indicates an important control on present-day in situ stress distribution. In this study, the relationship between stress magnitude in top Chang 71, Chang 72 and Chang 73 sublayer and the corresponding burial depth is conducted to analyze the effect of burial depth on stress distribution (Fig. 9). Obviously, for the Yanchang Formation Chang 7 shale oil reservoir of Ordos Basin, both the $S_{Hmax}$ and $S_{hmin}$ magnitudes show the linear relationships with burial depth (Eqs. 9 and 10).

$$S_{Hmax} = 0.0117h + 15.2490 \quad R^2 = 0.8997$$

(9)

$$S_{hmin} = 0.0107h + 11.4290 \quad R^2 = 0.8147$$

(10)

where $S_{Hmax}$ and $S_{hmin}$ are the horizontal maximum and minimum principal stress, respectively, $h$ indicates the burial depth, and $R$ is the correlation coefficient.
The studied region of Ordos Basin is a tectonically stable area; hence, the stress distribution is largely controlled by lithological changes (rock mechanics) due to the lack of faults and folds (Zoback et al. 2003; Zhou et al. 2007; Ju et al. 2015). Therefore, in this study, the relationship between rock Young’s modulus and stress magnitude is analyzed to understand rock mechanics on stress distribution.

The selected data for analysis are mainly from Wells Zu131, Zu115, Y410, Y296 and Y297 because these wells have both measured and predicted stress magnitudes. In addition, to avoid the effect of burial depth and Poisson’s ratio on the results, the Poisson’s ratio is fixed within a small scale ranging between 0.200 and 0.205. The burial depth for selected data is divided into two segments: 1533.25–1783.75 m and 2187.00–2351.25 m.

The results indicate that stress magnitudes increase with Young’s modulus (Fig. 10), suggesting that rock Young’s modulus exhibits a significant effect on stress transfer through the reservoir and that the stiffer rocks commonly conveyed higher stress magnitudes.

In addition, the differential stress between $S_{\text{Hmax}}$ and $S_{\text{hmin}}$ is an important parameter in hydraulic fracturing. Low differential stress can commonly produce a complex hydraulic fracture system (Zhou et al. 2007; Ju et al. 2018). Obviously, the horizontal differential stress becomes higher with the increase in Young’s modulus in the Yanchang Formation Chang 7.
reservoir (Fig. 10); hence, relatively high Young’s modulus will result in simple hydraulic fracture systems.

### 7.2 Vertical stress pattern

The magnitudes of in situ stress vary greatly with burial depth in the Yanchang Formation Chang 7 reservoir (Fig. 5), which is mainly caused by the difference in rock mechanics parameters, especially the Young’s modulus. Based on Zhou et al. (2007), there are mainly five types of vertical stress patterns (A–E), all of which are present in the Chang 7 shale oil reservoir of Ordos Basin (Fig. 5):

- **Type A: high–low–high (HLH).** Stress magnitudes in the roof and floor layers are much higher than those in the target fracturing layer. Vertical propagation of hydraulic fractures in this stress pattern will be largely limited due to the relatively high stress difference between layers.

- **Type B: low–low–high (LLH).** Stress magnitudes in the roof and target fracturing layers are generally close to each other, but are lower than those in the floor layer. The upward propagation of hydraulic fractures is easily in this pattern.

- **Type C: high–low–low (HLL).** Stress magnitudes in the floor and target fracturing layers are generally close to each other, but are lower than those in the roof layer. The downward propagation of hydraulic fractures is easily in this pattern.

- **Type D: interbedded.** Stress magnitudes change frequently in all layers. Hydraulic fractures can propagate both upward and downward.

- **Type E: uniform.** Stress magnitudes are generally unchanged in all layers. Hydraulic fractures can also propagate both upward and downward.

Vertical stress pattern is critical for understanding the vertical propagation of hydraulic fractures in layered media. Therefore, with accurate assessments of vertical stress pattern, the scale of hydraulic fracturing and the development of well network can be determined rationally (Feng et al. 2019).

### 8 Conclusions

In this study, the present-day in situ stress distribution within the Yanchang Formation Chang 7 shale oil reservoir is predicted based on well logs calibrated with measured data using the combined spring model. The effects of burial depth and Young’s modulus on stress distribution are also analyzed. The results in this study are expected to provide some new geological references for the exploration and development of shale oil within the Yanchang Formation Chang 7 oil-bearing layer of the Ordos Basin.

Generally, the following results and conclusions can be obtained:

1. In this study, a one-dimensional mechanical earth model is conducted, and the results indicate that the $S_{H\text{max}}$, $S_{h\text{min}}$, and $S_{v}$ magnitudes all increase with burial depth, and a dominant normal faulting stress regime is in the Yanchang Formation Chang 7 shale oil reservoir of Ordos Basin.

2. In the studied region, relatively high and low present-day stress magnitudes are distributed in the northwestern and southeastern regions, respectively.

3. The factor of burial depth indicates a linear relationship with burial depth; a larger burial depth results in a higher stress magnitude.

4. Rock Young’s modulus shows a great effect on the present-day stress distribution. Larger Young’s moduli produce higher stress magnitudes. In addition, the horizontal differential stress will become higher with
the increase in Young’s modulus, resulting in simple hydraulic fracture systems.

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