Stress Distribution in the Upper Shihezi Formation from 1D Mechanical Earth Model and 3D Heterogeneous Geomechanical Model, Linxing Region, Eastern Ordos Basin, Central China

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Abstract: The Upper Shihezi sedimentary rocks in the Linxing region has been estimated with a significant volume of tight sandstone gas. However, lateral distribution of the present-day stress magnitude is poorly understood, which limits further gas production. Hence, a one-dimensional mechanical earth model and a three-dimensional heterogeneous geomechanical model are built to address this issue. The results indicate that the strike-slip stress regime is dominant in the Upper Shihezi Formation. Relatively low stresses are mainly located around wells L-60, L-22, L-40, L-90, etc, and stress distributions exhibit the similarity in the Members H2 and H4. The differential stresses are relatively low in the Upper Shihezi Formation, suggesting that complex hydraulic fracture networks may be produced. Natural fractures in the Upper Shihezi Formation contribute little to the overall gas production in the Linxing region. In addition, the minimum principal stress gradient increases with Young’s modulus, suggesting that the stiffer rocks commonly convey higher stress magnitudes. There is a strong interplay between stress distribution and heterogeneity in rock mechanics. Overall, the relative error between the predicted and measured results is less than 10%, implying that the predicted stress distribution is reliable and can be used for subsequent analysis in the Linxing region.

Key words: stress distribution, numerical simulation, tight sandstone gas, Upper Shihezi Formation, Linxing region, Ordos Basin

1 Introduction

In general, the internal stress within the Earth’s crust is closely related to gravitational loading and tectonic stress (Bell, 1996; Kang et al., 2010). Knowledge of the present-day stress state can help better understand hydrocarbon migration and accumulation (Zoback, 2007; Tingay et al., 2010; Rajabi et al., 2016; Liu et al., 2017; Ju et al., 2018a). The Earth’s surface is commonly considered to be a free boundary and the gravitational acceleration is directed downwards; hence, characterizing the stress state typically involves determining the magnitudes of horizontal maximum (S$_{Hmax}$) and minimum (S$_{Hmin}$) principal stresses, vertical stress (S$_v$), and the horizontal stress orientation (Bell, 1996; Tingay et al., 2009; Brooke-Barnett et al., 2015). In addition, based on their relative magnitudes, three types of in-situ stress regime are generally

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determined, namely, the normal ($S > S_{Hmax} > S_{min}$), strike-slip ($S_{Hmax} > S > S_{min}$), and reserve ($S_{Hmax} > S_{min} > S$) faulting stress regime (Anderson, 1951).

The newly released World Stress Map (WSM) database (Heidbach et al., 2018) and previous studies (e.g., Ju et al., 2017) contain information on horizontal stress orientations in the Linxing region of eastern Ordos Basin. However, lateral distribution of the present-day stress magnitude is poorly understood, which, commonly, is irregular, heterogeneous and difficult to describe utilizing precise analytical solutions. In addition, at a local scale, there are many factors, e.g., the development and distribution of faults and folds, lithological changes, basement structures, that can affect the lateral distribution of stress magnitude (Bell, 1996; Heidbach et al., 2007; Brooke-Barnett et al., 2015; Liu et al., 2017; Ju et al., 2019).

The techniques for stress distribution analysis mainly include actual stress measurements (Zhao et al., 2005; Kang et al., 2010), indirect measurements based on well logging data (Brooke-Barnett et al., 2015; Rajabi et al., 2016; Ju et al., 2017; Liu et al., 2017), and numerical simulation methods (Fischer and Henk, 2013; Liu et al., 2017; Ju et al., 2019), etc. Furthermore, in tectonically stable regions, stress distribution may be largely controlled by lithological changes. Hence, two-dimensional (2D) numerical models and three-dimensional (3D) numerical models with the same rock mechanics parameter for an entire layer are no longer suitable for accurately predicting the present-day stress distribution. The reason lies in the fact that every single geological layer is regarded as homogeneous within those above models, which is definitely different from the real formation.

The Linxing region of eastern Ordos Basin is famous for the unconventional gas resources (e.g., tight sandstone gas, coalbed methane, and shale gas), however, previous tight sandstone gas studies within this region were mainly focused on the Lower Shihizei, Shanxi and Taiyuan formations (Zhao et al., 2016; Wang et al., 2017). Recently, the Upper Shihizei sedimentary rocks in the study area have also been estimated with host large volumes of tight sandstone gas (Wang et al., 2018); however, little attention has been paid to the geological conditions of this formation. Therefore, in this study, focused on the Upper Shihizei sedimentary rocks in the Linxing region of eastern Ordos Basin, a one-dimensional mechanical earth model (1D MEM) was calculated and a three-dimensional heterogeneous geomechanical model (3D HGM) was proposed and analyzed, providing tools for accurate prediction of the present-day stress distribution. It plays an important role in a better understanding of the geomechanical properties, and hence more accurate evaluation and production of tight sandstone gas for the Upper Shihizei sedimentary rocks in the Linxing region.

2 Geological Setting

The Ordos Basin in central China covers an area of over 2.5 × 10^5 km^2, and is characterized by stable subsidence, migrated depression, and obvious twisting (Liu et al., 2006; Ju et al., 2015). This Basin experienced a long and complex multicycle geological history ranging from the Middle Proterozoic to the Tertiary. During the Late Carboniferous to Triassic, the entire basin region subsided, entering a transitional period from marine to continental sedimentation. The present-day geomorphology indicates that central parts of the Basin are tectonically stable, surrounded by large numbers of faults and folds (Fig. 1; Yang, 2002).

The Linxing region is an economically significant area located in the eastern Ordos Basin (Fig. 1). It is a tectonically stable region and the strata generally dip northwestwards with the angle ranging between 5° and 10° (Fig. 2). A significant volume of unconventional gas has been found within this region (Guo et al., 2012; Ju et al., 2017). The Upper Shihizei, Lower Shihizei, Shanxi and Taiyuan formations are important layers for tight sandstone gas production; however, the geomechanical properties of the Upper Shihizei Formation in this region, in particular, their impacts on the unconventional gas, have been not yet fully understood, and thus require further studies.

The Upper Shihizei Formation in the Linxing region is deposited in a delta sedimentary environment and can be divided into four members, namely Member H1, H2, H3 and H4 from top to bottom (Fig. 3). Based on 602 sandstone samples from 20 wells, the porosity in sandstones is measured varying between 0.9% and 23.0% with an average of 9.5%. The air permeability for the majority (63.9%) of samples is generally less than 1.0 mD. Gas testing results indicate that the practical open flow potential can reach approximately 15.5 × 10^4 m^3/d within the Members H2 and H4 (Wang et al., 2018).

Obviously, both the porosity and air permeability within the Upper Shihizei Formation are relatively poor; hence, the production of tight sandstone gas requires some special techniques, such as the hydraulic fracturing approach. To improve the designs and operations of hydraulic fracturing, the present-day stress distributions in the Upper Shihizei Formation Members H2 and H4 should be accurately predicted.

3 Stress Variation from 1D MEM

3.1 Method for 1D MEM

The 1D MEM define the variations in the magnitude of the three principal stresses with burial depth. Among them, the $S_z$, or weight of the overburden, is the simplest to calculate based on Eq. (1), which is the integration of rock densities from the surface to a particular depth underground (Zoback et al., 2003; Brooke-Barnett et al., 2015).

$$S_z = \int_0^z \rho(z) gzdz$$

where $S_z$ is the vertical stress (MPa), $g$ is the gravitational acceleration ($m/s^2$), $\rho(z)$ is the density of the overburden rock as a function of burial depth (kg/m^3), and $z$ is the burial depth from the surface to a particular depth underground (m).

In the study area, density logs are not acquired from the
Fig. 1. Simplified regional geological map of the Ordos Basin in central China.

Fig. 2. Structural map of the Upper Shihezi Formation in the Linxing region, eastern Ordos Basin.
ground level. Generally, the shallow $S_v$ can be obtained from a relationship between density and sonic velocity data (Tingay et al., 2003); however, no velocity data are available between ground level and the first density data point. Hence, an extrapolation method was used here and a gradient of approximately 23000 Pa/m was identified in the open hole section to determine the $S_v$.

The calculations of horizontal stresses are based on the gravity-tectonic scenarios using the Eq. (2) (Bertotti et al., 2017).

$$S_{\text{Hmax}} = \frac{\mu}{1-\mu} (S_v - aP_o) + \frac{\mu}{1-\mu} S + aP_o \quad (2a)$$

$$S_{\text{hmin}} = \frac{\mu}{1-\mu} (S_v - aP_o) + S + aP_o \quad (2b)$$

where $S_{\text{Hmax}}$ and $S_{\text{hmin}}$ are the horizontal maximum and minimum stress, respectively (MPa), $\mu$ is the static Poisson’s ratio (unitless), $\alpha$ is the effective stress coefficient (unitless), $P_o$ is the pore pressure (MPa), and $S$ is the additional tectonic stress (MPa).

Generally, in the right hand of Eq. (2), the first term is a linear elastic term that transforms vertical stress to the horizontal stresses. The second term is about the external source of stress such as tectonic stress. The third term indicates the fluid pressure in the pore of the rock. Under the gravity-tectonic scenario, the $S_{\text{Hmax}}$ and $S_{\text{hmin}}$ are different. The $S_{\text{Hmax}}$ is a result of pore pressure, tectonic stress and the Poisson’s effect of the overburden. Meanwhile, the $S_{\text{hmin}}$ is calculated from pore pressure and the Poisson’s effect of both overburden and tectonic stress. The static Poisson’s ratio in Eq. (2) is an important parameter, which is commonly determined from rock mechanics experiments; however, those measured values are not continuous with burial depth. Therefore, in this study, the dynamic Poisson’s ratio is first calculated based on Eq. (3) (Fjaer et al., 2008), which is vertically continuous; after that, the relationship between static and dynamic Poisson’s ratio is fitted (Fig. 4) to obtain continuously changed static values with burial depth.

$$\mu_d = \frac{2-(V_p'/V_s')^2}{2(1-(V_p'/V_s')^2)}$$  \hspace{1cm} (3)

where $\mu_d$ is the dynamic Poisson’s ratio (unitless), $V_p'$ is the compressional wave velocity (m/s), $V_s'$ is the shear wave velocity (m/s), and $\rho$ is the rock density from bulk density logs (g/cm$^3$).

### 3.2 Results and analysis

In this study, tectonic stress is included in the gravity-tectonic scenario in addition to gravity. For the Upper Shihezi Formation in the Linxing region, several measured in-situ stress magnitudes are derived from extended leak-off tests (XLOTs) in wells L-40, L-60 and L-62 (Table 1) based on Eq. (4) (Bredenhoft et al., 1976; White et al., 2002; Zoback et al., 2003; Ju et al., 2017).

$$S_{\text{hmin}} = P_e \quad (4a)$$

$$S_{\text{Hmax}} = 3S_{\text{hmin}} - P_r - P_o \quad (4a)$$

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

Therefore, the additional tectonic stress $S$ can be
calculated based on Eq. (2) and those measured stress data in Table 1, and the magnitudes are 25.02 MPa, 20.63 MPa and 26.08 MPa for Well L-40, Well L-60 and Well L-62, respectively.

Stress variations with burial depth are calculated and plotted in Fig. 5. Generally, from the top to bottom of the model, the \(S_{H\text{max}}\) and \(S_{h\text{min}}\) are always the maximum and minimum principal stress, respectively, indicating that the strike-slip stress regime is dominant in the Upper Shihezi Formation of Linxing region.

### Table 1

<table>
<thead>
<tr>
<th>Well</th>
<th>Measured depth (m) Minimum-Maximum/Average</th>
<th>Interpreted (P_r) (MPa)</th>
<th>Interpreted (P_t) (MPa)</th>
<th>Interpreted (P_s) (MPa)</th>
<th>Measured minimum principal stress magnitude (MPa)</th>
<th>Measured maximum principal stress magnitude (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L-40</td>
<td>1300.10-1317.40/1308.75</td>
<td>29.06</td>
<td>26.75</td>
<td>12.97</td>
<td>26.75</td>
<td>38.22</td>
</tr>
<tr>
<td>L-60</td>
<td>1466.60-1472.10/1469.30</td>
<td>31.70</td>
<td>26.05</td>
<td>14.90</td>
<td>26.05</td>
<td>31.55</td>
</tr>
<tr>
<td>L-62</td>
<td>1495.90-1500.80/1498.35</td>
<td>34.61</td>
<td>30.12</td>
<td>13.68</td>
<td>30.12</td>
<td>42.07</td>
</tr>
</tbody>
</table>

where \(x\), \(y\), and \(z\) are used to indicate the direction of the plane on which the strain is acting in the Euclidean space, \(\varepsilon_{xx}\), \(\varepsilon_{yy}\), and \(\varepsilon_{zz}\) are the linear strain components (unitless), \(\gamma_{xy}\), \(\gamma_{yz}\), and \(\gamma_{zx}\) are the shear strain components (unitless), \(i\), \(j\) and \(k\) are the displacements along the \(x\)-, \(y\)- and \(z\)-plane, respectively (unitless).

Based on the relationship between stress and strain, the stress can be obtained as follows:

\[
\sigma = [E][\varepsilon]
\]

where \([\sigma]\) is the stress matrix (MPa), \([E]\) is the elasticity matrix (MPa), and \([\varepsilon]\) is the strain matrix (unitless).

Eqs. (5) and (6) form a 3D geomechanical model, which can be numerically solved by implementing the 3D geomechanical properties. As a result, the present-day stress distribution for given geological bodies can be predicted. The simulations generally involve the following:

![Fig. 5. 1D MEMs for the Upper Shihezi Formation in different wells of Linxing region.](image)

(a) Well L-40, (b) Well L-60, and (c) Well L-62. Dark grey dots: the \(S_{H\text{max}}\), black dots: the \(S\), and light grey dots: the \(S_{h\text{min}}\).
five steps as shown in Fig. 6:
i) building the 3D geometric framework from the bottom up,
ii) creating the 3D rock mechanics field in the Petrel E&P software platform (Schlumberger Limited, Houston, USA), and obtaining the corresponding parameters within each cell,
iii) integrating the geometric framework with rock mechanics parameters by setting a “searching length” for the connections between cells in the Petrel E&P software platform and elements in the ANSYS software (Appendix),
iv) constructing the 3D HGM by applying suitable boundary forces and displacements, and finally,
v) solving the geomechanical model to calculate the present-day in-situ stress distribution with a calibrating approach by comparing the predicted results with actually measured stress data from the XLOTs.

4.2 Geological model
Initially, the 3D geometric framework containing different layers is built utilizing the FE ANSYS software following the bottom up (namely, key points → lines → areas → volumes). It is important to make sure that the contact between two different volumes is tightly connected, which is critical for the next step of modeling. Then, the framework is meshed with triangular elements to reduce the calculation complexity and improve the accuracy (Liu et al., 2017), producing a series of nodes and elements, totally, 50,370 nodes and 232,882 elements in this study (Fig. 7a). According to the characteristics of different element types in the ANSYS software, the SOLID 185 element type is selected for the meshing.

Rock mechanics parameters applied to the 3D geometric framework are static values, hence, similarly, the continuous static Young’s modulus with burial depth within a single well is also determined based on the fitting relationship between logging interpretations (namely, the dynamic Young’s modulus; Eq. 7; Fjaer et al., 2008) and rock mechanics experiments (Fig. 8).

\[
E_d = \frac{\rho V_p^2 (3V_p^2 - 4V_s^2)}{V_p^2 - V_s^2} \tag{7}
\]

where \(E_d\) is the dynamic Young’s modulus (GPa), \(V_p\) is the...
compressional wave velocity (m/s), \(V_s\) is the shear wave velocity (m/s), and \(\rho\) is the rock density from bulk density logs (g/cm\(^3\)).

The Petrel software is employed to determine the 3D rock mechanics field from distributed wells. The field can be obtained based on three main steps as follows:

i) data input. Loading well logs with calculated static rock mechanics parameters and creating a blocked 3D network, which is fundamental to produce reality-oriented models.

ii) structural modeling, which includes pillar gridding, makeup horizons, and layering. Pillar gridding is the process of generating the grid, the size of which should be at the same level as the element size in the ANSYS software. Makeup horizons and layering are used for vertical divisions.

iii) property modeling, including data upscaling and petrophysical modeling. When upscaling, Petrel will first find the 3D grid cells that the wells penetrate, and then, rock mechanics parameters that fall within the cell will be averaged to produce one value for that cell. Petrophysical modeling in this study is the process of assigning rock mechanics parameters to each of the 3D grid. When well logs have been scaled up to the resolution of the cells in the 3D grid, the values for each cell along the well trajectory can be interpolated between the wells in the 3D grid. This process includes a calculation for solving complex mathematical equations, and variogram is commonly used to analyze and describe the spatial changes of parameters (Kamali et al., 2013).

After all the steps, rock mechanics parameters in the Petrel software will be integrated with a geometric framework in the ANSYS software to build a 3D HGM (Fig. 7b) based on the above-mentioned method in section 4.1 and the Appendix. Hence, each element within the ANSYS software is associated with appropriate and different rock mechanics parameters.

### 4.3 Boundary conditions

The boundary conditions of the geological model include external forces (tectonic stresses and gravity loading) and displacement conditions. Commonly, the gravity loading can be automatically applied in the ANSYS software by setting the gravitational acceleration and rock density; whereas, the tectonic stresses are determined based on geological and/or experimental interpretations (e.g., hydraulic fracturing tests). According to a report from Ju et al. (2017), the \(S_{Hmax}\) orientation is NW-WNW – ESE-trending in the Linxing region from interpretations of borehole breakout and drilling-induced tensile fractures, which is used for numerical simulations in this study. The stress magnitude of \((0.0325 \ h \ -5.1692)\) MPa for \(S_{Hmax}\), and \((0.0249 \ h \ -5.8404)\) MPa for \(S_{Hmin}\) \((h:\) burial depth) are applied in the WNW-ESE direction and NNE-SSW direction, respectively. In addition, to prevent the geological model from rotation and displacement, the top surface is set free and the bottom of the model is vertically fixed.

### 4.4 Results and error analysis

Applying the 3D HGM as described above to the Linxing region, the present-day stress distribution within the Upper Shihezi Formation (especially in the Members H2 and H4) can be determined. The results are shown in Fig. 9. In this study, it is assumed that compressive stresses are negative and tensile stresses are positive.

As indicated in Fig. 9, the present-day maximum (\(\sigma_1\)) and minimum (\(\sigma_3\)) principal stress magnitudes vary between \(-38.5\) MPa and \(-52.0\) MPa, and \(-25.0\) MPa and \(-34.0\) MPa, respectively for the Upper Shihezi Formation Members H2 and H4 of Linxing region. The stress magnitudes in Member H4 are slightly larger than those in Member H2. In addition, it can be found that stress distributions in both members show the similarity. Relatively low-stress values are mainly located around wells L-60, L-22, L-40, L-90, etc (Fig. 9).

The reliability of simulation results is verified by comparing the measured in-situ stress data from wells L-40, L-60, L-62. The relative errors are generally less than 10% (Table 2) as calculated based on Eq. (9). Hence, it shows that the 3D HGM developed in this study can be used to accurately predict the present-day stress distribution under given geological and boundary conditions.

\[
r = \frac{S_m - S_s}{S_m} \times 100\% \tag{9}
\]

where \(r\) is the relative error (unitless), \(S_m\) and \(S_s\) are the measured and calculated stress value, respectively (MPa).

In addition, the results from 1D MEM indicate that the Upper Shihezi Formation experiences the dominant slip-stress regime, hence, the \(\sigma_1\) and \(\sigma_3\) are \(S_{Hmax}\) and \(S_{Hmin}\), respectively in this study.

As mentioned before, the Upper Shihezi Formation in the Linxing region received little attention previously. For this reason, this formation has rarely been considered for tight gas production and hence, wide-spread fracturing and horizontal wells have not yet been deployed. Therefore, the results in Fig. 9 represent the important efforts in revealing the lateral distribution of present-day stress magnitude within the Upper Shihezi Formation of Linxing...
region, which may provide several significant implications for tight sandstone gas production, which will be discussed in details later.

5 Discussions

5.1 Effects of rock mechanics on stress distribution

In the tectonically stable Linxing region, stress distribution may be largely controlled by lithological changes (rock mechanics) due to the lack of faults and folds. Taking the Upper Shihezi Formation Member H2 as a case study, the relationship between rock Young’s modulus and stress gradient is analyzed (Fig. 10). It can be found that the minimum principal stress gradient increases with the dynamic Young’s modulus, suggesting that rock mechanics can exhibit a significant effect on stress transfer through the reservoir and that the stiffer rocks commonly convey higher stress magnitudes. In addition, the results also reflect that there is a strong interplay between stress distribution and heterogeneity in rock mechanics (Pham and Chang, 2018).
5.2 Pore pressure effect

Pore pressure and the in-situ stress field are interrelated. The changes in pore pressure will influence the present-day in-situ stress state. Generally, the increase of pore pressure can reduce both the effective and differential stress at the same time (Hillis, 2001; Binh et al., 2007), resulting in the creation of new fracture sets and/or reactivation of pre-existing natural fractures and faults if pore pressure is large enough (Hillis, 2001; Tingay et al., 2003; Ju et al., 2018b).

Engelder and Fischer (1994) derived a formula that accounts for the change of horizontal stress with a change in pore pressure using simply the equations of linear elasticity under the assumption of no lateral strains (Eq. 10).

\[
\Delta S_h = a \frac{1 - 2\mu}{1 - \mu} \Delta P_o
\]

where \(\Delta S_h\) is the change of horizontal stress (MPa), \(a\) is the effective stress coefficient (unitless), \(\mu\) is the Poisson’s ratio (unitless), and \(\Delta P_o\) is the change in pore pressure (MPa).

In this study, the \(\Delta S_h\) caused by \(\Delta P_o\) is analyzed in wells L-40, L-60, and L-62 and illustrated in Fig. 11, which indicates that their relationship generally follows \(\Delta S_h = (0.25–0.45) \Delta P_o\) in the Upper Shihezi Formation of the Linxing region.

5.3 Implication for hydraulic fractures

Tight sandstone gas production typically involves hydraulic fracturing to stimulate the production of natural gas. There are many geological factors that affect the propagation of hydraulic fractures, e.g., the present-day stress state, mechanical layering, and the development and distribution of natural fractures, etc (Philipp et al., 2013; Fatahlaanshi et al., 2016; Liu et al., 2017).

One of the most important factors is the stress difference between the present-day maximum and minimum principal stresses, as defined by Eq. (11), which is widely used to understand the propagation pattern of hydraulic fractures in reservoirs. Hydraulic fracture networks under a higher differential stress magnitude are usually simple, and the propagation of a hydraulic fracture is largely determined by the orientation of maximum principal stress. On the contrary, a lower differential stress magnitude (e.g., less than 10.0 MPa for tight sandstones and 9.0 MPa for shale from experimental results by Liu et al., 2019 and Guo et al., 2014, respectively) can produce complex hydraulic fracture networks in most cases (Renshaw, 1994; Guo et al., 2014; Liu et al., 2019). Furthermore, Guo et al. (2014) also indicate that the complexity of hydraulic fracture does not increase any more with the decrease of stress difference under a low-level condition, such as a stress difference of 3.0 MPa.

\[
\Delta \sigma = |\sigma_1 - \sigma_3|
\]

where \(\Delta \sigma\) is the stress difference (MPa), and \(\sigma_1\) and \(\sigma_3\) are the present-day maximum and minimum principal stress, respectively (MPa).

In the Upper Shihezi Formation Members H2 and H4 of Linxing region, the predicted \(\Delta \sigma\) values vary between 6.0 MPa and 13.2 MPa and mainly range from 6.0 MPa to 10.0 MPa (Fig. 12). The differential stress magnitudes are relatively low, implying that the present-day stress field within the Members H2 and H4 might contribute to the generation of complex hydraulic fracture networks.

5.4 Implication for natural fractures

Generally, in tight sandstone gas reservoirs, the development of natural fractures can significantly improve the fluid flow capability. In the imaging logs, natural fractures commonly display as continuous or discontinuous sinusoidal waves and can be easily traced, whereas drilling-induced fractures either appear as two vertical/sub-vertical fractures on opposite sides of the borehole, or are complex appearing in en-echelon fractures or chevron pattern around the borehole wall (Hillis and Reynolds, 2003; Zoback et al., 2003; Ju et al., 2018b). In this study, observations from the borehole imaging logs and drill cores indicate that natural fractures are not well developed within the Upper Shihezi Formation of Linxing region, natural fractures are generated striking mainly in ~NE-SW-trending (Fig. 13).
available; hence, the productivity of each fracture set is unable to evaluate. However, considering the ~WNW–ESE-trending present-day $S_{\text{Hmax}}$ orientation, ~NE–SW-trending fracture strike, and the low fracture density, it can be predicted that natural fractures may contribute little to the overall tight sandstone gas production in the Upper Shihezi Formation of Linxing region, eastern Ordos Basin.

6 Conclusions

(1) A one-dimensional mechanical earth model (1D MEM) is conducted in this study, which indicates that the strike-slip stress regime is dominant in the Upper Shihezi Formation of Linxing region.

(2) A three-dimensional heterogeneous geomechanical model (3D HGM) for the Upper Shihezi Formation in the Linxing region of Ordos Basin is established by considering spatial variations of rock mechanics parameters. The simulation results indicate that the maximum and minimum principal stress magnitudes within the Upper Shihezi Formation Members H2 and H4 are generally between -38.5 MPa and -52.0 MPa, and -25.0 MPa and -34.0 MPa, respectively.

(3) The effects of rock mechanics and pore pressure on in-situ stresses are analyzed. The results indicate that the relationship generally follows $\Delta S_h = (0.25–0.45) \Delta P_o$. The minimum principal stress gradient increases with the dynamic Young’s modulus, suggesting that stiffer rocks convey higher stress magnitudes, and that rock mechanics can greatly influence stress distributions.

(4) The implications of in-situ stresses on hydraulic and natural fractures are discussed. Stress difference values within the Upper Shihezi Formation Members H2 and H4 are between 6.0 MPa and 13.2 MPa, suggesting that complex fracture networks may be produced. Natural fractures within the Upper Shihezi Formation are not well developed and strike mainly in ~NE–SW-trending; hence, they contribute little to the overall gas production under the present-day stress state.

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Appendix

The ANSYS Parametric Design Language (APDL) codes for integrating the geometric framework with rock mechanics parameters are listed as follows:

```
**dim,mpara1,,aa,6,6,6,6,6,6
vread,mpara1(1,1),property data text name,txt,jik,6,aa,0,0,0,0,0,0,0,0,0,0,0,0,(6F13.3)
do,i,aa
   mp.ex,i,mpara1(i,4)
   mp.prxy,i,mpara1(i,5)
   mp.dens,i,mpara1(i,6)
endo
xo=initial x value
yo=initial y value
zo=initial z value
**2+(mpara1(di,1)-xo)**2+(mpara1(di,2)-yo)**2+(mpara1(di,3)-zo)**2
*if,dist1,le,xdist,then
   ldist=xdist
   rowi=di
*endif
*endif
emodif,ei,mat,rowi
endo
```

References


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