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REVIEW

A workflow to Predict the Present-day in-situ Stress Field in Tectonically Stable Regions

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ABSTRACT

Knowledge of the present-day in-situ stress distribution is greatly important for better understanding of conventional and unconventional hydrocarbon reservoirs in many aspects, e.g., reservoir management, wellbore stability assessment, etc. In tectonically stable regions, the present-day in-situ stress field in terms of stress distribution is largely controlled by lithological changes, which can be predicted through a numerical simulation method incorporating specific mechanical properties of the subsurface reservoir. In this study, a workflow was presented to predict the present-day in-situ stress field based on the finite element method (FEM). Sequentially, it consists of: i) building a three-dimensional (3D) geometric framework, ii) creating a 3D petrophysical parameter field, iii) integrating the geometric framework with petrophysical parameters, iv) setting up a 3D heterogeneous geomechanical model, and finally, v) calculating the present-day in-situ stress distribution and calibrating the prediction with measured stress data, e.g., results from the extended leak-off tests (XLOTs). The approach was successfully applied to the Block W in Ordos Basin of central China. The results indicated that the workflow and models presented in this study could be used as an effective tool to provide insights into stress perturbations in subsurface reservoirs and geological references for subsequent analysis.

1. Introduction

In-situ stress refers to the internal stress within the Earth's crust, which is closely related to gravitational and tectonic stresses [1,9]. Knowledge of the present-day in-situ stress distribution is greatly important in a wide range of fields including oil and gas exploration and development [2,7,15,16,17,19,23], wellbore stability assessment [13,23,25], reservoir management [3,21], and CO_2 sequestration [5], etc.

In general, plenty of factors, e.g., the development of faults, contrasts in rock mechanical properties, and basement structures, etc. can cause stress perturbations and produce local stresses that may significantly deviate from the regional stress field [4,8,14]. Therefore, within a reservoir scale, stress

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magnitudes and orientations are frequently not homogeneous, which may lead to incorrect pre-drilling prediction [8].

In tectonically stable regions, faults and folds are usually not developed, and the present-day in-situ stress variations may be largely controlled by lithological changes. Currently, the majority of available two-dimensional (2D) and simple three-dimensional (3D) models are not suitable for understanding stress distributions because the whole reservoir or layer is regarded as homogeneous and assigned identical mechanical parameters. Such assumptions are often inconsistent with the actual geological conditions, resulting in relatively large errors during stress field simulations [18,20]. Therefore, complex 3D heterogeneous models with specific mechanical properties of the subsurface reservoir are required to obtain quantitative understandings of the present-day in-situ stress distributions.

In this study, a workflow consisting of 3D heterogeneous models has been developed to predict the present-day in-situ stress distribution with a case study in the Block W of Ordos Basin. The FEM has been proven to be a valid approach to address such reservoir issues [11,12]. The results in this study were verified with measured stress data, suggesting the proposed workflow could be used as an effective tool for predicting the present-day in-situ stresses and hence providing some important geological references in subsequent analysis of a given reservoir.

2. The General Workflow for Stress Field Prediction in Tectonically Stable Regions

The finite element (FE) technique was utilized in this study to gain quantitative insights into the present-day stress distributions because this approach allows complex geometries and heterogeneous mechanical properties. In this study, a workflow was developed to predict the present-day in-situ stress field with five steps shown in Figure1. The details were described in the following sections.

2.1 3D Geometric Framework

The first step of this workflow development is to build a 3D geometric framework, which is generally labor-intensive. The FE software ANSYS (Ansys Inc., Houston, USA) was employed to construct the 3D geometric framework of a given reservoir in this study. A typical framework building procedure generally includes a few sub-steps as outlined as follows:

(1) Choosing an appropriate element type. For solving this kind of issue, the elements of Solid 185 and Solid 186 within the ANSYS software are the proper choices.

(2) Generating different solid model features from the bottom up. That is, create key points, and then define lines, areas, and volumes as needed. Commonly, the initial input data for different layer surfaces are derived from interpretation of available 3D seismic.

(3) Applying the Boolean operators or specific number controls to join separate solid model regions together as appropriate.

(4) Setting meshing controls to establish desired mesh density, and creating nodes and elements by meshing the solid model. The spatial resolutions and element sizes inside the model are controlled by the study area scale and device conditions.

2.2 Petrophysical Parameters

Creating a 3D petrophysical parameter field is completed in the Petrel E&P software platform (Schlumberger Limited, Houston, USA), which is also labor-intensive. The general outline follows:

(1) Data (well heads, well tops and well logs, etc.) preparation and loading. Well heads contain the position of each well and measured depth along the path. Well tops are the markers representing significant points. Well logs include basic logs (density, gamma curve, acoustic log, etc.) and calculated logs (Young's modulus, Poisson's ratio, etc.).

(2) 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.

(3) Property modeling, including scale up well logs and petrophysical modeling. Scale up well logs will average the values to the cells in the 3D grid. Petrophysical modeling is the process of assigning petrophysical property values to each cell of the 3D grid using geostatistical methods, e.g., the Sequential Gaussian Simulation Algorithm.

2.3 Integrating 3D Geometric Framework with Petrophysical Parameters

The grids used for property modeling and flow simulations in the Petrel E&P software platform are different from those in the FE ANSYS software. Hence, it is necessary to integrate the previously built geometric framework with petrophysical parameters so as to build a 3D heterogeneous geological model. The procedure of integrating 3D geometric framework with petrophysical parameters is given as follows:

(1) Exporting petrophysical parameters, including rock density, Young's modulus, and Poisson's ratio, from Petrel E&P software platform combined with corresponding cell center xyz coordinates.

(2) Calibrating these mechanical properties utilizing static ones obtained from rock mechanics experiments on drill

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cores.

(3) Setting a "searching length" for the connections between cells in the Petrel E&P software platform and elements in ANSYS software, which is determined based on the element size.

(4) Integrating the framework with petrophysical parameters by means of the ANSYS Parametric Design Language (APDL), and thus, the 3D heterogeneous geological model is built. The codes for this implementation are listed in the Appendix.

2.4 3D Heterogeneous Geomechanical Model

Applying suitable boundary forces and displacements to the 3D heterogeneous geological model obtained from Section 2.3 will construct the geomechanical model, as described in the following procedure:

(1) Determining the applied boundary force orientations. Those can be derived from interpretations of borehole stress-induced failures (e.g., borehole breakout and drilling-induced tensile fracture [14,1519,25], paleomagnetic analysis [24], earthquake focal mechanism inversion [10,22], etc.

(2) Determining the applied boundary force magnitudes. Vertical force magnitudes are generally calculated from the bulk density of rocks and can be automatically applied in the ANSYS software by setting the gravitational acceleration. Initial horizontal force magnitudes are commonly obtained from the regional analysis.

(3) Determining the applied boundary displacements. Commonly, the top portion is set as a free surface and the bottom is fixed with respect to vertical movements.

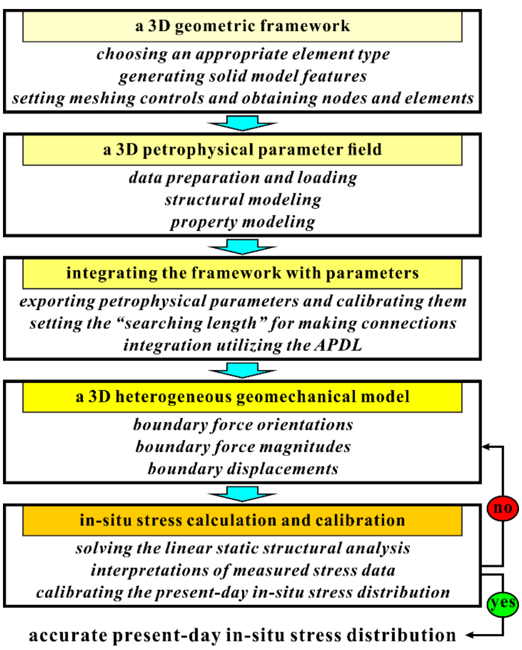

Figure 1. Summary of the workflow for predicting the present-day stress field in tectonically stable regions

2.5 Prediction of In-situ Stress Distribution and Validation

Finally, the geomechanical model is numerically solved to obtain the present-day in-situ stress distributions. The results are further calibrated with measured stress data for validation, e.g., the extended leak-off tests (XLOTs).

(1) The geomechanical model developed above is numerically solved through the linear static structural analysis solver in the FE ANSYS software.

(2) The calibration and validation are carried out by comparing the calculated stresses with actually measured stress data, e.g., the extended leak-off tests (XLOTs) [15,25] and the acoustic emission experiment on drill cores [6]. If most of the calculated errors are relatively low, ranging between -0.1 and 0.1, the calculated stresses will be used for predicting the present-day in-situ stress distribution. Otherwise, the geomechanical model requires rebuilt by repeating previous procedures.

3. A case Study in the Block W of Ordos Basin

The workflow outline presented above is applied to the Block W of Ordos Basin, central China, within which, faults and folds are not developed. It is a tectonically stable region with flat sedimentary layers. The Block W is an important area for unconventional gas production in the Ordos Basin of China, including tight sandstone gas and coalbed methane (CBM). For example, the L Formation acts as one of the most economic tight sandstone gas reservoirs within the Block W.

First, the 3D geometric framework (Figure 2) and 3D petrophysical parameter field (Figure 3) for the Block W were built utilizing the ANSYS software and Petrel E&P software platform, respectively. The 3D geometric framework was integrated with petrophysical parameters by using those codes in the Appendix.

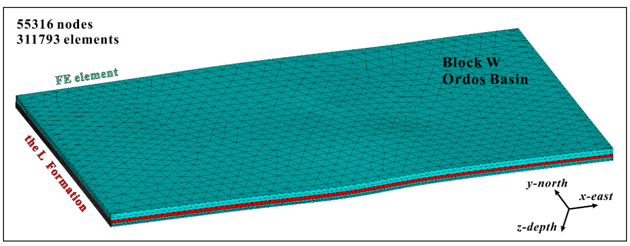

Figure 2. The 3D geometric framework for the Block W in Ordos Basin, central China

Interpretations of borehole breakouts and DITFs indicated that the horizontal maximum principal stress (S_{Hmax}) orientation was ~E-W-trending within the Block W (Figure 4). Multiple attempts have been made in simulation in terms of the calibration utilizing the XLOTs results from

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four wells (Table 1) within the study area to obtain the best fit present-day stress distributions (Figure 5).

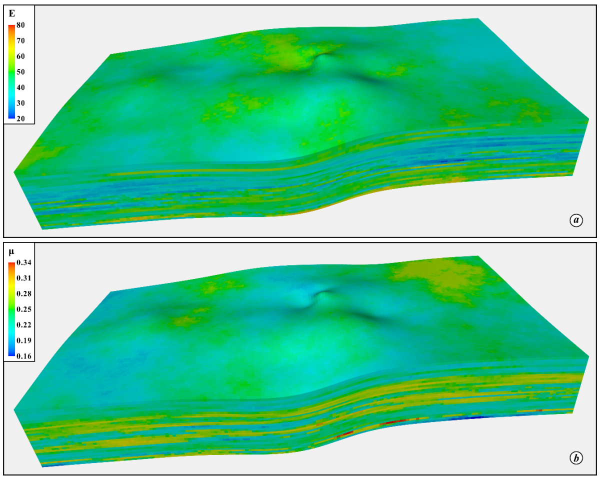

Figure 3. The 3D distributions of dynamic Young's modulus (a) and dynamic Poisson's ratio (b) for the Block W in Ordos Basin

Note: E is the dynamic Young's modulus (GPa), μ is the dynamic Poisson's ratio, and vertical exaggeration × 5.0.

Table 1. The comparison between actually measured and modelled stress magnitudes in the Block W of Ordos Basin

Well	Measured minimum principal stress magnitude (MPa)	Modelled minimum principal stress magnitude (MPa)	Error[(a)]
W-3	26.89	29.23	0.0870
W-6	37.63	28.99	-0.2296
W-7	29.87	30.88	0.0338
W-8	28.42	31.01	0.0911

Note: [(a)] the error is calculated based on the equation of (modelled data-measured data)/measured data.

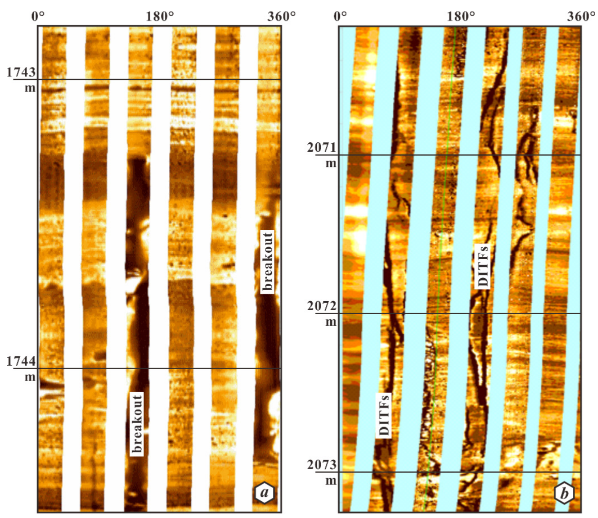

Figure 4. Borehole breakouts (a) and drilling-induced tensile fractures (DITFs) (b) interpreted from imaging logs in the Block W of Ordos Basin

The plots shown in Figure5 nicely display and elucidate the present-day in-situ stress perturbations in the L Formation, which can be used for numerous applications within the Block W of Ordos Basin, e.g., guiding the development of tight sandstone gas.

4. Conclusions

A better understanding of a reservoir largely relies on the sufficient knowledge of present-day in-situ stresses, which contributes to successful gas exploration and production, hydraulic fracturing design and borehole stability. In tectonically stable regions, conventional 2D and simple 3D models can not reveal the specific present-day in-situ stress perturbations. The complex 3D heterogeneous models were developed to provide the fundamental base for a general workflow to predict the present-day in-situ stress field. The workflow consists of five steps, namely, (1) building a three-dimensional (3D) geometric framework,(2) creating a 3D petrophysical parameter field, (3) integrating the geometric framework with petrophysical parameters, (4) setting up a 3D heterogeneous geomechanical model, and finally, (5) calculating the present-day in-situ stress distribution and calibrating the prediction with measured stress data. The workflow was further presented in details by implementing it to the Block W of Ordos Basin as a case study. The results indicated that this proposed workflow can be used to accurately predict the present-day stress field in tectonically stable regions. The information on the in-situ stress distribution can be used for improved plannings of numerous applications.

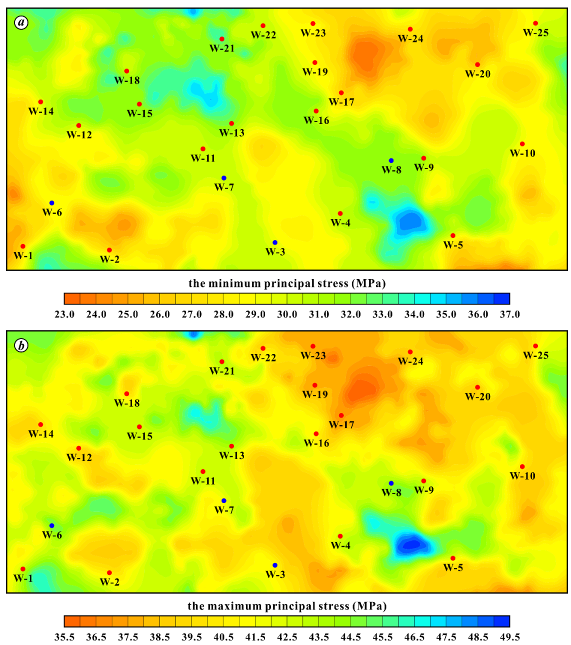

Figure 5. The maximum (a) and minimum (b) principal stress within the L Formation of Block W, Ordos Basin

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It is assumed that positive values are compressive stresses in this study.

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Appendix

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

```
/prep7
aa=lines of property data
*dim,mpara1,,aa,6,,,
*vread,mpara1(1,1),property data text name,txt,,jik-
,6,aa,,0,
(6F13.3)
*do,i,1,aa
mp,ex,i,mpara1(i,4)
mp,prxy,i,mpara1(i,5)
mp,dens,i,mpara1(i,6)
*enddo
xo=initial x value
yo=initial y value
zo=initial z value
*do,i,1,aa
 mpara1(i,1)=mpara1(i,1)-xo
 mpara1(i,2)=mpara1(i,2)-yo
 mpara1(i,3)=mpara1(i,3)-zo
*enddo
*do,ei,1,element number
  xx=0
  yy=0
  zz=0
*do,ni,1,4
   xx=xx+nx(nelem(ei,ni))
   yy=yy+ny(nelem(ei,ni))
   zz=zz+nz(nelem(ei,ni))
*enddo
 xx=xx/4
 yy=yy/4
 zz=zz/4
 ldist=searching length
 rowi=1
*do,di,1,aa
   dist1=(mpara1(di,1)-xx)**2+(mpara1(di,2)-yy)**2+
(mpara1(di,3)-zz)**2
   *if,dist1,le,ldist,then
      ldist=dist1
      rowi=di
   *endif
   *enddo
    emodif,ei,mat,rowi
   *enddo
```

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