Research article

Comprehensive evaluation technology for shale gas sweet spots in the complex marine mountains, South China: A case study from Zhaotong national shale gas demonstration zone

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Abstract

The exploration and development of marine shale gas reservoirs in South China is challenged by complex geological and geographical conditions, such as strong transformation, post maturity, complex mountains and humanity. In this paper, the evaluations on shale gas sweet spots conducted in Zhaotong demonstration zone in the past six years and the construction of 500 million m³ shale gas productivity in Huangjinba region were discussed, and the results of shale gas reservoir evaluations in China and abroad were investigated. Accordingly, it is proposed that another two key indicators be taken into consideration in the evaluation on shale gas sweet spots in marine mountains in South China, i.e. shale gas preservation conditions and pore pressure, and the research on ground stress and natural microfracture systems should be strengthened. Then, systematic analysis was conducted by integrating shale gas multidisciplinary data and geological and engineering integration study was carried out. Finally, a 3D model, which was composed of “geophysics, reservoir geology, fracture system and rock geomechanics”, was established for shale gas reservoirs. Application practice shows that the geological engineering integration and the 3D reservoir modeling are effective methods for evaluating the shale gas sweet spots in complex marine mountains in South China. Besides, based on shale gas sweet spot evaluation, 3D spatial congruency and superposition effects of multiple attributes and multiple evaluation parameters are presented. Moreover, the short-plate principle is the factor controlling the distribution patterns and evaluation results of shale gas sweet spots. It is concluded that this comprehensive evaluation method is innovative and effective in avoiding complex geological and engineering risks, so it is of guiding significance in exploration and development of marine shale gas in South China.

Keywords: South China; Marine shale gas; Reservoirs; Sweet spot; 3D reservoir model; Geological engineering integration; Comprehensive evaluation; Zhaotong (Yunnan) national shale gas demonstration zone

Shale gas, as a clean unconventional energy source, is the focus for exploration in recent years due to its abundant resources and the successful development in the United States [1]. Zhaotong exploration area in northern Yunnan—Guizhou was granted with the first shale gas prospecting license in China in 2009 and was listed in the first national shale gas demonstration zones in South China established by PetroChina in 2012. Currently, in this demonstration zone, commercial breakthroughs have been obtained through shale gas wells in the marine Upper Ordovician Wufeng Fm and Lower Silurian Longmaxi Fm. In addition, four shale gas sweet spots have been selected and Huangjinba shale gas producing area with a productivity of 500 million m³ has been basically established.

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The proven shale gas in place (GIP) has been booked to the government. Through studies and practices in the past years, a systematic exploration and development scheme suitable for marine shale gas reservoirs in the mountains of South China has been formed, which is “orderly play selection → stage evaluation → production capacity construction by play → beneficial development”. It opens an efficient and leading development mode for the geological engineering integration of marine shale gas [1–4] and lays a solid foundation for the exploration and development of shale gas in the complex marine mountains of South China.

1. Evaluation and selection of shale gas sweet spots in mountains

In Zhaotong demonstration zone, the high-quality Wufeng and Longmaxi shales, as the target formations, are developed at the bottom of the lower member of Longmaxi and Wufeng Fms [5]. It can be divided into five sub-layers (pay zones), i.e. I1, I2, I3, I4 and I5 (Fig. 1, Table 1). Under the control of the depositional environment and sedimentary facies belt of Guangxi Period and the Eastern Yunnan—Central Guizhou paleoulift, the high-quality shale gas reservoirs exist in the synclinorium of Jianwu, Mu’ai and Yiliang in the north of Northern Yunnan—Guizhou Depression [5–9]. These reservoirs, in nearly NEE—EW trending, presents the mountain—hill geomorphic features similar to Yunnan—Guizhou Plateau.

The organic-rich shales in Zhaotong demonstration zone was deposited in the same sedimentary environment and represents similar reservoir properties to the Haynesville, Barnett and Marcellus shales in North America [10–12], but they are older and higher in evolution degree. However, its geological engineering and surface conditions are significantly different due to different hydrocarbon generation, burial environment and evolution history in the late stage. The shales in Zhaotong demonstration zone remained in depression after being reformed due to multi-phase orogenic events since the Indosinian epoch, representing intense and abrupt lateral deformation as well as complicated geological stress background and natural fractures. The shale gas reservoirs have already entered into an overmature stage when hydrocarbon generation tends to be stagnant. Accordingly, the occurrence pattern of shale gas is dominated by the preservation and re-accumulation of primary gas pools. In addition, the formation pore pressure of shale gas pools drops and represents non-continuous distribution pattern due to the loss and destruction of shale gas. The shale gas pools in North American that are developed in stable craton platform are mostly at a moderate—high evolution stage and contain a plenty of wet gas and dry gas, while those in Zhaotong demonstration zone are dominated by primary gas pools with weak deformation and high formation pore pressure, which are continuously distributed in a large area and associated with shale oil and tight oil. In terms of surface topography, Zhaotong demonstration zone represents mountain—hill geomorphology with a large number of high mountains and deep valleys, sparse flat bars and concentrated population, while North America represents a great plain with a vast territory and a spare population. Therefore, in the complex marine mountain shale gas exploration area of South China represented by Zhaotong demonstration zone, two key indicators, i.e. shale gas preservation conditions and pore pressure, are particularly critical and important for the enrichment and occurrence of shale gas.

Compared with Changning, Weiyuan and Fuling shale gas demonstration zones in the Sichuan Basin [13–15], the shales in Huangjinba of Zhaotong demonstration zone have the same...
or similar static parameters, such as sedimentary facies, geochemical indicators, gas content and brittleness index (Table 2), but significantly different sedimentary burial and tectonic reworking history, crustal stress, fracture features, reservoir properties and pore pressure, representing unique shale gas enrichment and occurrence features. First, Sichuan—Chongqing shale gas enrichment and occurrence region has simple structure and large contiguous area. For example, the gas-bearing area is over 500 km² in Jiaoshiba (Fuling) and over 1000 km² in Weiyuan and Changning. However, Zhaotong demonstration zone has complex structure, representing the synclinorium formed in response to the superimposition of multi-phase tectonic compressions and strike-slipping. Accordingly, the shale gas enrichment and occurrence region (synclinal tectonic belt) is small in contiguous area and disperse in distribution. Second, Sichuan—Chongqing shale gas enrichment and occurrence region is characterized by simple crustal stress environment, multiple compression—torsions and small horizontal stress difference (generally less than 15 MPa), which may not bring great challenges to the drilling fracturing technology. In contrast, for Zhaotong demonstration zone is located in the triangle zone of Sanjiang strike-slip belt, the crustal stress environment is extremely complex, which represents as the superimposition of strike-slip and compression—torsion with horizontal stress difference of over 20 MPa. This brings huge challenges to the safety of drilling and volume fracturing. Third, the pore pressure coefficient of Sichuan—Chongqing shale gas enrichment and occurrence region is generally high, mostly over 1.5, while the pore pressure coefficient of Zhaotong demonstration zone is only high in YS108 well block closed to synclinal axis (Table 2). The production test results of Zhaotong demonstration zone reveal that the original shale pore pressure coefficient is mostly 1.45—1.96 in the vertical appraisal well with daily gas production over $1 \times 10^6$ m³ (the coefficient lower than 1.2 suggests a low-yield well or dry well). Therefore, in the evaluation on the marine shale gas sweet spots in South China represented by Zhaotong demonstration zone, great importance should be attached to the special geological conditions of the marine mountain shale gas in South China, in addition to the eight regular indicators (i.e. burial depth and thickness, organic matter abundance and maturity, physical property and gas-bearing potential, material composition and mechanical property) of shale gas in China and abroad [14]. Therefore, another two key indicators should be taken into account, namely shale gas preservation condition and pore pressure (Fig. 2).

Practical exploration evaluations reveal that, in regional caprock denudation and missing regions, fault development zones and hydrogeological desalination zones, shale gas pools generally turn into gas-free regions (zone) with low formation pressure coefficient due to destruction, while in the slope belts with good sealing capacity, shale gas is well preserved and the productivity of shale gas wells increases with the increase of

<table>
<thead>
<tr>
<th>Sub-layer division and evaluation of the lower member of Wufeng—Longmaxi Shale reservoirs in Zhaotong demonstration zone.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sub-layer (Pay zone)</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>I₁</td>
</tr>
<tr>
<td>I₂</td>
</tr>
<tr>
<td>I₃</td>
</tr>
<tr>
<td>I₁—I₂</td>
</tr>
</tbody>
</table>

Note: Data after “%” refer to average value.

Table 1

<table>
<thead>
<tr>
<th>Item</th>
<th>Zhaotong demonstration zone (Huangjinba)</th>
<th>Chongning demonstration zone</th>
<th>Weiyuan demonstration zone</th>
<th>Fuling (Jiaoshiba)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tectonic setting</td>
<td>Synclinal axis-slope belt</td>
<td>Gentle slope belt in the north flank of syncline</td>
<td>Paleohigh slope</td>
<td>Box-shaped anticline</td>
</tr>
<tr>
<td>Regional tectonic stress</td>
<td>(strike-slip + extrusion)</td>
<td>Extrusion</td>
<td>Extrusion</td>
<td>Dominated by extrusion</td>
</tr>
<tr>
<td>TVD of high-quality shale/m</td>
<td>2030—2950</td>
<td>2450—2650</td>
<td>1800—3697</td>
<td>2100—2500</td>
</tr>
<tr>
<td>Thickness of high-quality shale/m</td>
<td>31—38</td>
<td>30—46</td>
<td>24—40</td>
<td>30—45</td>
</tr>
<tr>
<td>TOC</td>
<td>2.1—6.7%</td>
<td>2.8—6.3%</td>
<td>2.2—5.3%</td>
<td>2.0—8.0%</td>
</tr>
<tr>
<td>Porosity</td>
<td>2.0—5.0%</td>
<td>2.9—5.0%</td>
<td>2.4—5.9%</td>
<td>4.0—7.0%</td>
</tr>
<tr>
<td>Gas content/m³ (⁻¹)</td>
<td>2.0—4.5</td>
<td>2.2—5.5</td>
<td>2.5—4.35</td>
<td>4.7—5.7</td>
</tr>
<tr>
<td>Pressure coefficient</td>
<td>1.60—1.96 (4 wells)</td>
<td>1.30—2.02 (4 wells)</td>
<td>1.40—1.96 (5 wells)</td>
<td>1.35—1.65 (13 wells)</td>
</tr>
<tr>
<td>Clay content</td>
<td>21.5—31.0%</td>
<td>25.2%</td>
<td>21.0—38.0%</td>
<td>30.0%</td>
</tr>
<tr>
<td>Horizontal stress difference/MPa</td>
<td>18—30</td>
<td>10—13</td>
<td>15—9</td>
<td>3—6</td>
</tr>
<tr>
<td>Young's modulus/MPa</td>
<td>35000</td>
<td>33940</td>
<td>19930</td>
<td>35000</td>
</tr>
<tr>
<td>Poisson's ratio</td>
<td>0.20</td>
<td>0.21</td>
<td>0.18</td>
<td>0.21</td>
</tr>
<tr>
<td>Brittleness index</td>
<td>47—65</td>
<td>55—65</td>
<td>46—69</td>
<td>50—65</td>
</tr>
<tr>
<td>Development of natural fractures</td>
<td>Developed, strike-slip fault can be seen</td>
<td>Locally developed</td>
<td>Locally developed</td>
<td>Developed</td>
</tr>
</tbody>
</table>
formation pressure coefficient. Thus, the areas with good sealing capacity and stable tectonic movement should be selected for evaluating shale gas sweet spots, since it is far away from faults and represents stagnated or slowly micro-dialysis reducing hydrogeological environment.

2. Identification and characterization of mountainous shale gas reservoirs

By virtue of technical efforts in well logging and seismic exploration in Zhaotong demonstration zone in recent years, a series of technologies (e.g. well log acquisition, processing and interpretation) applicable for the marine mountain shale gas in South China are formed [16–21], and the well-seismic correlation and the framework seismogeological interpretation profiles through key wells are established in order to identify and characterize the shale gas reservoirs in the zone [22–27]. In view of log responses, the shale gas layers in Zhaotong demonstration zone present high GR, high DT and low $v_s/v_p$ (Fig. 3), in addition to the anomalies of high resistivity, low density and low CN. In seismic profile, the top boundary of the carbonaceous + sandy shale in the lower member of Longmaxi Fm and the bottom boundary of the limy shale in the upper member of Longmaxi Fm represent wave trough with poor continuity, while the bottom boundary of the Wufeng—Longmaxi shale and the top boundary of the limestone of Ordovician Baota Fm represent wave crest with strong amplitude, low—moderate frequency and good continuity. The gas-rich interval of high-quality shale represents low-frequency wave impedance (Fig. 3), indicating that the high-quality shale and gas-rich interval of Zhaotong demonstration zone are easily identified, tracked and characterized.

3. Prediction methods for sweet spots of mountainous shale gas reservoirs

Based on the Petrel E&P software platform which involves multi-disciplinary data of geological engineering and systematic analysis [28], through the construction of the 3D geological model and the prediction of reservoir attribute, natural fracture and pore pressure parameter, the 3D characterization and superimposition of the reservoir attributes of the shale gas geological body in Huangjinba producing area in Zhaotong demonstration zone are realized by applying geophysical data (well logs and seismic data), reservoir geology, fracture system and lithomechanics modeling technology, in order to comprehensively evaluate and select the sweet spots of shale gas reservoirs. The attribute prediction of shale reservoirs involves eight indicators in terms of geological quality and engineering geology, including thickness and burial depth, organic matter abundance (TOC) and maturity ($R_o$), gas content and physical properties (porosity and permeability), rock mechanical properties (Young’s modulus and Poisson’s ratio), mineral composition (brittleness index), and three dimensional crustal stress (compressibility). Natural fractures prediction is aimed to identify the morphology and sealing capacity of the faults, fracture-concentrated belts and natural micro-fractures of
different scales and levels, reflect the preservation conditions of shale reservoirs and characterize the evaluation parameters of secondary permeability by 3D seismic ant tracking method; while formation pore pressure prediction is aimed to obtain the gas-bearing property, preservation condition and sealing capacity of shale reservoirs.

3.1. 3D model construction and characterization technology for reservoir geological body

The construction of the 3D spatial framework of shale gas reservoirs is the basis and premise for the prediction of sweet spots and characterization of 3D space. It includes geophysical horizon velocity modeling, fine structural interpretation and reservoir geological modeling. High-resolution spectral broadening processing was conducted in the 154 km² 3D seismic data of Huangjinba, with frequency band increasing to 10–65 Hz from 5 to 60 Hz and the dominant frequency increasing to 45 Hz from 35 Hz. Through well-seismic calibration, fine time—depth conversion and velocity analysis were conducted in order to construct a fine model of time domain and seismic velocity. Through the tracking and accurate interpretation of overlying strata, the burial depth of high-quality shale as well as the faults and folds of target zones were predicted in order to draw the high-resolution depth structural map and construct the 3D geological model of the shale gas reservoirs in Huangjinba.

3.1.1. Horizon velocity modeling

The following three steps are involved.

Step 1: Construct the structural model of 3D area in time domain, including Leping Fm, Hanjiadian Fm, Longmaxi Fm and Pay zones I and II of the lower member of Longmaxi Fm and the top surface of Ordovician Baota Fm.

Step 2: Calculate horizon velocity according to the time—depth calibration results of appraisal wells and pilot wells in order to construct the 3D velocity model.

Step 3: Set up virtual wells in the horizontal section development wells in order to correct the velocity model of horizontal section.

3.1.2. Fine structural interpretation

Fine structural interpretation mainly includes two aspects. First, the structural interpretation framework was constructed through calibration of the target zones of key wells and the well-tie framework profiles. Based on the manual interpretation of 64 lines × 64 traces and 32 lines × 32 traces in the 3D area, the constrains for human—computer interaction automatic horizon tracking were constructed in order to complete the horizon interpretation of 1 line × 1 trace and ensure the horizon reliability. Second, the natural faults were interpreted by referring to framework profiles in an order of being “from big to small, from coarse to fine, from vague to clear”. During interpretation, the quality was controlled by referring to the testing results of horizon and discontinuities.

3.1.3. Reservoir geological modeling

Two methods were adopted in this modeling. One is VBM (Volume Based Modeling). It was applied to construct a target zone framework for seismic interpretation, such as the top surfaces of Longmaxi Fm, Pay zones II and I as well as Baota Fm in order to ensure that the 3D seismic structural interpretation controls layer, formation thickness controls sub-layer and virtual wells control horizon section when modeling bed plane by Petrel. The other is corner-point grid method. It was applied to construct multiple “fault columns”. Through editing the intersection line between bed plane and fault in faults, the connection relation between faults and bed planes were controlled.

3.2. Reservoir attribute inversion and reservoir fractures and fluid pressure prediction methods

3.2.1. Reservoir attribute inversion method

3.2.1.1. Pre-stack simultaneous AVO inversion. Taking well logs, seismic data and horizon as basic inputs, the high-quality shale interval of Wufeng Fm and the lower member of Longmaxi Fm as a target zone, the well logging quality control, petrophysical analysis, seismic data quality control and pre-processing and inversion scheme test were conducted in the producing area by using the AVO features of 3D seismic trace in order to obtain elastic parameters, such as P-wave impedance, vp/vs and Poisson's ratio. Seismic attribute inversion profiles show that the Pay zone I of the Longmaxi Shale is a set of good reservoir with low impedance, low vp/vs and good lateral continuity. Objective function was used to conduct pre-stack synchronization AVO inversion. It included the calculation and control of pre-stack seismic attributes, such as the comparison between the forward composite record of calculation results and seismic data, lateral variation, deviation between calculation results and low-frequency model, setting and selection of reflection coefficients, setting and selection of intense reflection coefficients and inversion and calculation of multi-track inversion.

3.2.1.2. Reservoir attributes prediction. Based on pre-stack simultaneous AVO inversion results, through several rounds of inversion tests and parameter optimization, the reliability of 3D elastic bodies were determined after P-wave impedance and vp/vs were highly consistent with well data. Based on a comprehensive analysis of the existing appraisal wells as well as the cores and test data of key pilot wells in the shale gas producing area, the correlation between the porosity, TOC and gas content of shale gas reservoirs and impedance and vp/vs was calculated after litho-electric calibration, then cross-plot was made based on the acoustic measurements of Well YS108 (Fig. 4) to identify the separation degree of rock attributes. Finally, reservoir attributes prediction was performed by applying seismic inversion parameters.

1) Porosity prediction

The cross-plots of P-wave impedance and total porosity as well as vp/vs and total porosity of target zones
in key wells (Fig. 5) reveal that the total porosity is negatively correlated with P-wave impedance, with correlation coefficient up to $-0.81$. The total porosity is less correlated with $v_p/v_s$, with correlation coefficient of $-0.65$. The total porosity was linearly regressed by both P-wave impedance and $v_p/v_s$. The correlation coefficient between the total porosity and the measured porosity was up to 0.83. Based on the regression formula and seismic inversion results, the 3D porosity cube of the shale gas reservoirs in the producing area was accurately predicted.

2) TOC and gas content prediction

The cross-plot of TOC and gas content of target zones in key wells reveals that TOC was closely correlated with well logging density, with correlation coefficient of 0.80. However, the density obtained from seismic inversion is less accurate than that obtained from P-wave impedance and $v_p/v_s$. The combined regression method of P-wave impedance, $v_p/v_s$ and density were applied in order to accurately predict the TOC value, with correlation coefficient of 0.90. The cross-plot of TOC and total gas content of target zones reveals that high TOC corresponds to high gas content and high porosity, with linear correlation coefficient of 0.97. Based on regression formula and seismic inversion results, the 3D TOC cube and total gas content cube were predicted.

3) Other attributes are predicted with similar methods. The Young's modulus and Poisson's ratio were calculated using impedance and $v_p/v_s$, based on which, the brittleness index was obtained ($v_p$ was the P-wave velocity, ft/s; $v_s$ was the shear wave velocity, ft/s; 1 ft $= 30.48$ cm). In general, the inversion results provide 3D trend constraints for reservoir fracture development and geomechanical modeling.

3.2.2. Natural fractures prediction methods

Through comparison, the ant-tracking method was applied. It is a complex seismic attribute algorithm with high precision developed by Schlumberger in its Petrel. The algorithm
comprises four steps. First, highlight the boundary features through seismic data preprocessing. Second, enhance the boundary features through edge detection technology. Third, construct the ant-tracking cube after the optimization of different ant-tracking parameters. Fourth, verify the reliability of ant volume and finally obtain the ant abnormal results.

Multiple data volumes were obtained through the full-angle and sub-angular superimposition of seismic data and migration processing, and then, the most applicable data volume was selected to predict fracture. Finally, optimal parameters were obtained by setting boundary conditions, adjusting parameters and constantly calculating. After the quality control and dip angle filtering of fracture prediction results, the ant abnormal value that reflected fault and natural micro-fractures was preserved. The ant tracking results had three levels in intensity and continuity (i.e. intense continuity and intense anomaly, moderate continuity and moderate anomaly, weak continuity and weak anomaly), respectively corresponding to the concentrated belt of large faults, moderate faults, small faults or natural micro-fractures and dip angle variation belts. The ant-tracking results demonstrate good regularity on plane and were well correlated with fault distribution, fault development regularity and regional geological setting. Generally, large faults represent blue obvious and continuous lines in plane, corresponding to obvious break in reflection event and intense anomaly in ant cube; small faults represent blue grey obvious and continuous lines in plane, corresponding to abrupt change in reflection event or dip angle and moderate anomaly in ant cube; fracture zone represent grey fuzzy lines or networks in plane, corresponding to slight change in reflection event and poor anomaly in ant cube (Fig. 6). The secondary reformation intensity of shale was judged based on the anomaly of ant cube. Specifically, intense anomaly corresponds to large fault and moderate fault development zones with poor shale gas preservation conditions, while poor anomaly corresponds to micro-fault and natural micro-fracture development zones with good shale gas preservation conditions, within which, reservoir permeability was improved.

3.2.3. Pore pressure prediction method

Based on overpressure mechanism, the theoretical model of pore pressure was calculated after the acoustic velocity field of demonstration zone was established. Then, it was checked by reservoir attributes, fracturing data and gas logging data. The following procedures were used. First, the P-wave velocity of key pilot wells was constructed to establish the initial velocity field, and then it was compared with the corrected P-wave velocity of horizontal wells. Second, a more accurate 3D velocity field model was obtained after the P-wave velocity of horizontal wells was considered, and then the latest P-wave velocity of horizontal wells was used for correlation in order to verify the reliability of the velocity field model. The reliable pressure model parameters obtained were used in the calculation of 1D lithomechanics. The 3D distribution and value of pore pressure were verified by the gas logging data of 20 existing wells, which provided reliable basis for subsequent geomechanical modeling, reservoir fracturing design, post-fracturing evaluation, drilling engineering, wellbore stability and drilling fluid optimization. The pore pressure and pressure gradient of the reservoir interval of the 6 key pilot wells in Huangjinba producing area reveal that the pore pressure increases from I5, up to the maximum value at the top of I4, representing the best sealing capacity; then, it decreases to the minimum value in I3 and rises again in Wufeng Fm. Comprehensive analysis shows that I3 and I4 are high-quality shale gas reservoirs with the maximum pressure and best sealing capacity.

3.3. Reservoir 3D spatial characterization and sweet spot selection

Based on the 3D spatial geological framework of reservoir geology and the Petrel platform, the 3D model of reservoir attributes, natural fractures and geomechanics was applied to characterize multiple parameters, including reservoir primary attributes (e.g. 8 geological engineering evaluation indexes), secondary attributes (e.g. fracture development and stress distribution, preservation condition and permeability evaluation index of reservoir secondary reformation), and fluid attributes (e.g. sealing capacity evaluation index of shale reservoirs and pore pressure coefficient), in order to realize the superimposition of 10 indicators of Huangjinba 3D area. This integration of shale gas geology and engineering studies represented the first application in China. This innovative method is international-leading, and the reservoir modeling results were high in accuracy and reliability. Based on the application of 3D reservoir modeling results of multiple parameters, the sweet spots of YS108 well block and I3—I4 at the bottom of lower member of Longmaxi Fm that had concentrated advantaged facies were selected as high-yield producing area (Fig. 1). On the other hand, through the systematic description and characterization of shale gas geology, engineering and regional variation regularity, the disadvantages of single factor evaluation can be overcome, and the contradiction between geology and engineering can also be effectively solved. Moreover, the systematic results can effectively guide the drilling track design, drilling fluid design and fracturing scheme.
optimization, operation scheme optimization and construction adjustment, so the risk in construction work can be avoided and the reservoir drilling ratio of horizontal wells, volume fracturing effect and wellbore integrity can be ensured.

### 3.3.1. Reservoir attribute modeling

Based on seismic inversion and log interpretation, the following work was performed. First, the 3D grid was designed, with lateral size determined by seismic bins and vertical size determined by well logging resolution. Second, the well logs were sampled for the grid that was penetrated by well trajectory, in order to scale up the well logs. Third, the inverted attributes were re-sampled for 3D grid. Fourth, for the completion of 3D reservoir attribute modeling, the lateral distribution of attributes was controlled by seismic inversion attribute as soft data and the vertical distribution of attributes was controlled by well logs as hard data. Sequential Gaussian method combined with attribute inversion was adopted to perform Co-Kriging attribute modeling. TOC and Young's modulus were co-simulated with inverted TOC and Young's modulus, respectively. The modeling results were used for reservoir 3D characterization and evaluation (Fig. 7).

### 3.3.2. Fracture system modeling

Based on ant tracking results, the randomly-generated fractures were combined into fracture networks by the Discrete Fracture Network (DFN) method in order to describe natural fracture system. The required parameters include fracture development strength, direction, inclination, extended length and height. In view of the development degrees and features of tectonic fractures, reasonable fracture mechanical strength was defined in order to embody actual mechanical features in geomechanical model. The application of 3D natural fracture modeling in the 3D characterization of fracture system and the evaluation of shale gas can effectively guide drilling fracturing design, help to effectively avoid faults and fractures during fracturing or to take use of micro-fractures.

### 3.3.3. Geomechanical modeling

Based on the 3D finite element grid constructed by reservoir geological 3D framework, the 3D lithomechanics parameters were determined using seismic inversion results and one-dimensional lithomechanics study results, including Young's modulus, Poisson Ratio, uniaxial compressive strength, friction angle, tensile strength. Faults and fracture zones were involved in 3D model in order to determine 3D pore pressure body. The in-situ crustal stress was determined with the 3D geomechanics software, VISAGE developed by Schlumberger Company, including the minimum horizontal principal stress, maximum horizontal stress and overburden pressure. The 3D geomechanical modeling results were used in the 3D characterization and evaluation of reservoir mechanics in order to effectively establish a drilling map focused on wellbore stability (no leakage and no collapse, no water-flooding and no overflow), effectively guide and optimize the drilling fluid design that is free from leakage and collapse and keep safe, smooth and fast drilling. Meanwhile, the geomechanical model can provide support in the selection of perforation interval and reasonable cluster and stage division, combined with fracture model, the risks of fracturing can be avoided, in order to form complex fracture networks and maximize the stimulated reservoir volume (SRV) of horizontal wells.

### 4. Conclusions

1) Jointly affected by the superposition of multi-phase compressional tectonic movements and strike slip, the shale gas geology of marine shales in Zhaotong demonstration zone in northern Yunnan—Guizhou is complex, forming several shale gas enrichment units and occurrence units with syncline as the dominant structure. The shale gas of Zhaotong demonstration zone enriched and occurred in the trough synclinorial zone in the lower member of Wufeng—Longmaxi Fm is characterized by poor continuity, small sweet spot unit area and scattered distribution, significantly different from that of Sichuan—Chongqing demonstration zone in the Sichuan Basin. The structural depression type of shale gas region which experienced intensive reformation is significantly controlled by preservation conditions.
2) The marine shale reservoirs in Zhaotong demonstration zone in northern Yunnan—Guizhou Depression experienced complex geological evolution of “intense reformation and over-mature evolution”. However, they have apparent logging and seismic response features. The eight indicators of primary attributes of target shale gas reservoirs were calculated by pre-stack technology based on well-seismic correlation, the secondary fracture system was predicted by ant algorithm and the pressure coefficient was calculated by pore pressure model in order to predict the multiple evaluation parameters of 3D reservoir attributes.

3) The 3D comprehensive evaluation method for shale gas sweet spots and modeling results have effectively guided the exploration and development in Huangjinba producing area in Zhaotong demonstration zone. This innovative and applicable method is proved effective and feasible for the complex shale gas reservoirs of South China. The study reveals that mountain shale gas reservoirs have primary attributes (e.g. TOC, mineral content, porosity and permeability), secondary attributes (e.g. faults and natural micro-fractures), fluid attributes (e.g. gas content, and fluid pressure) and geomechanical attributes (e.g. brittleness of shale reservoirs and compressibility of fracturing). The selection of sweet spots (body) fully embodies the spatial congruency and superposition effects of multiple attributes and multiple evaluation parameters. Short-plate principle is followed in the comprehensive evaluation and selection of shale gas sweet spots. The overall sealing preservation conditions are the premise for controlling the occurrence and distribution patterns of shale gas, while high formation pressure coefficient and good reservoir property determine the high productivity of individual wells.

4) The comprehensive evaluation technology for Zhaotong demonstration zone plays an important guiding and leading role in the exploration and development of shale gas sweet spots in complex marine mountains of South China. The first application of geological engineering integration and 3D reservoir modeling is innovative and effective in guiding the exploration and development of shale gas and avoiding development design and construction risks, which provides good reference for the conventional oil and gas exploration in China.

References


