Core-Based Geomechanical Profiling of a Continental Shale Oil Reservoir and Dynamic-to-Static Transformation Relationships of Mechanical Parameters

Shouding Li[1,2,*], *Bo* Zheng[1,2], *Peng* Guo[1,2], *Yanzhi* Hu[1,2], *Xiukuo* Sun[1,2], *Hang* Bian[1,2], *Zhuoran* Xie[1,2], *Fei* Tian[1,2], *Xiao* Li[1,2] and *Qingyun* Di[1,2]

[1]Key Laboratory of Deep Petroleum Intelligent Exploration and Development, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
[2]College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing 100049, China.

Abstract. Continental shale oil reservoirs commonly show rapid lithofacies changes, well-developed bedding, and strong vertical heterogeneity, making static mechanical parameters difficult to obtain from logging data alone. This study investigates the lower sweet spot of the Lucaogou Formation in the Jimsar Sag, Junggar Basin. Continuous cores were collected at the drilling site, and 86 groups of plug specimens were prepared from a 49 m interval. Using a self-developed mobile rock mechanics laboratory, triaxial compression, Brazilian splitting, magnetic susceptibility, chargeability, and resistivity tests were conducted shortly after core recovery. The results show strong depth-dependent variations in mechanical properties: triaxial compressive strength ranges from 190.76 to 672.26 MPa, elastic modulus from 13.92 to 34.54 GPa, Poisson's ratio from 0.12 to 0.36, and tensile strength from 8.58 to 30.24 MPa. Based on the dense core dataset, logging-derived dynamic parameters were calibrated, and lithology-specific dynamic-to-static conversion models were established for mudstone and sandstone. The proposed workflow provides practical support for geomechanical modeling, in-situ stress evaluation, breakdown pressure prediction, and hydraulic fracturing design.

1 Introduction

Shale oil is a general term for liquid petroleum hydrocarbons and various types of organic matter occurring in organic-rich shale strata. According to differences in depositional environments, shale oil can be classified into marine shale oil and lacustrine shale oil [1, 2]. In China, shale oil resources are dominated by lacustrine deposits and are mainly distributed in the Junggar, Ordos, Songliao, and Bohai Bay basins. Previous studies have shown that the technically recoverable shale oil resources in China are approximately 74-372×10^8 t [3], ranking among the highest worldwide. With the continuous advancement of unconventional oil and gas exploration and development technologies, lacustrine shale oil is expected to become an important replacement resource for steadily increasing Chinese crude oil production over the long term and is therefore of great significance for safeguarding national energy security and improving domestic crude oil self-sufficiency.

Compared with marine shale, lacustrine shale is characterized by frequent variations in depositional environments, complex lithofacies assemblages, well-developed laminae and bedding textures, and rapid vertical changes in mineral composition, pore structure, and mechanical properties. These features result in pronounced thin interbedding and strong heterogeneity. Such complex geological characteristics directly lead to strong spatial variability in reservoir geomechanical parameters and in-situ stress profiles, thereby posing substantial challenges to horizontal well drilling, wellbore stability evaluation, and hydraulic fracturing design. In particular, during volume fracturing of shale oil reservoirs, the heterogeneous distribution of parameters such as elastic modulus, Poisson's ratio, tensile strength, fracture toughness, and the three-dimensional in-situ stresses can significantly affect fracture initiation, vertical propagation across layers, lateral extension, and the formation of complex fracture networks. Therefore, establishing high-resolution geomechanical profiles that can accurately characterize lithofacies, mineral composition, geophysical properties, and rock mechanical properties is an important foundation for in-situ stress evaluation, three-pressure profile calculation, logging-based inversion of rock mechanical parameters, and fracturing optimization in lacustrine shale oil reservoirs.

The Permian Lucaogou Formation shale oil reservoir in the Jimsar Sag of the Junggar Basin is a typical lacustrine shale oil reservoir developed in a saline lake basin in China, and it also represents the first national-level demonstration area for lacustrine shale oil development in China. The Lucaogou Formation is buried at depths of approximately 800-4500 m, with an average burial depth of about 3570 m. The reservoir thickness ranges from 25 to 300 m, with an average thickness of approximately 200 m, and the favorable area contains shale oil resources of up to 11.12×10^8 t [4]. The shale oil reservoir in this area exhibits pronounced thin interbedding, complex lithological assemblages, thin sweet-spot intervals, and rapid spatial variations in sweet-spot distribution, accompanied by significant differences in reservoir physical and mechanical properties. Under the combined effects of rapid lithofacies variation, well-developed bedding, and heterogeneous mineral composition, the Lucaogou Formation shows marked

* Corresponding author: lsdlyh@mail.iggcas.ac.cn

differences in elastic parameters, strength parameters, and failure characteristics among different stratigraphic intervals and lithologies. These differences result in complex in-situ stress distributions, restrict the vertical propagation of hydraulic fractures, and make it difficult to form stable and effective volumetric fracture networks, thereby limiting the improvement of single-well productivity.

A large number of studies have been conducted on the fracturing stimulation of shale oil reservoirs in the Lucaogou Formation. Zhang [5] performed three-dimensional geological modeling of the Lucaogou shale oil reservoir and established a rock mechanical model based on logging data. However, conventional logging interpretation methods are limited by their vertical resolution and therefore have difficulty accurately characterizing the rapid variations in mechanical parameters within thinly interbedded structures. Wang et al. [6] conducted triaxial compression and tensile strength tests on core samples from the Lucaogou shale oil reservoir. Their results showed that the rock mechanical properties and in-situ stress states vary significantly among different lithologies in the Lucaogou Formation, and that interlayers with relatively high mechanical strength and in-situ stress are developed within the reservoir. Li et al. [7] carried out true triaxial hydraulic fracturing experiments on shale samples from the Lucaogou Formation, showing that interlayer thickness, horizontal stress difference, and fracturing fluid viscosity all have important effects on fracture height and propagation morphology. These studies indicate that the thinly interbedded structure and strong heterogeneity of the Lucaogou Formation are important geological factors controlling hydraulic fracture propagation. In particular, the heterogeneous distribution of mechanical parameters plays a key role in fracture propagation across layers and the formation of complex fracture networks.

However, most existing studies have focused on mechanical property testing of single-lithology samples, the establishment of logging interpretation models, or the analysis of hydraulic fracture propagation behavior, whereas studies on high-resolution continuous geomechanical profiles of lacustrine shale oil reservoirs remain relatively limited. Due to rapid lithofacies variations and well-developed laminae and bedding textures in lacustrine shale, conventional sampling intervals or logging interpretation results alone are insufficient to accurately capture the high-frequency variations in mineral composition, geophysical responses, and static mechanical parameters within thinly interbedded intervals. Meanwhile, discrepancies exist between the dynamic rock mechanical parameters derived from logging data and the static mechanical parameters obtained from laboratory rock mechanical tests. Without constraints from high-density core testing data, the interpretation results of rock mechanical models and in-situ stress profiles may be prone to bias. Therefore, it is necessary to conduct high-density and high-resolution tests of rock mechanical and geophysical properties based on continuous cores, and to establish conversion relationships between dynamic and static parameters. This provides a reliable basis for logging-based inversion of rock mechanical parameters, calculation of the three principal in-situ stresses, and optimization of hydraulic fracturing engineering parameters.

Based on the above issues, this study focuses on the lower sweet-spot interval of the Lucaogou Formation in the Jimsar Sag, Xinjiang Oilfield, which is mainly composed of distal bar and sheet sand deposits of the delta front. Using a mobile rock mechanics laboratory system, continuous shale cores were obtained at the drilling site, followed by high-density sampling and multiple types of experimental analyses. Through triaxial compression deformation tests, Brazilian splitting tests, and measurements of magnetic susceptibility, polarizability, and electrical resistivity, a high-resolution geomechanical profile incorporating mineral composition, geophysical properties, and rock mechanical properties was established. On this basis, the correlations between dynamic mechanical parameters derived from logging data and static mechanical parameters obtained from core tests were analyzed. Dynamic-to-static conversion formulas for elastic modulus, Poisson’s ratio, tensile strength, and other parameters of different lithologies were then established, and the vertical heterogeneous distribution characteristics of geomechanical parameters in the lower sweet-spot interval of the Lucaogou Formation were revealed. This study provides a theoretical basis and parameter support for refined geomechanical modeling, in-situ stress evaluation, and hydraulic fracturing optimization of lacustrine shale oil reservoirs.

2 Geological setting

The lower sweet-spot interval of the Lucaogou Formation, which is the target interval of this study, is mainly composed of distal bars and sheet sands of delta-front deposits. By comparison, the upper sweet-spot interval is dominated by shore–shallow lacustrine beach-bar deposits, including bioclastic shoals, sandy debris shoals, and sandy shoals. Across the Jimsar Sag, the Lucaogou Formation generally becomes thicker from north to south and from east to west, with an average thickness of approximately 200–350 m and a maximum thickness of up to 400 m. The studied well is a vertical well with a total depth of 3845 m. In this study, full-diameter cores from the lower sweet-spot interval were obtained for geomechanical parameter testing.

3 Geomechanical parameter testing

3.1. Sample preparation

High-density sampling was conducted on drilling cores from the lower sweet-spot interval of the Lucaogou Formation in the Jimsar Sag, Junggar Basin, with consideration of different lithologies and depths. The sampling scheme is shown in Table 1. The total target sampling interval was 49 m, from which 86 samples were collected, corresponding to an average sampling density of 1.8 samples/m.

Fig. 1. Sample preparation: (a) Samples selection with different depths and lithologies; (b) Diamond wire cutting machine; (c) Rock cores processing; (d) Samples after processing.

For each sampling point, two types of cylindrical specimens were prepared. Specimens with a diameter of 10 mm and a length of 20 mm were used for triaxial compression deformation tests, corresponding to a length-to-diameter ratio of 2.0. The specimen dimensions and end surfaces were checked before testing to ensure geometric consistency. Triaxial compressive strength, elastic modulus, and Poisson's ratio were obtained from these tests. Disc specimens with a diameter of 10 mm and a thickness of 10 mm were used for Brazilian splitting tests to determine tensile strength. Because shale and mudstone are fragile, all specimens were processed using dry wire cutting to minimize damage to the rock samples during preparation. In total, 86 groups of rock specimens were successfully prepared. It should be noted that the relatively small specimen size may introduce a size effect in the measured mechanical strength. Smaller specimens may contain fewer pre-existing microcracks or weak planes and may therefore yield relatively higher strength values than larger-scale cores or the in-situ formation. Therefore, the measured mechanical parameters are mainly used to characterize relative variations among different depths and lithologies and to calibrate logging-derived dynamic parameters, rather than to directly represent the absolute strength of the formation at field scale.

Table 1. Sampling schemes of rock cores Sampling schemes of rock cores.

No.	Depth (m)	Sub-layer	Sub-layer thickness (m)	Number of samples	Sampling density (samples/m)
1	3661-3678	p_2l_1	17	26	1.53
2	3678-3688	$p_2l_1^{2-1}$	10	18	1.80
3	3688-3700	$p_2l_1^{2-2}$	12	20	1.67
4	3700-3710	$p_2l_1^{2-3}$	10	22	2.2

3.2. Experimental methods

All experiments were conducted using a vehicle-mounted rock mechanics testing system, as shown in Fig. 2. This system miniaturizes conventional rock mechanics testing equipment and integrates it into a containerized laboratory (Fig. 2a). The miniaturized triaxial testing machine occupies an area of only 1 m² and weighs 1.2 t, while maintaining the same accuracy and stiffness as a conventional testing machine. It enables rapid rock mechanical experiments and petrophysical property measurements at the construction site. The containerized laboratory is divided into a sample preparation room, a testing room, and an auxiliary room according to function (Fig. 2b). The sample preparation room is used for dry drilling, cutting, and grinding of rock samples. The testing room houses the main body of the triaxial testing machine and is mainly used for rock mechanical and physical property tests. The auxiliary room is used to install supporting equipment, such as the gas supply station, chiller, and external air-conditioning unit.

The triaxial compression tests were conducted with reference to the general procedures of ASTM D7012, and the Brazilian splitting tests were conducted with reference to ASTM D3967. Because miniature specimens were used due to the limited core material and the need for high-density sampling, the tests should be regarded as standard-referenced rather than strictly standard-sized tests. During the triaxial tests, the confining pressure was set to 100 MPa. This value is broadly consistent with the deep-burial stress level of the sampled interval at depths of 3661-3710 m, as estimated from burial depth and rock density. A constant confining pressure was used for all samples to ensure comparability among different depths and lithologies. The axial displacement loading rate was set to 0.01 mm/min, corresponding to an axial strain rate of approximately $5.0 * 10^{-4}$ min^{-1} for the 20 mm-long specimens. This low loading rate was selected to approximate quasi-static loading conditions and to reduce rate-dependent effects on the measured mechanical parameters. Linear variable differential transformers (LVDTs) were used to measure the axial and radial deformation of the rock specimens.

For the Brazilian splitting tests, the axial displacement loading rate was also set to 0.01 mm/min, and a high-precision pressure sensor was used to measure the axial load. Before testing, no solvent or chemical core cleaning was performed. Only surface debris and cutting residues were removed during dry drilling, cutting, and grinding. The specimens were tested in an as-received state to avoid possible changes in mechanical properties caused by chemical cleaning or long-term storage. With this testing system, the cores could be processed and tested immediately after sampling in the core storage facility, thereby reducing the influence of long-term storage on the mechanical properties of the rocks. In this study, a total of 86 triaxial compression deformation tests and 86 Brazilian splitting tests were completed.

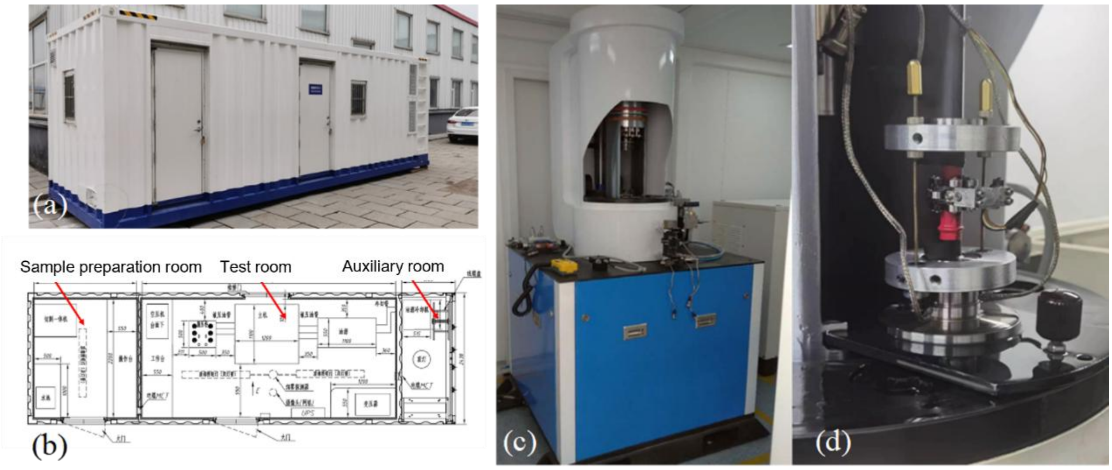

Fig. 2. Car-mounted rock mechanics testing system: (a) External view of the testing system; (b) Internal layout diagram of the testing system; (c) Triaxial testing machine; (d) Installation of the axial and radial displacement sensors.

3.3. Results

Triaxial compression deformation tests and Brazilian splitting tests were conducted at 86 sampling points, and the triaxial compressive strength, elastic modulus, Poisson’s ratio, and tensile strength of 86 groups of specimens were obtained. The main lithologies of the studied interval include mudstone, silty mudstone, siltstone, and argillaceous siltstone. In the Lucaogou Formation, thin mudstone and sandstone layers alternate frequently. The typical triaxial compression test results of mudstone and sandstone samples are shown in Fig. 3. As shown in Fig. 3, after triaxial failure, the sandstone samples mainly developed a single shear fracture with a relatively smooth fracture surface. In contrast, the mudstone samples developed not only a dominant shear fracture but also transverse fractures. Moreover, the shear fracture surfaces in the mudstone samples were rougher than those in the sandstone samples, resulting in a higher degree of fragmentation in mudstone than in sandstone.

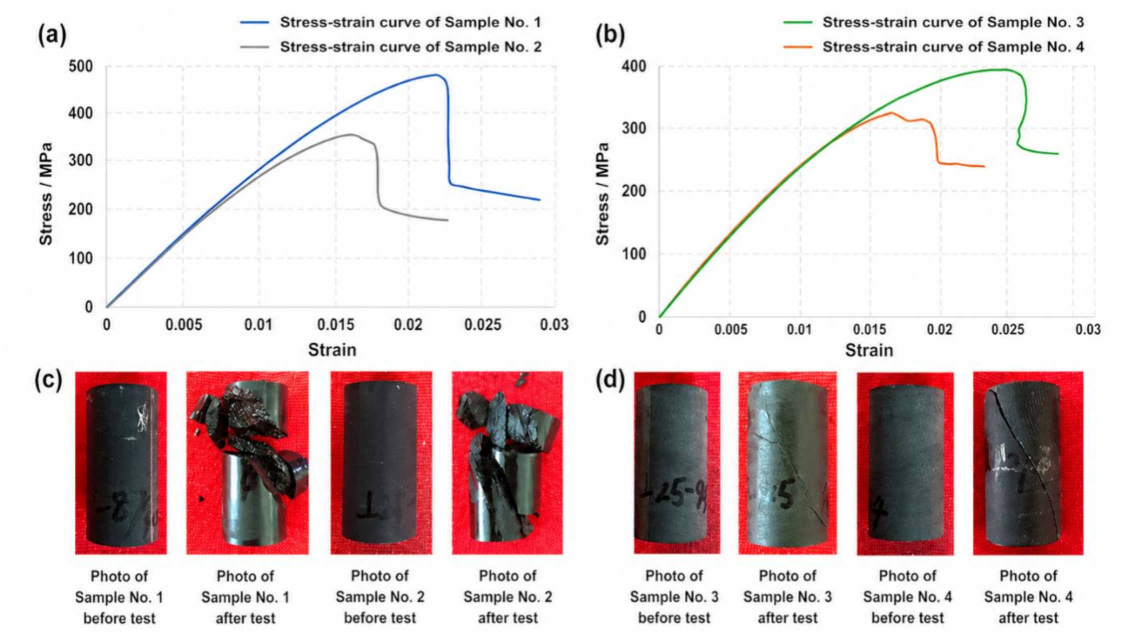

Fig. 3. Mechanical testing results of typical samples: (a) Stress-strain curves of mudstone samples 1 and 2; (b) Stress-strain curves of sandstone samples 3 and 4; (c) Photographs of mudstone samples 1 and 2 before and after failure in triaxial tests; (d) Photographs of sandstone samples 3 and 4 before and after failure in triaxial tests.

Based on the mechanical parameter test results of 86 groups of specimens from different depths, profiles of triaxial compressive strength, elastic modulus, Poisson's ratio, and tensile strength were plotted, as shown in Fig. 4. The results show that, under a confining pressure of 100 MPa, the triaxial compressive strength ranges from 190.76 to 672.26 MPa, the elastic modulus ranges from 13.92 to 34.54 GPa, Poisson's ratio ranges from 0.12 to 0.36, and the tensile strength ranges from 8.58 to 30.24 MPa. The overall trends of the mechanical parameter profiles indicate that the mechanical parameters of the Lucaogou Formation fluctuate strongly and vary over a wide range. This is mainly attributed to the intense lithofacies variations associated with thin interbedded strata.

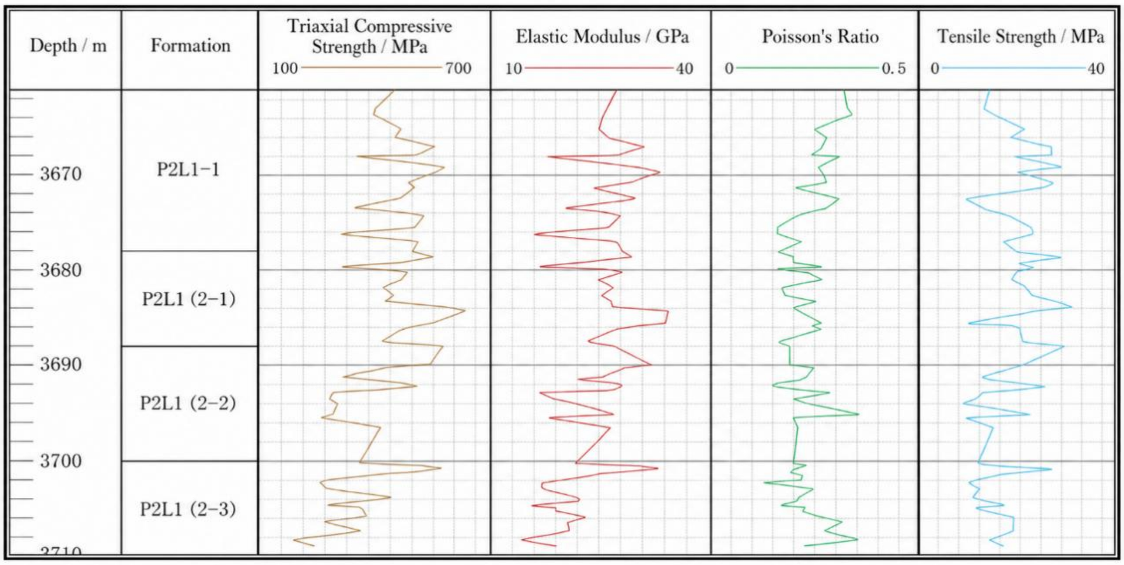

Fig. 4. Geomechanical parameter testing results of the Lucaogou shale oil reservoir.

In this study, mechanical tests were conducted to obtain the vertical distribution of geomechanical parameters in the lower sweet-spot interval of the Lucaogou Formation. These parameters can be used for the calculation and prediction of in-situ stress and hydraulic fracturing breakdown pressure. The in-situ stress was calculated using the Liu-Wu model proposed by Huang et al. [8], as expressed below:

$$\sigma_H = (\frac{\nu}{1-\nu} + \xi_1)(\sigma_v - \alpha P_p) \quad (1)$$

$$\sigma_h = (\frac{\nu}{1-\nu} + \xi_2)(\sigma_v - \alpha P_p) \quad (2)$$

where σ_H is the maximum horizontal principal stress, σ_h is the minimum horizontal principal stress, σ_v is the vertical stress, ν is Poisson's ratio, P_p is the pore pressure, ξ_1 and ξ_2 are the tectonic stress coefficients, and $\alpha$is the effective stress coefficient. Poisson's ratio ν was assigned according to the mechanical test results, σ_v was calculated based on burial depth and rock density, and P_p, ξ_1 and ξ_2 were assigned by lithology according to the actual logging data of the sampled well. The effective stress coefficient α was set to 1.

The hydraulic fracturing breakdown pressure was calculated using the formula adopted by Huo [9]:

$$P_m = 3\sigma_h - \sigma_H - \alpha P_p + T \quad (3)$$

where P_m is the breakdown pressure, and T is the tensile strength obtained from laboratory tests.

The in-situ stress profiles and breakdown pressure profile derived from the laboratory test data were plotted, as shown in Fig. 5. The results indicate that the in-situ stresses vary sharply in the vertical direction, with some layers showing abrupt decreases or increases in stress magnitude. Meanwhile, the breakdown pressure predicted using the above formula also exhibits strong variations. These results demonstrate that the geomechanical parameters and in-situ stresses of the Lucaogou Formation are characterized by pronounced heterogeneous distributions, with marked differences among different layers. The influence of these interlayer differences on hydraulic fracture propagation requires further investigation.

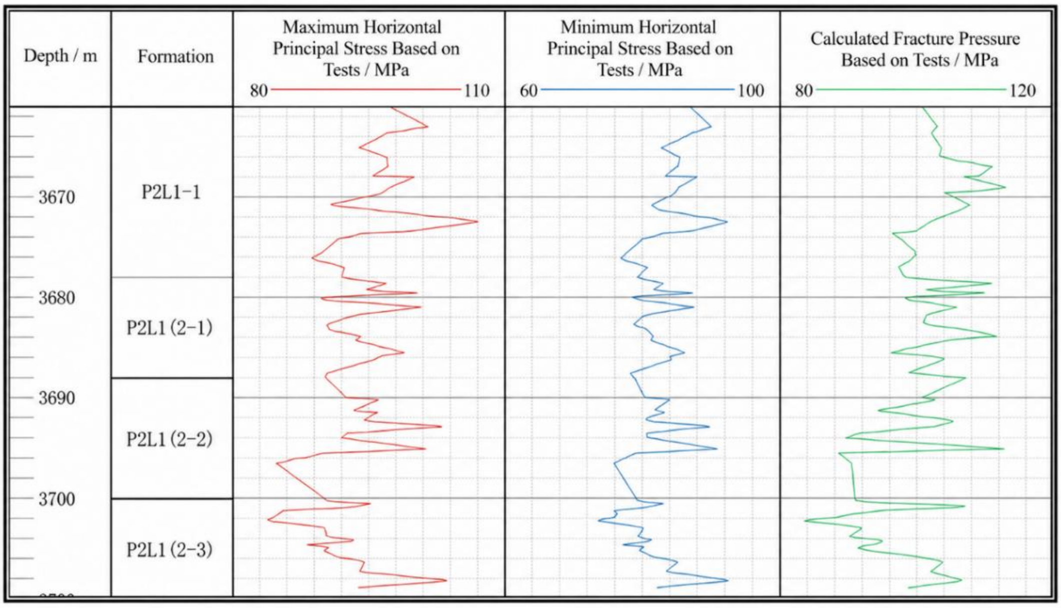

Fig. 5. Calculation results of the in-situ stress and breakdown pressure profiles in the Lucaogou shale oil reservoir.

3.4. Mineral composition and geophysical properties

In addition to rock mechanical parameters, electrical resistivity, polarizability, magnetic susceptibility, and XRD-based mineral composition tests were conducted under the same high-density sampling framework to further characterize the relationships among lithofacies, mineral composition, and logging responses in the lower sweet-spot interval of the Lucaogou Formation. The XRD results show that the core samples are mainly composed of quartz, feldspar, carbonate minerals, clay minerals, and a small amount of pyrite. The carbonate minerals mainly include calcite and dolomite, whereas the clay mineral fraction is dominated by illite, mixed-layer illite/smectite, and chlorite. These minerals vary with depth and lithology, indicating strong mineralogical heterogeneity within the studied interval.

The core-measured results were also compared with the logging RT curve. Fig. 6 shows the variations in core-measured electrical resistivity, logging RT, core-measured polarizability, core-measured magnetic susceptibility, and pyrite content with depth. Compared with mechanical tests alone, these geophysical and mineralogical parameters provide additional constraints for identifying lithological variations within thinly interbedded intervals from the perspectives of electrical conductivity, magnetic mineral content, and mineral composition. These results provide multi-source constraints for the establishment of a refined core-based geomechanical profile.

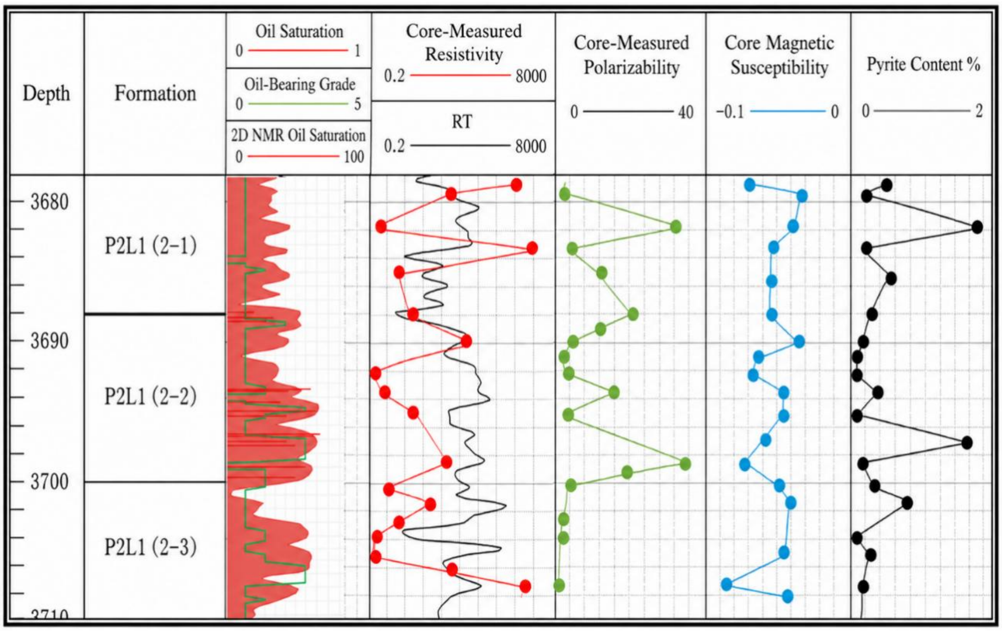

Fig. 6. Core-measured petrophysical and mineralogical profiles of the Lucaogou shale oil reservoir.

As shown in Fig. 6, the core-measured electrical resistivity shows a certain correspondence with the logging RT curve in terms of vertical variation trends. This indicates that high-density core-based electrical property measurements conducted at the well site can effectively calibrate logging responses and help identify thin interbedded variations that are difficult to characterize precisely using conventional logging data with limited vertical resolution. Electrical resistivity, polarizability, and magnetic susceptibility all exhibit obvious fluctuations at different depths, indicating that the lower sweet-spot interval of the Lucaogou Formation is characterized not only by strong variations in mechanical parameters, but also by pronounced vertical heterogeneity in geophysical properties. Variations in electrical and magnetic responses are generally related to mineral composition, pore structure, organic matter, and the distribution of conductive minerals, and can therefore provide a basis for lithological classification and fine-scale correlation within sweet-spot intervals.

Meanwhile, the pyrite content profile shows that the degree of pyrite enrichment varies among different layers. Local enrichment of conductive and magnetic minerals, such as pyrite, can influence the responses of core electrical resistivity, polarizability, and magnetic susceptibility. It may also affect the mechanical properties of rocks by changing mineral cementation patterns and microstructures. Therefore, integrated analysis of XRD-derived mineral composition, pyrite content, electrical resistivity, magnetic susceptibility, and mechanical parameters such as triaxial compressive strength, tensile strength, and fracture toughness is helpful for understanding the heterogeneity of lacustrine shale oil reservoirs from three perspectives: mineral composition, geophysical response, and mechanical properties. These multi-type test results further demonstrate that the profile established in this study is not merely a mechanical parameter profile, but a high-resolution integrated geomechanical profile that combines mineral composition, geophysical properties, and mechanical properties. This profile provides a more reliable parameter basis for establishing dynamic-to-static conversion relationships of logging-derived mechanical parameters, calculating the three principal in-situ stresses, and simulating hydraulic fracture propagation.

4 Dynamic-to-static conversion relationships of mechanical parameters

Basic rock elastic parameters, such as Young's modulus and Poisson's ratio, are important references for drilling, hydraulic fracturing, and underground engineering design, and their accurate determination is fundamental to the design of oil and gas exploration and development schemes. According to the testing method, rock elastic parameters can be classified into dynamic and static parameters. Dynamic parameters are mainly calculated from rock density and compressional- and shear-wave velocities, which are commonly obtained from acoustic logging or laboratory ultrasonic tests. In contrast, static parameters are obtained from rock mechanical tests, such as triaxial compression tests, and are mainly calculated based on the stress–strain response of rocks during loading.

By comparison, dynamic parameters have the advantages of rapid acquisition, low cost, strong continuity, and good field applicability. Although static parameters require longer testing periods and higher costs, they can better reflect the actual deformation behavior of rocks under underground engineering disturbances and are therefore more consistent with the practical requirements of drilling, hydraulic fracturing, and reservoir stimulation. Therefore, in practical oil and gas exploration and development, conversion relationships between dynamic and static parameters are usually first established through laboratory petrophysical and rock mechanical tests. Continuous profiles of dynamic rock mechanical parameters are then obtained from logging data and further converted into static mechanical parameter profiles required for engineering applications.

Because logging-derived dynamic parameters and laboratory-measured static parameters are obtained under different measurement conditions, they commonly differ in magnitude. In the Lucaogou Formation, thin interbedding and strong lithological heterogeneity further increase this discrepancy and limit the applicability of generalized dynamic-to-static conversion models developed for relatively homogeneous strata. Therefore, core-constrained and lithology-specific conversion relationships are required to obtain reliable static mechanical parameter profiles for drilling safety evaluation and hydraulic fracturing design.

Therefore, based on the high-density core testing results from the study area, it is necessary to further analyze the correlations between logging-derived dynamic rock mechanical parameters and laboratory-measured static mechanical parameters, and to establish lithology-specific dynamic-to-static conversion equations for parameters such as elastic modulus, Poisson's ratio, and tensile strength.

In this study, the dynamic mechanical parameters of the rocks were first calculated based on acoustic logging data and then compared with the static mechanical parameters obtained from laboratory triaxial compression tests and Brazilian splitting tests. The commonly used SLB dynamic-to-static parameter conversion formulas can be expressed as follows:

$$E_s = -3.265 \times 10^{-6} E_d^2 + 19.06 E_d - 2.304 \times 10^7 \quad (4)$$

$$\nu_s = 1.9498 \ln(\nu_d) - 0.2938 \quad (5)$$

where E_s is the static Young's modulus, E_d is the dynamic Young's modulus, ν_s is the static Poisson's ratio, and ν_d is the dynamic Poisson's ratio. Such empirical formulas can reflect the overall relationship between dynamic and static parameters to some extent. However, for lacustrine shale oil reservoirs, the mineral composition, degree of bedding development, and microstructure differ substantially among different lithologies. Therefore, a unified conversion formula is difficult to apply simultaneously to both mudstone and sandstone. In this study, the samples were further classified according to lithology, and dynamic-to-static conversion relationships of rock mechanical parameters were established separately for mudstone and sandstone.

For mudstone samples, a clear nonlinear correlation was observed between the logging-derived dynamic elastic modulus and the static elastic modulus obtained from laboratory tests. As the logging-derived elastic modulus increases, the laboratory-measured elastic modulus generally shows an increasing trend, although the data points exhibit a certain degree of scatter. This scatter is mainly related to the well-developed bedding, complex mineral composition, and microfracture development in mudstone. Through polynomial fitting, the dynamic-to-static conversion relationship for the elastic modulus of mudstone was established as follows:

$$E_s = 0.0025E_d^3 - 0.3011E_d^2 + 12.411E_d - 147.14 \quad (6)$$

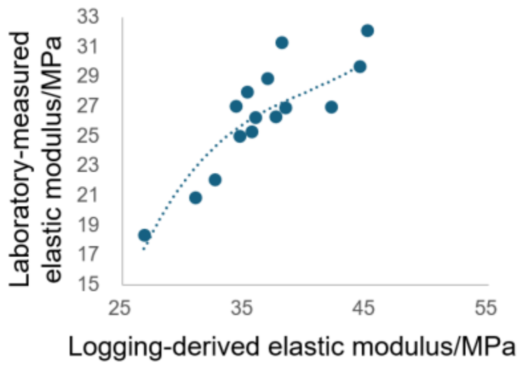

Fig. 7. Dynamic-static transformation relationship of elastic modulus for mudstone.

The fitting correlation coefficient is $R^2 = 0.69$, indicating that this equation can reasonably capture the variation trend between the dynamic and static elastic moduli of mudstone. A nonlinear relationship was also observed between the dynamic and static Poisson's ratios of mudstone, and the corresponding conversion equation is expressed as follows:

$$v_s = 396.24v_d^2 - 223.14v_d + 31.614 \quad (7)$$

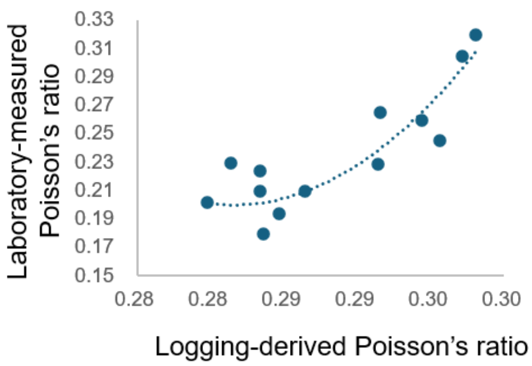

Fig. 8. Dynamic-static transformation relationship of Poisson's ratio for mudstone.

The fitting correlation coefficient is $R^2 = 0.75$. In addition, based on the relationship between the logging-predicted tensile strength and the static tensile strength obtained from Brazilian splitting tests, the conversion equation for the tensile strength of mudstone was established as follows:

$$T_s = 0.0326T_d^{2.2601} \quad (8)$$

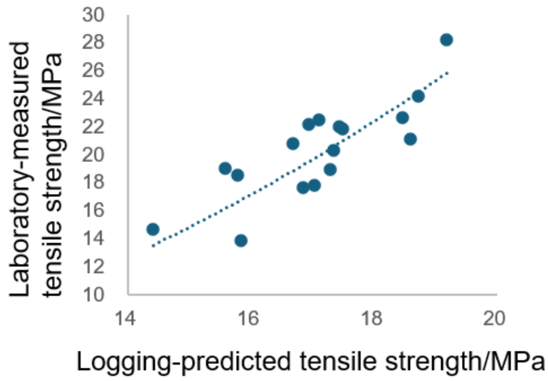

Fig. 9. Dynamic-static transformation relationship of tensile strength for mudstone

The fitting correlation coefficient is $R^2 = 0.73$. The above results indicate that the dynamic and static mechanical parameters of mudstone show good correlations. However, owing to the effects of bedding, clay mineral content, and microstructure, the parameter conversion relationships exhibit pronounced nonlinear characteristics.

For sandstone samples, the overall correlation between logging-derived dynamic parameters and laboratory-measured static parameters is better than that observed for mudstone. Sandstone has a more pronounced grain-supported structure and weaker internal heterogeneity than mudstone; therefore, the correspondence between dynamic and static mechanical parameters is more stable. According to the fitting results, the dynamic-to-static conversion equation for the elastic modulus of sandstone is expressed as follows:

$$E_s = 0.0022E_d^3 - 0.2449E_d^2 + 9.0363E_d - 84.631 \quad (9)$$

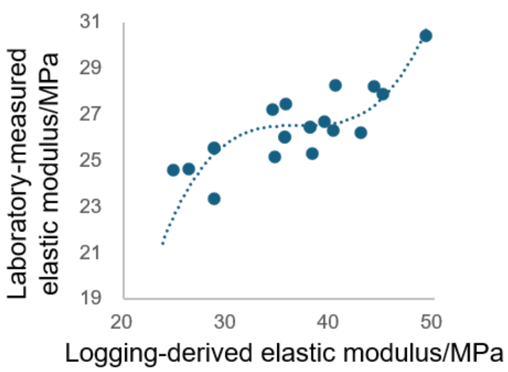

Fig. 10. Dynamic-static transformation relationship of elastic modulus for sandstone.

The fitting correlation coefficient is $R^2 = 0.76$. The dynamic-to-static conversion equation for Poisson's ratio of sandstone is expressed as follows:

$$\nu_s = 100.77\nu_d^2 - 52.168\nu_d + 6.896 \quad (10)$$

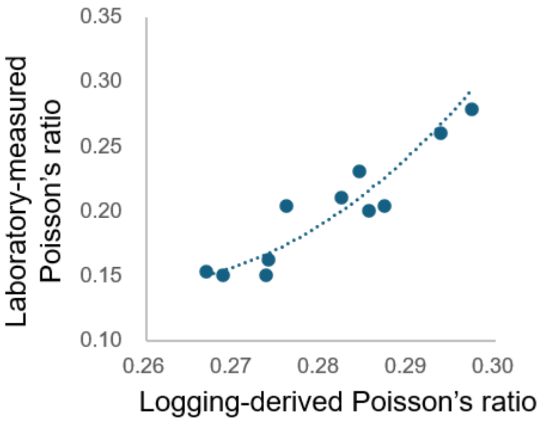

Fig. 11. Dynamic-static transformation relationship of Poisson's ratio for sandstone.

The fitting correlation coefficient is $R^2 = 0.82$, indicating that the dynamic-to-static conversion relationship for Poisson's ratio of sandstone is relatively stable. The conversion equation for the tensile strength of sandstone is expressed as follows:

$$T_s = -0.0109T_d^3 + 0.8632T_d^2 - 17.62T_d + 119.16 \quad (11)$$

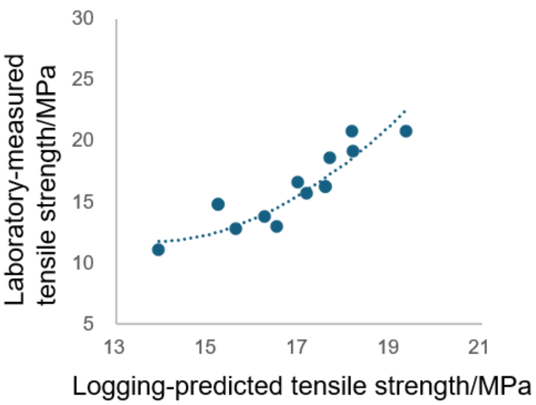

Fig. 12. Dynamic-static transformation relationship of tensile strength for sandstone.

The fitting correlation coefficient is $R^2 = 0.74$. According to the fitting results, the dynamic-to-static conversion relationships for the elastic modulus, Poisson's ratio, and tensile strength of sandstone all exhibit good correlations, among which the conversion relationship for Poisson's ratio is the most significant.

The fitting results for mudstone and sandstone indicate that the dynamic-to-static conversion relationships of mechanical parameters differ markedly among lithologies. For mudstone samples, the dynamic–static parameter relationships show relatively strong scatter due to well-developed laminae and bedding textures, relatively high clay mineral content, and more developed microfractures and weak planes. In contrast, sandstone samples are relatively compact and exhibit a more pronounced grain-supported structure, resulting in better correlations between dynamic and static parameters. Therefore, in thinly interbedded lacustrine shale oil reservoirs, the use of a unified dynamic-to-static conversion formula may overlook the mechanical differences among lithologies, thereby affecting the calculation accuracy of static mechanical parameter profiles, in-situ stress profiles, and breakdown pressure profiles.

The lithology-specific dynamic-to-static conversion formulas established in this study can convert continuous dynamic parameters derived from logging data into static rock mechanical parameters that are more consistent with engineering requirements. This method not only retains the advantage of the vertical continuity of logging data but also calibrates the logging-derived parameters using laboratory rock mechanical test results, thereby enabling a more accurate characterization of the vertical heterogeneity of mechanical parameters in the lower sweet-spot interval of the lacustrine shale oil reservoir in the Lucaogou Formation, Jimsar Sag. The static elastic modulus, Poisson's ratio, and tensile strength profiles obtained based on these conversion relationships can further provide a reliable parameter basis for calculating the three principal in-situ stresses, predicting breakdown pressure, evaluating wellbore stability, and simulating hydraulic fracture propagation.

5 Conclusions

This study focuses on the lower sweet-spot interval of the Lucaogou Formation in the Jimsar Sag, Junggar Basin. Different from conventional studies based mainly on limited core tests or generalized logging interpretation models, this work establishes a dense core-based geomechanical dataset by combining on-site mobile rock mechanics testing, petrophysical measurements, XRD mineralogical analysis, and logging calibration. The dataset provides direct constraints for characterizing the vertical heterogeneity of the thinly interbedded lacustrine shale oil reservoir and for establishing lithology-specific dynamic-to-static conversion relationships. The main conclusions are as follows:

(1) A dense core-based geomechanical profile was established from 86 groups of plug specimens collected over a 49 m continuous core interval. The results reveal strong vertical fluctuations in mechanical properties within the lower sweet-spot interval. The triaxial compressive strength, elastic modulus, Poisson's ratio, and tensile strength vary over wide ranges, indicating pronounced mechanical layering controlled by thin interbedding and lithological heterogeneity.

(2) The core-derived static mechanical parameters were used to calculate the three principal in-situ stresses and breakdown pressure profiles. The results show obvious layered fluctuations and local abrupt changes in stress and breakdown pressure, suggesting that mechanical heterogeneity may strongly influence hydraulic fracture

initiation, vertical propagation, and fracture-height containment.
(3) Lithology-specific dynamic-to-static conversion relationships were established by integrating laboratory-measured static parameters with logging-derived dynamic parameters. The conversion relationships for elastic modulus, Poisson's ratio, and tensile strength differ between mudstone and sandstone and generally exhibit nonlinear characteristics. This finding indicates that a unified conversion model may introduce bias in strongly heterogeneous lacustrine shale oil reservoirs. The proposed core-calibrated workflow provides practical support for refined geomechanical modeling, drilling safety evaluation, in-situ stress prediction, and hydraulic fracturing design.

References

1. W. Zhao, S. Hu, L. Hou, et al., Pet. Explor. Dev. 47, 1-10 (2020)
2. M. Li, X. Ma, Z. Jin, et al., Oil Gas Geol. 43, 1-25 (2022)
3. C. Zou, Z. Yang, R. Zhu, et al., J. Asian Earth Sci. 178, 3-19 (2019)
4. J. Huo, J. He, Y. Gao, et al., Xinjiang Pet. Geol. 40, 379-388 (2019)
5. R. Zhang, Geological modeling of shale oil reservoir of Lucaogou Formation in Jimusaer (Dissertation, China University of Petroleum, Beijing, 2021)
6. X. Wang, L. Liang, L. Zhao, et al., Oil Gas Geol. 40, 661-668 (2019)
7. J. Li, Y. Zou, S. Shi, et al., Geofluids 2022, 6598575 (2022)
8. R. Huang, J. Zhuang, Oil Drill. Prod. Technol. 3, 1-14 (1986)
9. J. Huo, Evaluation of high-quality shale oil reservoirs in Jimsar, Xinjiang (Petroleum Industry Press, Beijing, 2021)