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Characterization methods for current *in-situ* stress in oil and gas reservoirs: a mini review

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In-situ stress plays a crucial role in governing various parameters such as the distribution of oil and gas accumulation zones, the fracture pattern of reservoirs, formation fracture pressure, and collapse pressure. Understanding the distribution characteristics of current *in situ* stress of reservoirs has significant implications for exploration and development of oil and gas. This paper focuses on the characterization methods for current *in situ* stress of oil and gas reservoirs, discussing the research progress in testing methods, computational approaches, numerical simulations, and seismic prediction methods. The results indicate that the testing method including the on-site testing method and the laboratory testing method offer the relatively high accuracy, but this method only provides point-specific magnitude and direction of current *in situ* stress. The Computational approaches can obtain continuous profiles of current *in situ* stress along individual wells. After using the testing method for calibration, we can obtain relatively accurate calculation results. The numerical method can predict current *in situ* stress over large areas, but it requires rigorous model setup, boundary definition, and parameter selection. The seismic prediction method also can predict broad distribution of current *in situ* stress, but this method is influenced by many factors and we had better apply this method in conjunction with other methods. In the future, engineers and researchers should innovate testing technologies and instruments, and establish models and processes for joint use of multiple methods, and explore the development of novel current *in situ* stress prediction models based on artificial intelligence and big data.

KEYWORDS

current *in situ* stress, characterization method, testing method, computational approaches, numerical simulation, seismic prediction, oil and gas reservoirs

1 Introduction

In-situ stress primarily results from factors such as the gravity of overlying rock layers, formation pressure (pore pressure), tectonic stress, and thermal effects (Banerjee and Chatterjee, 2021; Bouchachi et al., 2022). *In-situ* stress is typically represented by a vertical principal stress (S_v) and two horizontal principal stresses (S_{Hmax} and S_{hmin}) (Gowida et al., 2022). Current *in situ* stress refers to the current stress state of rock formations in comparison to past stress conditions. Current *in situ* stress plays a crucial role in the analysis of oil and gas migration and accumulation patterns, engineering design of well drilling, hydraulic fracturing design of reservoirs, and the location of exploration and development well (Radwan et al., 2021; Wu et al., 2022a). Clarifying the distribution characteristics of current *in situ* stress is an important aspect of oil and gas exploration and development (Baouche et al., 2023). In this context, studying only localized, single-well, and stratified micro-scale stress distribution and stress field states are insufficient. It's essential to conduct macroscopic, regional research on current *in situ* stress.

TABLE 1 Statistics of the testing method for current *in situ* stress of reservoirs.

Category	Name	Test content	Advantage	Disadvantage
(1) On-site testing methods (well drilling)	1) Hydraulic Fractures	Magnitude of horizontal stress	Wide range of use; The result is reliable and accurate	Costly; Complex operation; High technical requirements for testing
	2) Micro-Hydraulic Fractures			
	3) Sleeve Fracture			
	4) Hydraulic Test of Pre-existing Fractures			
	5) Diagnostic Fracture Injection Test			
	6) Micro-seismic Monitoring	Direction of horizontal stress	The result is reliable and accurate	It cannot be used alone; High technical requirements for testing
	7) Borehole breakout	Direction of horizontal stress	Suitable for deep-hole; High accuracy	Difficult to observe borehole breakout and highly restrictive
	8) Drilling Induced Fractures	Direction of horizontal stress	Suitable for deep-hole; High accuracy	Difficult to observe drilling Induced Fractures and highly restrictive
	9) Borehole Deformation	Direction of horizontal stress	Suitable for deep-hole	Difficult to observe borehole deformation and highly restrictive
(2) laboratory testing methods (rock core)	1) Acoustic Emission method	Magnitude of stress	Wide range of use; The result is reliable and accurate	Kaiser point is difficult to determine; Costly; High technical requirements for testing
	2) Anelastic Strain Recovery	Magnitude of stress	Suitable for deep-hole and soft rock	Multiple influencing factors; Relatively low accuracy; Complex operation
	3) Differential Strain Curve Analysis	Magnitude of stress	Relatively high test result; Regardless of the placement time of the core	Multiple influencing factors
	4) Differential Wave Velocity Analysis	Direction of horizontal stress	Simple; Regardless of the placement time of the core	Relatively low accuracy
	5) Circumferential Velocity Anisotropy	Direction of horizontal stress	Simple operation; Economical	Relatively low accuracy
	6) Drilling Induced Fracture in Core/Core Discing	Direction of horizontal stress	Simple operation; Economical	Highly restrictive
	7) Overcoring of Archived Core	Magnitude and Direction of Horizontal Stress	Simple operation; Economical	Highly restrictive and Relatively low accuracy
	8) Petrographic Examination of Microcracks	Direction of horizontal stress	High reliability as a validation method	Need professional equipment; Complex operation
	9) Axial Point Load Test	Direction of horizontal stress	Simple operation	Difficulty in determining the cause of anisotropy

At home and abroad, the exploration and development depth of oil and gas reservoirs generally ranges from 1,000 to 10,000 m, and the depth are deeper than the depth of current *in situ* stress research in fields like mining, water resources, and tunnel engineering. Methods for characterizing current *in situ* stress of oil and gas reservoirs differ substantially from those used for characterizing current *in situ* stress of shallow rock layers. Researchers have proposed numerous approaches to characterize current *in situ* stress of oil and gas reservoirs (Hikweon and See, 2018; Fang et al., 2022; Garavand and Hadavimoghaddam, 2022; Zhou et al., 2023).

2 Testing methods

The testing method is one of the earliest techniques used to characterize current *in situ* stress of reservoirs (Yin et al., 2018). Compared to other characterization methods, this approach provides the most direct and accurate information regarding the direction and magnitude of current *in situ* stress (Aadnoy et al., 2013; Kim et al., 2017; Subrahmanyam, 2019; Krietsch et al., 2022). According to Table 1, the testing method can be divided into two categorys: the on-site testing method for well drilling and the laboratory testing method for rock core samples (Kruszewski et al., 2022).

There are many on-site testing methods for well drilling. Hydraulic fracturing is the most commonly used method for measuring current *in situ* stress in oil and gas reservoirs (Yang et al., 2021). This technique is characterized by its simplicity, broad applicability, and independence from the elastic parameters of the rock. It is also the most reliable testing method for current *in situ* stress of reservoirs (Xiong and Hampton, 2021). Building upon hydraulic fracturing, additional methods have been proposed, including Micro-Hydraulic Fractures (M-HF), Sleeve Fracture

(SF), Hydraulic Test of Pre-existing Fractures (HTPF), and Diagnostic Fracture Injection Test (DFIT). These methods extend the scope of hydraulic fracturing. However, the use of hydraulic fracturing alone can only determine the magnitude of current *in situ* stress and can't determine the direction. Usually, micro-seismic monitoring is combined with hydraulic fracturing to define the direction of current *in situ* stress (Agharazi, 2016; Li et al., 2019; Li et al., 2020; Li et al., 2022a; Li et al., 2023a).

The analysis methods of borehole collapse, induced wellbore cracks, and borehole deformation can determine the direction of current *in situ* stress. However, these methods are significantly influenced by factors such as formation stress state, rock mechanics properties, drilling parameters, and testing instruments, leading to considerable result variability. Additionally, these methods struggle to determine the magnitude of *in situ* stress (Gao, 2021; Wang et al., 2021; Ye et al., 2023). Core samples can measure both the magnitude and direction of current *in situ* stress. Acquiring high-quality oriented core samples is a fundamental and essential requirement for conducting testing work. Alternatively, other methods can be employed to determine the orientation of core samples, such as measuring the geomagnetic information carried by the core. However, the precision of these tests can impact the accuracy of subsequent experimental result.

Laboratory testing methods for rock cores can effectively determine the value of current *in situ* stress. Core based current *in situ* stress testing methods include Acoustic Emission method (AE), Anelastic Strain Recovery (ASR), Differential Strain Curve Analysis (DSCA), Differential Wave Velocity Analysis (DWVA), Circumferential Velocity Anisotropy (CVA), Drilling Induced Fracture in Core (DIFC)/Core Discing (CD), Overcoring of Archived Core (OCAC), Petrographic Examination of Micro-cracks and Axial Point Load Test.

The Acoustic Emission Method is related to the stress state of rock and the generation and propagation of elastic waves. Therefore, rocks with better elastic properties will exhibit a noticeable Kaiser effect, resulting in relatively accurate test of current *in situ* stress (Goodfellow and Young, 2014; Wu et al., 2022b). However, the Kaiser effect may not be prominent for porous and loose rocks, leading to relatively low accuracy of test result (Holcomb, 2013). Additionally, determining the Kaiser point during the experimental process can be challenging. To enhance the accuracy of current *in situ* stress test, the acoustic emission test can be complemented with other testing methods.

The Stress Relief Method based on viscoelastic strain recovery demonstrates high effectiveness and cost-effectiveness. However, the reliability of result from individual test is diminished due to numerous influencing factors (Sugimoto et al., 2021). In practice, supplementary prior information can be used to validate the accuracy of this method. When combined with the Differential Strain Curve Analysis method, better testing results can be achieved, and the influence of core placement time on test results can be minimized (Sanada et al., 2013).

The Differential Wave Velocity Analysis method and the Circular Wave Velocity Anisotropy Analysis method can determine the direction of current *in situ* stress based on the speed of acoustic wave in core samples (Ren and Hudson, 1987). These two methods are significantly affected by rock properties, rock structures, and micro-fractures, resulting in relatively lower accuracy when used individually to determine the direction of current *in situ* stress.

Analyzing cylindrical cores or core-induced cracks to determine the direction of current *in situ* stress will yield highly accurate results. However, the occurrence of cylindrical cores and core-induced cracks is extremely rare, and orientation can be challenging, limiting the applicability of this method (Li and Schmitt, 1998).

The Secondary Stress Relief Method of cores can be used to determine the direction and estimate the value of current *in situ* stress (Hoskins and Russell, 1981). However, not all cores exhibit distinct stress relief characteristics, and rock structure may introduce significant errors during testing.

Microfracture lithofacies analysis and axial point load analysis can also determine the direction of current *in situ* stress. However, the accuracy of result obtained from these methods when used individually is relatively low. They can serve as supplementary or validation methods for other testing techniques (Liang et al., 1998).

Relative to other methods, result obtained through the testing method is the most accurate. However, this method has challenges like limited data volume, high cost, and complex testing procedures.

3 Computational approaches

In order to reduce the cost of exploration and development and obtain more stress information, researchers employ well-logging data to determine the direction and magnitude of current *in situ* stress within reservoirs.

(Wang et al., 2022a). Well-logging data possesses characteristics such as large testing depth, large amount of information, and relatively continuous data, making characterization methods based on well-logging data have unique advantages. This approach can obtain a profile of continuous current *in situ* stress from top to bottom along the well drilling (Urban and Aguilera, 2015; Zhang and Yin, 2019).

Currently, the calculation of vertical principal stress has little dispute and its value is considered equal to the overlying rock mass's gravity and can be obtained by integrating density data from the surface to the target depth (Radwan et al., 2021).

Using acoustic well logging data, the magnitude of horizontal stress can be estimated along the well drilling (Figure 1A). Due to the formation and existence conditions of stress in the formation are closer to the rock's static testing environment, estimating horizontal stress using static mechanical parameters is more accurate (Musa et al., 2021). Therefore, it is necessary to convert dynamic mechanical parameters to static mechanical parameters using the attenuation coefficient calculated from the acoustic well logging data and then compute the horizontal principal stress within the formation. Various models exist for the calculation of horizontal principal stress, including uniaxial strain models, Mohr-Coulomb failure models, Coulomb-Naive failure models, combined spring models, Gassmann models, poroelastic strain models, biaxial strain models, and Huang's model (Fan et al., 2014; Rasouli and Sutherland, 2014). While these models possess simple mathematical formulations and relatively low calculation precision, calculated result can be analyzed and corrected

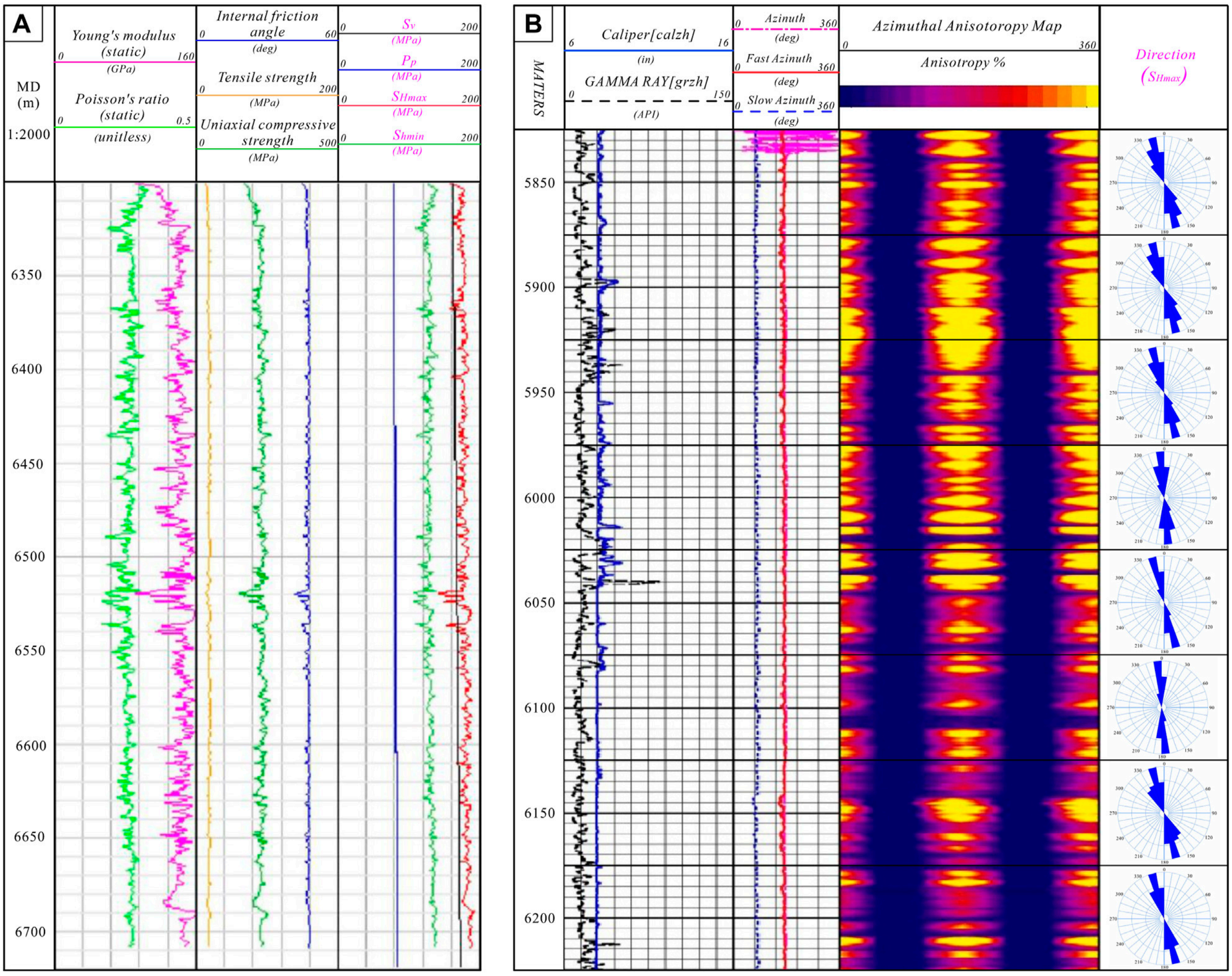

FIGURE 1
Continuous distribution profile of current *in situ* stress based on logging data: **(A)** The magnitude of current *in situ* stress; **(B)** The direction of current *in situ* stress.

based on actual current *in situ* stress testing data to meet the requirements of oil and gas reservoir exploration and development. Additionally, selecting the appropriate calculation model for horizontal stress according to the research area's characteristics and acquired data are crucial to fully leverage the advantages of current *in situ* stress estimation methods based on the date of acoustic well logging.

Acoustic well logging data can also be used to identify current *in situ* stress direction and obtain continuous profiles of direction of current *in situ* stress (Figure 1B). The principle involves utilizing the characteristics of shear wave splitting in anisotropic formations, extracting fast and slow shear wave velocities and orientations from multipole acoustic well logging waveform data, and determining the directions of maximum and minimum horizontal stress based on the orientation of the fast shear wave. Additionally, micro-resistivity imaging well logging or borehole acoustic imaging well logging can identify the orientation of borehole collapse sections, induced fracture zones, and stress release fractures, allowing for the determination of horizontal principal stress direction (Willams et al., 2015). Furthermore, the well deviation logging provides borehole radius and dip angles of strata, aiding in determining borehole collapse orientation and thus deducing horizontal principal stress direction (Wang et al., 2022b).

Result obtained by calculating and analyzing current *in situ* stress magnitude and direction based on well-logging data need calibration through other testing methods to attain greater accuracy. Furthermore, this method only provides continuous *in situ* stress profiles along well depth and cannot predict *in situ* stress across the entire field, particularly in areas that have not been drilled.

4 Numerical methods

Some scholars have employed large-scale numerical simulation techniques for the inversion analysis of current *in situ* stress (Radwan and Sen, 2021). Based on relevant geological data, a three-dimensional geological computational model is established. Using measured stress values from known locations and appropriate statistical analysis methods, optimal factors for evaluating the stress field are selected (Ning et al., 2021). The constitutive relationship of rock mechanics is established, and a more realistic distribution characteristic of current *in situ* stress is obtained through numerical methods. By using numerical methods, we can predict the magnitude and direction of current *in situ* stress.

Numerical methods can predict widely ranging and continuous current *in situ* stress, yielding relatively accurate predictive results in undrilled areas. The accuracy of numerical simulation is directly related to the resemblance between the model and the actual reservoir and the accuracy of the model's boundary loads. In practical applications, numerical methods are often combined with other analytical methods to enhance the accuracy of simulation results (Scelsi et al., 2019; Miao et al., 2022).

Common numerical methods include finite difference method, variational method, discrete method, boundary method, and finite element method (Sun, 2023; Sun et al., 2023). The finite difference method has a more rigorous theoretical foundation, but it mainly discretizes the fundamental governing equations and generally applies to geometric shapes with simple outlines. The finite element method discretizes the objects constituting the system and this method can simplify the analyzed object's complex mechanical properties and boundary conditions, thus having a broader scope of application. The finite element method also features relatively simple calculation procedures, high discretization accuracy, and easy convergence of computation results, making it the primary numerical simulation method for stress field studies (Sharafisafa et al., 2023). The application of variable method, discrete method, and boundary method are relatively limited.

In recent decades, with the rapid development of computer technology, more and more scholars have been dedicated to numerical simulation research of current *in situ* stress of oil and gas reservoirs. Commonly used finite element analysis software includes NASTRAN, ANSYS, ABAQUS, COMSOL, ADINA, and so on. These software packages can solve complex linear and nonlinear problems, but each has relatively suitable domains. ANSYS and ABAQUS have simpler modeling methods, comprehensive pre-and post-processing, and higher accuracy in computed result, making them widely applied tools (Li et al., 2022b; Li et al., 2023b; Zhao et al., 2023).

5 Seismic prediction methods

In addition to numerical methods to predict regional current *in situ* stress, seismic data volume can also be utilized to estimate current *in situ* stress in a region (Yang et al., 2022). This method can provide a continuous distribution of current *in situ* stress in the study area, even in areas with few wells, and this method can overcome the limitations of location constraints. It offers lateral predictions of current *in situ* stress for the working area, providing theoretical guidance for well deployment and hydraulic fracturing development.

Common seismic prediction methods include the two-dimensional stress analysis method based on thin plate theory (Ma et al., 2020), the prediction of *in situ* stress magnitude based on pre-stack elastic parameters (Wang et al., 2020), and the prediction of *in situ* stress direction based on pre-stack azimuthal differences (Goodway et al., 2012).

The process of two-dimensional *in situ* stress seismic prediction based on thin plate theory (Figure 2A) involves analyzing the relationship between rock elastic parameters such as compressional wave velocity, shear wave velocity, density, Young's modulus, Poisson's ratio, and *in situ* stress. Sensitivity characterization parameters for *in situ* stress are selected (Gray et al., 2012). Nonhomogeneous elastic parameter inversion based on scattering theory is used to invert elastic parameters such as compressional to shear wave velocity ratio, Poisson's ratio, Lamé constants, and shear modulus (Ma, 2023). Trend surface analysis is employed to fit the surface using fault data as constraints. Based on the calculated tectonic curvature distribution, a three-dimensional finite difference numerical simulation method using an elastic thin plate model is applied to simulate and estimate current *in situ* stress. This method integrates pre-stack seismic elastic parameter inversion technology to construct a refined nonhomogeneous mechanical model. By combining stress field numerical simulation and seismic inversion technology, the influences of factors such as structure, faults, formation thickness, and lithology are more reasonably considered, greatly improving the accuracy of simulation result.

Predicting current *in situ* stress magnitude based on pre-stack elastic parameters (Figure 2B) involves utilizing rock physics elastic parameters as the foundation. Multivariate linear regression establishes a stress calculation formula based on three elastic parameters, and followed by a multi-factor correction. Finally, pre-stack inversion technology is used to obtain elastic parameters such as Young's, bulk, and shear modulus for the working area. The formula is used for fitting and correction to calculate the maximum and minimum stresses.

Predicting current *in situ* stress direction based on pre-stack azimuthal differences (Figure 2C) is built upon AVO forward modeling. With the assistance of transverse isotropy theory, pre-stack wide azimuthal seismic data is processed for azimuthal angle extraction. Different azimuthal AVO attributes are derived, and the relationship between seismic azimuthal and current *in situ* stress direction is established using azimuthal variation in transverse wave velocities due to *in situ* stress-induced azimuthal anisotropy (Ma et al., 2017). Validation and comparison are performed using FMI imaging and sonic anisotropy logging data to determine the *in situ* stress direction ultimately.

Using seismic data for current *in situ* stress prediction often requires establishing an *in situ* stress prediction model (Zhang et al., 2015). First, the relationship between stress and rock elastic and physical parameters (such as Young's modulus, Poisson's ratio, density, compressional wave velocity, etc.) is clarified. Then, seismic inversion methods extract relevant parameter information from seismic data and indirectly predict current *in situ* stress (Yang et al., 2023). This model-based current *in situ* stress prediction method provides good spatial coverage but is highly dependent on the accuracy of the current *in situ* stress prediction model (Ma et al., 2018). All factors affecting current *in situ* stress will significantly increase model complexity, reducing the method's applicability (Li, 2023). It's best to use this method with other methods to enhance prediction accuracy.

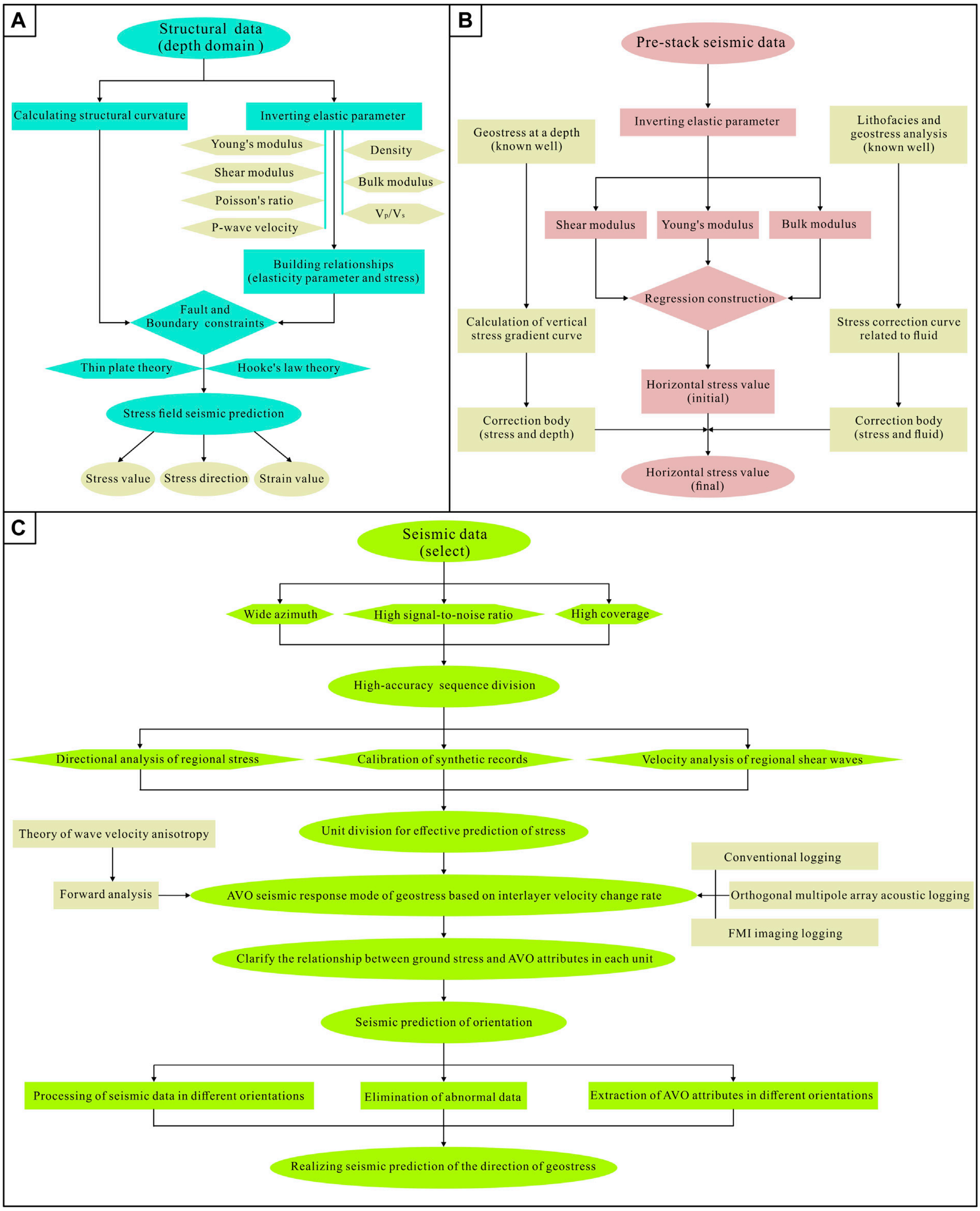

FIGURE 2
Technical roadmap for seismic prediction of current *in situ* stress: **(A)** Based on the theory of thin plates; **(B)** Based on pre-stack elastic parameters; **(C)** Based on pre-stack orientation differences.

6 Conclusion and recommendations

Due to the close relationship between current *in situ* stress and various issues in the process of oil and gas exploration and development, such as the migration and accumulation of oil and gas, wellbore stability during drilling, design of horizontal wells, reservoir modification, and well network arrangement in water injection development, scholars at home and abroad have proposed various methods for characterizing the current *in situ* stress of oil and gas reservoirs. We systematically review those methods for characterizing the current *in situ* stress of oil and gas reservoirs and arrive at the following conclusions.

(1) Testing methods encompass on-site testing and laboratory testing. While testing methods can obtain accurate results, the testing cost is relatively high, and the obtained stress data are limited to specific points.
(2) Continuous stress profiles can be obtained through calculating based on well-logging data. High accuracy magnitude and orientation of current *in situ* stress can be achieved by calibrating with testing method.
(3) Numerical methods can predict wide-ranging and continuous current *in situ* stress. Utilizing accurate modeling, boundary condition setting, parameter optimization, and known data of current *in situ* stress, accurate prediction result in unexplored areas can be achieved.
(4) Stress estimation using seismic data volume can also predict continuous current *in situ* stress, even in areas with few wells. However, it is influenced by multiple factors and should be used in conjunction with other testing methods to obtain reliable estimation result.

While various methods for characterizing current stress can measure, estimate, and predict stress from single points to wellbore profiles and even broader areas, a further in-depth research is still required for characterization methods of current *in situ* stress.

(1) Advancements in testing techniques and instruments. Researchers believe that the basic theory of stress testing has not undergone significant changes. The development of future testing methods will primarily focus on innovation in testing techniques and instruments (Wang, 2014). With the exploration and development of deep and ultra-deep oil and gas reservoirs, there is an increasing demand for testing deep-seated current *in situ* stress, necessitating the study of techniques and instruments for testing the current *in situ* stress in deep and ultra-deep reservoirs.
(2) Determination of combined application modes and procedures for various methods. Testing methods, computational approaches, numerical methods, and seismic prediction methods all contribute to research of *in situ* current stress of oil and gas reservoirs. However, each method has advantages, disadvantages, and limitations. Determining combined application modes and procedures for various methods based on reservoir conditions, geological structures, lithological characteristics, drilling designs, and fracturing methods is an ongoing challenge for engineers and researchers. This challenge aims to simultaneously satisfy the requirements of oil and gas exploration and development while minimizing time and cost.
(3) Development of new models for stress prediction based on artificial intelligence and big data. Uncertainties still exist even after calibrating geological mechanical models with core test and fracturing data. Artificial intelligence method can establish reliable and accurate prediction model without presupposing rocks' *in situ* mechanical behavior and physical properties (Li, 2022; Mahmoodzadeh et al., 2023). Therefore, by combining rock mechanics theory with big data methodologies, new methods for stress prediction and uncertainty characterization are significant trends in the future development of current *in situ* stress prediction technology.

Author contributions

TZ: Funding acquisition, Investigation, Methodology, Project administration, Writing–original draft, Writing–review and editing, Conceptualization, Data curation, Formal Analysis. QQ: Formal Analysis, Funding acquisition, Project administration, Supervision, Validation, Visualization, Writing–review and editing.

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Conflict of interest

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