Application of Geophysical Technology in CCS/CCUS Geological Storage

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Summary

CCS/CCUS is being deployed at large scale, expanding across industries through joint efforts. Geophysics plays a crucial role in CCS/CCUS geological storage operations. For saline aquifer evaluation, an innovative seismic characterization system was developed using a dual-parameter approach combining fluid mobility and Vp/Vs ratios. This achieved quantitative characterization with 80% accuracy in blind well tests. In CO_2 plume monitoring, a high-order THMC (Thermo-Hydro-Mechanical-Chemical) coupling scheme reduced simulation errors from 21% to 4%. For effectiveness evaluation, 3D fault body assessment replaced conventional 2D methods through improved fault permeability and transmissibility analysis. Integrated monitoring using microseismic, fiber-optic and time-lapse VSP technologies enabled full lifecycle management. These developments provide crucial support for precise and secure geological storage, validated through multiple benchmark projects worldwide.

Introduction

CCS/CCUS is projected by the International Energy Agency (IEA) to contribute over 15% of global carbon emission reductions by 2050. In terms of potential, global geological storage capacity is estimated at around 10 trillion tons, sufficient to support large-scale carbon emission reduction needs and provide a buffer period for energy transition[1]. However, the field of geological carbon storage faces many challenges related to storage scalability, injectivity, effectiveness, and safety[2].

First, site selection requires breakthroughs in multi-source data integration. Conventional methods struggle to accurately synthesize geological, geophysical, and reservoir property data, leading to insufficient precision in predicting storage capacity in low-porosity and low-permeability reservoirs. Additionally, existing saline aquifer standards exhibit poor applicability, constraining vertical layer selection and areal zoning, thereby hindering reliable assessment of storage potential.

Second, dynamic numerical simulation is constrained by the complexities of multi-field coupling (flow-chemical-mechanical) and reservoir heterogeneity (such as bedding and fractures). Traditional models fail to adequately capture the time-varying behaviours of CO_2-water-rock interactions, resulting in a lack of precision in subsequent storage parameter design.

Third, effectiveness evaluation faces significant limitations in fault sealing assessment. The spatial correlation between lithological variations within fault zones (e.g., cataclasites and clay smearing) and sealing capacity remains poorly understood. Moreover, the applicability of traditional single-parameter evaluation method such as the Shale Gouge Ratio (SGR) in complex fault systems is questionable.

Fouth, CCS/CCUS needs to establish a full-cycle and multi-dimensional safety system centered on leakage prevention. Conventional oil and gas monitoring methods cannot be directly applied, and existing geophysical methods are difficult to achieve real-time dynamic monitoring of CO_2 migration and formation response during the sequestration process. The breakthrough of the above challenges will directly determine the leap of CCS technology from theoretical potential to engineering practice, and is of strategic significance for the realization of China's carbon emission reduction goals as scheduled[3].

Methods

1. Seismic characterization of saline aquifers

Based on analyzing the fluid mobility attribute and conducting cross-plot analysis of the Vp/Vs, clarify the characteristics of saline aquifers and construct a saline aquifer identification factor accordingly. Based on histogram analysis of this factor, verify its effectiveness in distinguishing saline aquifers from other fluid reservoirs and mudstone layers. Obtaining the Vp/Vs volume from pre-stack simultaneous inversion and the fluid mobility attribute from post-stack seismic (Figure 1a), then combining these two volumes to obtain the identification factor volume (Figure 1b), realize the 3D quantitative prediction of saline aquifers.

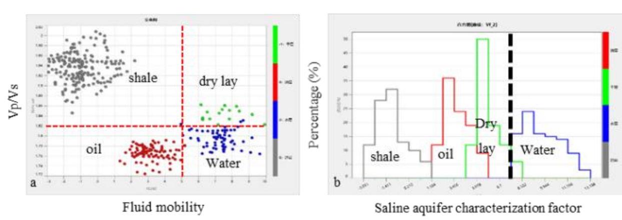

Figure 1: Geophysical and petrophysical plots for fluid and aquifer characterization

a: Crossplot of fluid mobility versus Vp/Vs

b: Histogram of saline aquifer characterization factor

2. Long-term simulation of CO_2 plume

In numerical simulation, differentiated solutions must be constructed based on the core mechanism differences, such as structural, residual, dissolution, and mineralization[4]. Precise characterization is achieved through customized simulation framework and parameter system. Structural sequestration achieves physical isolation relying on geological traps. It needs to use the Bayesian fusion framework to break through the limitations of well logging data and generate high-precision models. Residual sequestration locks CO_2 via capillary force. It modifies relative permeability curves with pore structure parameters and fits hysteresis coefficients through experiments to characterize the trapping efficiency of different lithologies. Dissolution sequestration is based on the dissolution equilibrium between CO_2 and formation water. Building a multi-field coupling framework is required to break through the limitations of the traditional Henry's law. Mineralization sequestration generates stable carbonates through the reaction of CO_2 with rock minerals. Its core lies in long-term multi-field coupling, and the simulation needs to solve the problem of "macro-micro" scale disconnection.

3. Fault sealing evaluation based on 3D Modeling

Considering the problems existing in traditional methods, we apply 3D modeling-based approach to evaluate fault sealing. First, high-precision attribute modeling is conducted by calculating shale content, porosity, and permeability of single wells. Then, fault attributes are extracted and analyzed based on the attribute model. It can be applied in areas with few or no wells and overcome the inter-well heterogeneity.

In addition, apart from calculating the SGR, it enables the calculation of fault permeability and fault conductivity, thus overcoming the limitations of single evaluation methods (Table 1).

Table 1: Comprehensive evaluation criteria for fault sealing based on multiple parameters

Evaluation Parameter	Sealing Grade	Evaluation Criteria
SGR	Good	>0.3
	Moderate	0.2-0.3
	Poor	<0.2
Fault	Good	<0.01 mD

Permeability (K_f)	Moderate	0.01-0.1mD
	Poor	>0.1 mD
Fault Transmissivity (TM)	Good	<0.1
	Moderate	0.1-0.5
	Poor	>0.5
Judgment	Safe	All three parameters reach "Good"
	Basically Safe	Two "Good" + one "Moderate"
	Risky	Any parameter reaches "Poor"

4. CCS/CCUS full-cycle monitoring

The integrated monitoring combining microseismic, fiber optics, and VSP has emerged as a critical approach for ensuring secure storage and dynamic early warning in CCUS projects. This technique can effectively identifiy risks such as caprock fracturing or fault reactivation, detects CO_2 fluid fronts or potential leakage, and quantitatively analyze the diffusion range of CO_2. It enables dynamic characterization of CO_2 migration pathways, assessment of caprock integrity, and leakage early warning, thereby supporting full lifecycle management of well integrity. It has proven effective in monitoring caprock integrity, optimizing gas injection pressure, predicting casing deformation risks, and providing practical solutions to challenges related to safety, precision, and cost-effectiveness in CCUS monitoring operations[5].

Microseismic monitoring can assess geological integrity, caprock integrity, pathways for fluid migration, and causes of gas channeling. Furthermore, it can optimize injection and production parameters based on real-time monitoring results, provide effective guidance for CO_2 utilization and storage.

Comparing to conventional monitoring, fiber-optic monitoring demonstrates strong adaptability to complex exploration environments and represents a scientifically advanced and modern logging approach. It will further enhance the efficient development of oil and gas wells and provide robust data support for dynamic reservoir management.

Time-lapse VSP monitoring of CO_2 plume migration requires strict consistency between two or more successive data acquisitions. Compared to surface seismic techniques, VSP offers advantages such as operational flexibility, deeper reservoir penetration, accurate time-depth relationships, reduced near-surface absorption and attenuation, and higher resolution.

Cases

1 Million-ton scale carbon capture, utilization and storage demonstration project in Oilfield A

Oilfield A is actively advancing its million-ton scale CCS/CCUS storage planning. CO_2 capture, transportation, and utilization are relatively mature, storage techniques remain underdeveloped, particularly in the critical area of geological site selection and evaluation. To achieve large-scale, safe, and efficient geological CO_2 storage, a comprehensive geological evaluation system is required to meet the challenges such as geological prediction, sealing integrity studies, storage potential assessment, and plume migration forecasting.

1.1 Scalability evaluation

By constructing a saline aquifer SF (seismic characterization factor) through a dual-parameter conversion, blind well verification demonstrated an 80% consistency rate, this achievement enables high-precision quantitative characterization of saline aquifers. Based on the SF volume prediction results, multiple CCS geological units were identified in the relevant area, providing a reliable foundation for CO_2 storage site selection (Figure 2).

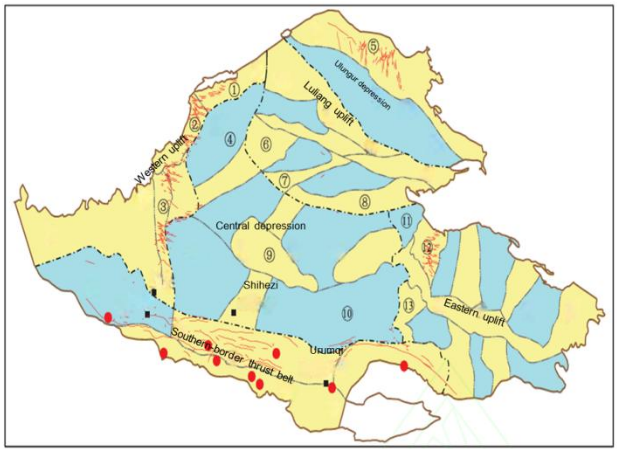

Figure 2: Distribution map of reliable traps in Oilfield A

1.2 Injectivity evaluation

During injectivity evaluation, storage mechanisms are optimized and tailored solutions developed. Reservoir properties are obtained through water chemistry analysis, petrophysical modeling, and logging response analysis. These parameters are integrated with seismic-derived geological structures. Using multi-field coupled numerical modeling, long-term CO_2 plume behavior is simulated under dual constraints of well and seismic data.

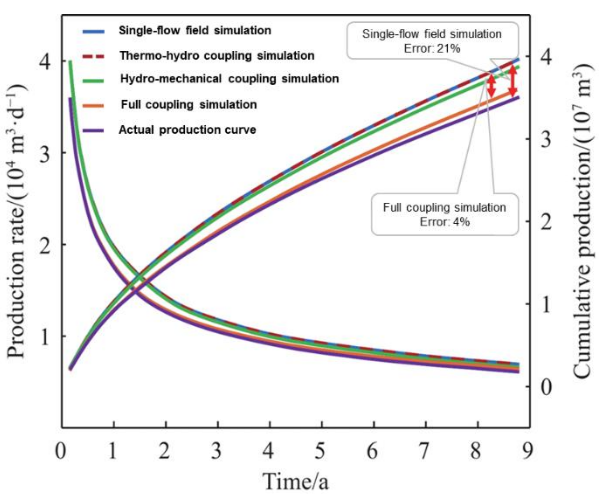

Figure 3: Accuracy comparison between numerical simulation and core fitting curves under multi-field coupling effects

Practice demonstrates that the simulation accuracy is significantly improved, the error rate is decreased from 21% to 4% (Figure 3). It enables more precise prediction of CO_2 plume morphology, front advancement velocity, and distribution range at different injection stages. These results provide reliable guidance for optimizing injector placement, adjusting injection rates and pressures, and ensuring stable and efficient CO_2 injection operations.

1.3 Effectiveness evaluation

Conventional methods for evaluating fault sealing primarily rely on well interpolation and cannot be applied in areas with limited well data due to the accuracy is affected by interwell heterogeneity. By establishing a 3D attribute model integrating well log and seismic data, fault sealing can be evaluated across different scales whether in areas with or without well coverage (Figure 4).

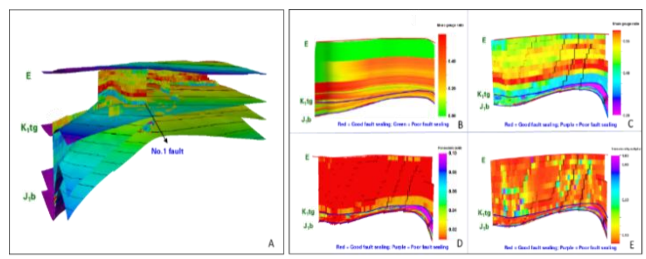

Figure 4: Attribute distribution maps of fault 1

A: Spatial distribution and location of fault 1. B：SGR distribution calculated by conventional method. C: SGR distribution calculated by 3D modeling method. D: Fault permeability distribution calculated by 3D modeling method. E. Fault transmissibility distribution calculated by 3D modeling method.

1.4 Results

Addressing four requirements including prediction and characterization of typical saline aquifer formations, study of CO_2 leakage mechanisms and formation sealing integrity, evaluation of storage potential, and prediction of CO_2 plume migration with optimized injection parameters, detailed assessments of scalability, injectivity and effectiveness have achieved good results. Strong supports are provided in completing reliability and effectiveness evaluations of CCS geological targets, identifying 95 verified storage formations with a theoretical storage capacity of 1.7 billion tons, and contributing to the design of a million-ton scale CCS demonstration project.

2 300,000-ton CCS demonstration project

In 2010, Company B initiated a CO_2 geological storage pilot. Over a span of more than ten years, BGP provided technical support for site selection and long-term injection monitoring through geological studies, 3D seismic and VSP surveys. Figure 9 demonstrates the effect of time-lapse amplitude difference through cross-correlation. The observed increase in VSP time difference and amplitude response across multiple gas injection phases reflects formation changes post-injection.

From 2013 to 2015, six time-lapse VSP surveys were conducted to characterize the CO_2 plume migration front, providing clear visualization of its subsurface distribution and extent (Figure 5). Repeated monitoring confirmed excellent storage integrity with no leakage detected, establishing this project as China's first successful large-scale carbon storage demonstration. Technical services are currently being provided for its second-phase CCS project.

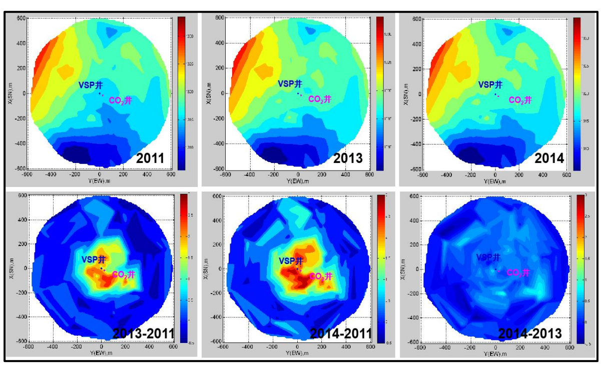

Figure 5:Amplitude map at 1300ms (2350m, Gas Injection Depth) time slice

3. Operation safety monitoring of CCUS-EOR in Oilfield C

For optimizing CO_2 flooding pilot areas, production test results from surrounding vertical wells, geological and engineering sweet spot development should be considered comprehensively. Specifically, target zones should exhibit high production rates, superior oil-bearing properties, high brittleness, and low differential horizontal stress ratio, while avoiding fracture-developed areas to prevent gas channeling during injection. This study integrated Vp/Vs ratios, brittleness, differential horizontal stress ratios, and fracture prediction results to select the M well area as the CO_2 flooding pilot zone. For the CCUS-EOR test block in Oilfield C, microseismic monitoring effectively assesses caprock integrity, gas migration patterns, and fault activation risks (Figure 6).

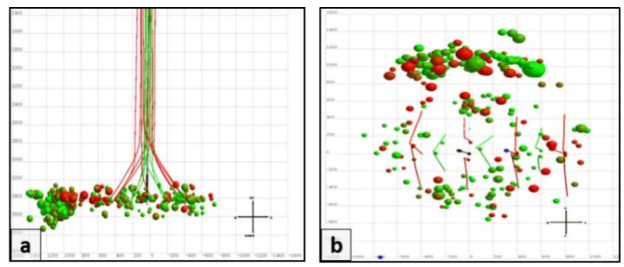

Figure 6: Microseismic monitoring of the pilot area

a: Vertical distribution of microseismic events

b:Horizontal distribution of microseismic events

4 Site selection and storage monitoring

The peridotite formation in area D exhibits ideal reservoir conditions for permanent CO_2 mineralization due to its distinctive physical characteristics of high electrical resistivity and gravity high anomalies. For the storage engineering in this area, a two-phase geophysical exploration and monitoring strategy was adopted. This approach leverages the advantages of gravity and transient electromagnetic (TEM) techniques to achieve precise control in storage site selection, well placement, and monitoring of deep fluid migration (Figure 7).

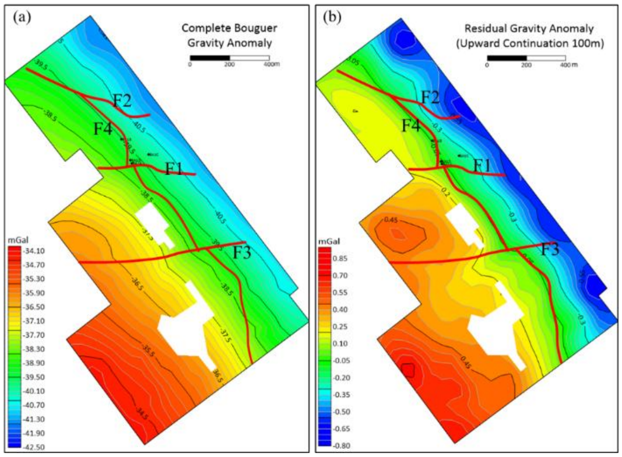

Figure 7: Fault interpretation results based on gravity data

a: Bouguer gravity anomaly. b: Residual gravity anomaly

Conclusions

Geophysical technology provides high-precision data & predictive analysis, ensuring safe & cost-effective carbon storage & utilization.

Geophysical technology enables precise and secure CCS/CCUS storage through four key technical solutions: saline aquifer characterization, THMC coupling scheme, 3D fault sealing prediction, and integrated lifecycle monitoring.

BGP has built a multidisciplinary CCS/CCUS technical system, integrating geology, geophysics & engineering, and now offers full chain of geological storage & monitoring solutions for CCS/CCUS operations.

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