Supplementary file

Advances in monitoring technologies for CO_2 geological storage: A review from the laboratory to field-scale applications

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Since the beginning of the 21st century, countries (such as the United States, Canada, Australia, Japan, and the United Arab Emirates) have accelerated the industrial deployment of CO_2 capture projects, making significant contributions to CCUS development. Notable examples include Canada's Boundary Dam and Quest projects, as well as China's Enping offshore CO_2 storage demonstration project. In both pilot-scale studies and large-scale demonstration projects, monitoring CO_2 leakage is of critical importance, particularly in relation to wellbore integrity, subsurface CO_2 migration, and potential leakage through the caprock (Fig. S1).

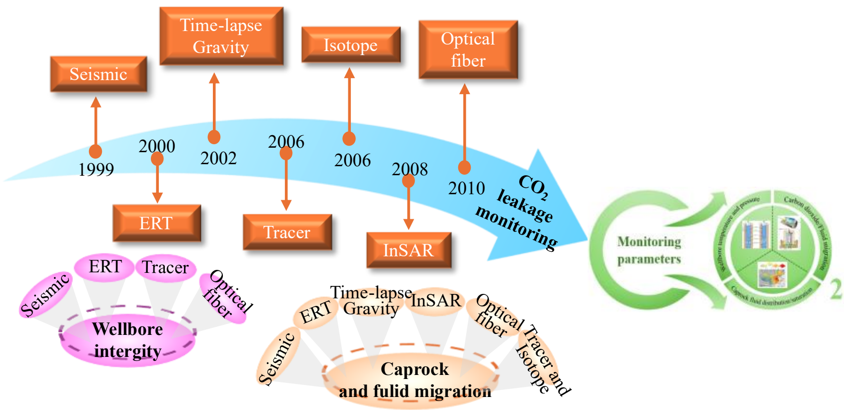

Fig. S1. Progress in monitoring methods for CO_2 leakage.

At present, distributed optical fiber sensing technology is widely applied and includes underground hydraulic fracturing monitoring (Saw et al., 2025), seismic monitoring (Cang et al., 2025), CO_2 plume monitoring (Chen et al., 2025), casing leakage monitoring (Gemeinhardt and Sharma, 2024), and gas lift optimization (Wang et al., 2025). Among available methods, optical frequency domain reflectometry (OFDR) offers superior accuracy, resolution, and sensitivity compared to optical time domain reflectometry (OTDR), and requires lower light source power for equivalent dynamic ranges (Ding et al., 2023; Lv et al., 2025).

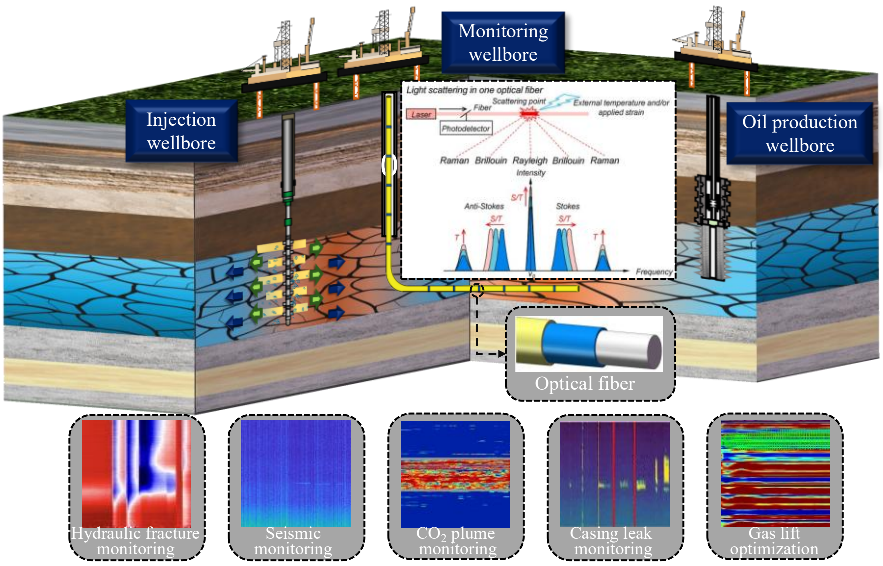

Fig. S2. Application of distributed optical fiber sensing technology and schematic diagram of three kinds of scattered lights (Li and Liu, 2019; Zhang et al., 2019; Liu et al., 2024).

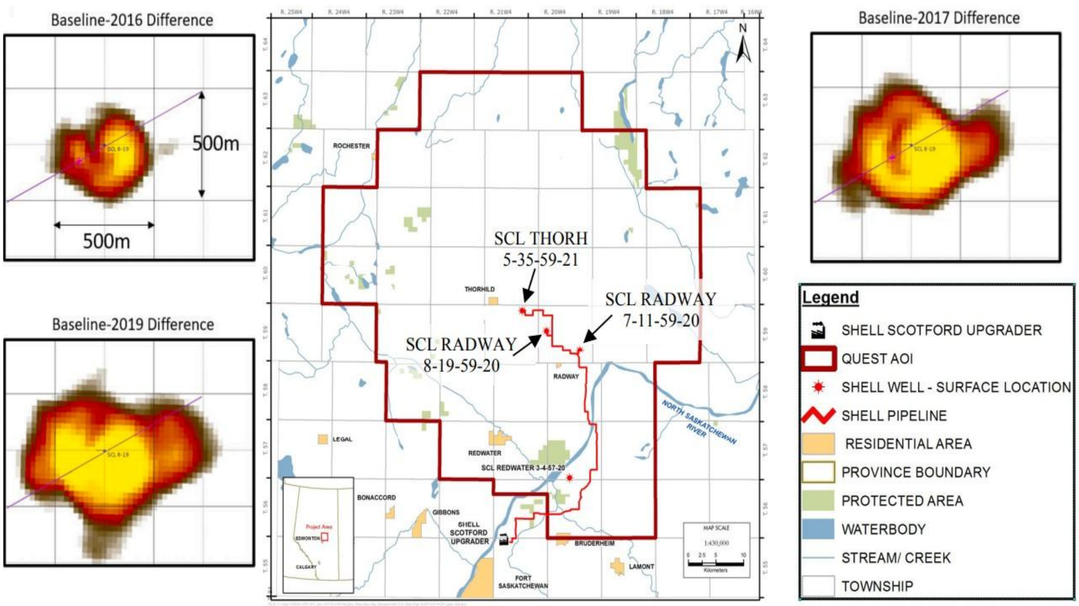

Fig. S3. Delayed seismic monitoring results of the Quest project (Rock et al., 2014; Stephen et al., 2022).

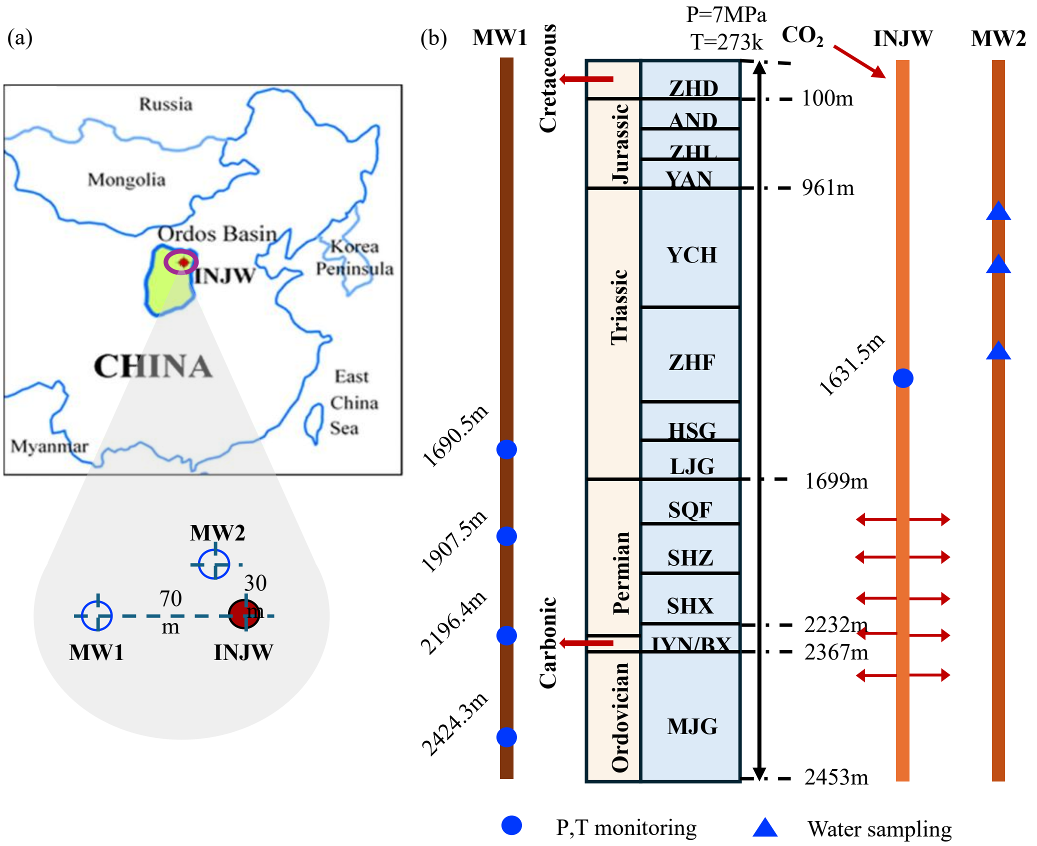

Fig. S4. Shenhua CCS demonstration project site information and underground monitoring system: (a) Location of the Shenhua CCS Project and (b) Schematic diagram of underground monitoring for the Shenhua CCS Project (Zhang et al., 2016).

Table S1. Research on the diffusion coefficient of CO_2 in water/brine.

Reference	Research methods	Temperature (°C)	Pressure (MPa)	Solution	Diffusion coefficient ($\times 10^{-9}$ m^2/s)
Lu et al. (2013)	Raman spectroscopy	-5-200	10-45	Water	0.8-16.1
Kouhi et al. (2025)	MLP prediction model	210-673	0.1-100	Brine	0.0007-285
Omrani et al. (2022)	MD molecular dynamics simulation	21-150	10-30	Water/Brine	0.9109-11.2775
Li et al. (2021)	Experiment	40-100	8-30	Brine	1.66-9.61
Amin et al. (2020)	ANFIS and evolutionary algorithms	0-200	0.1-49.3	Brine	0.139-1.95
Ahmadi et al. (2020)	Experiment	25-80	2.074-18.533	Water	1.68-7.22
Reza et al. (2013)	Experiment and modeling	32-50	5.9-6.9	Brine	3.52-6.16
Zarghami et al. (2017)	Pressure attenuation method	50-75	17.45	Water/Brine	3.6-5.3
Zhang et al. (2023b)	Pressure attenuation method	13-30	0.1-5	Brine	0.126-1.730

Notes: Multilayer perceptron (MLP); Molecular dynamics (MD); Adaptive neuro-fuzzy inference system (ANFIS).

Table S2. Research on the sealing performance and safety monitoring of the caprock.

Caprock seal integrity	Temperature (°C)	Pressure (MPa)	Formation type	Monitoring methods	Breakthrough pressure
CO_2 breaks through the capillary tube (Hildenbrand et al., 2004; Li et al., 2005)	35	7.5	Shale	Pressure and temperature sensors	3.6-4.0 MPa
	50(CO_2)/ 30(CH_4)	20	Argillaceous rock	Pressure sensors	CO_2: 0.1-4.9 MPa CH_4: 0.1-3.6 MPa
	59	7.3	Anhydrite and dolomite	Pressure sensors	N_2: More than 30 MPa CO_2: 21 MPa
CO_2 dissolves into the caprock (Berne et al., 2010; Cheng et al., 2024; Fani et al., 2024)	23 ± 1	20	Limestone and sandstone	NMR, radioactive tracer	Carbonate caps may provide additional CO_2 storage
	50	20.7	Sandstone	SEM, EDX, XRD	Sample porosity increases
	42	16.8	Shale	SEM, EDX, XRD	Shale undergoes chemical reactions under $scCO_2$ conditions
	38	9.87	Dolomite	SEM, EDX, XRD	Dolomite dissolves in $scCO_2$
	50	12	Shale	NMR, SEM	The breakthrough pressure drops to 22.22%
	60	8	Carbonates and sandstone	SEM, EDX, XRD, Ion Chromatography	The solubility of CO_2 in solutions of different salinities increases with increasing pressure and decreases with increasing salinity
Clay minerals adsorb CO_2 (Heller and Zoback, 2014)	40	0.34-5.52	Shale rich in clay	Three-axis compression test	The adsorption capacity of CO_2 is approximately 2 to 3 times that of CH_4
	25-45	15-29	Shale, sandstone and limestone (65% clay)	MIP, XRD, SEM	Limestone gas breakthrough pressure in 1.2-2.9 MPa, and mudstone breakthrough pressure in 5-13 MPa

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