Research Article

Evaluating the Sealing Effectiveness of a Caprock-Fault System for CO₂-EOR Storage: A Case Study of the Shengli Oilfield

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An effective sealing system is crucial for CO₂-EOR storage, and these sealing systems are typically composed of the caprocks and faults that surround a reservoir. Therefore, the sealing effectiveness of a caprock-fault system must be evaluated at various stages of CO₂-EOR storage projects. This paper presents a new evaluation framework that considers specific site characteristics and a case study on the sealing effectiveness of the caprock-fault system in the Shengli Oilfield. The proposed method is a weighted ranking system where a set of 17 indicators has been developed for the assessment and ranking of the G89 block in terms of their sealing ability for CO₂ sequestration. Additional indicators are involved in the method, such as the newly proposed parameter, frontier displacement work which reflects the influence of formation pressure, displacement pressure resistance, and caprock thickness. The new approach considers the sealing mechanisms of caprocks and faults as well as the configuration relationships between them. The method was used to evaluate the sealing effectiveness of the G89 block that has a considerable number of faults and good sealing ability of caprock in the Shengli Oilfield.

1. Introduction

CO₂ geological storage (CGS) is widely recognized as an effective approach for reducing CO₂ levels in the atmosphere [1–3]. As a further CGS initiative, CO₂ geological utilization and storage (CGUS) [4], which fall under the wider scope of CCUS (Carbon Capture, Utilization, and Storage) technology, were proposed for the full utilization of CO₂ and the maximization of its additional value prior to underground storage. Of the identified CGUS options, CO₂-enhanced oil recovery (EOR) storage (CO₂-EOR storage), which is different from the CO₂-EOR operations traditionally used in Tertiary oil recovery, is a subject of increasing interest because of its overall advantages over other CGS options. CO₂-EOR storage is essentially a cooptimization process of CO₂ storage and EOR designed to improve oil production simultaneously sequestering CO₂ [5, 6], which can achieve cost advantages and social and economic benefits [7, 8].

A number of CO₂-EOR projects have been conducted worldwide [9–11]. In China, several CO₂-EOR projects have

been conducted by PetroChina, Yanchang Petroleum, and Sinopec in the Jilin Oilfield, Jingbian Oilfield, and Shengli Oilfield, respectively [8, 12–14]. The Shengli Oilfield (Figure 1) is the target site in this paper. The CO₂-EOR pilot operations designed to explore whether the gradual decreasing trend of oil production could be overcome began at this site early in 2007 [15]. The active enhancement effect observed at the site and a desire to improve CO₂ reductions inspired Sinopec to move forward with CO₂-EOR storage research in 2012 at the Shengli Oilfield with the support of the National Key Technology R&D Program of China. In this project, a method of screening suitable target blocks for CO₂-EOR storage was required and investigated. The effectiveness of a seal system is of overriding importance for realizing effective geological sequestration of CO₂ [16, 17]; therefore, such systems must be evaluated carefully.

Caprock is the principal seal system for CO₂ storage, and although the hydrodynamic sealing capacity of caprock has been frequently discussed for hydrocarbon migration [19], few studies have focused on the sealing capacity for

FIGURE 1: Location of the Sinopec Shengli Oilfield (after [18]).

CO₂ storage. In practice, most CO₂-EOR storage projects utilize the same evaluation methodologies and indicators [20]; however, the differences related to CO₂ storage are rarely discussed. Moreover, the structural or geometric characteristics of caprock, such as the thickness, have not been properly detailed [21].

Compared with many overseas projects, in the Shengli Oilfield reservoir, a considerable number of faults have been observed and the configuration relationships between caprock and faults are very complex. Therefore, the effectiveness of the fault sealing ability must be evaluated carefully when selecting appropriate sites. Current researches on the conditions that allow faults to seal or leak principally occur in the field of hydrocarbon exploration [19]. Although research on the structural control of fluid flow in hydrocarbon reservoirs is in nascent stages, various hydrocarbon leakage indicators have been identified for faults [22]. Integrity is a restraint on the fault sealing capacity, and it is currently a focal parameter in the literature; however, studies into the static sealing effectiveness of fault systems that consider CO₂ migration and the internal fault structure have made limited progress [23–25].

Here, we present a study detailing an approach to evaluating the baseline sealing effectiveness of the caprock-fault system of a CO₂-EOR storage project in the Shengli Oilfield based on a new evaluation framework. The baseline evaluation refers to an investigation of feasibility performed before the project begins. The new evaluation method is based on the evaluation criteria for CO₂-EOR storage and includes comprehensive key parameters related to caprocks, faults, and their matching relationships. Parametric normalization

and ranking are employed to organize the indicator system. In the selection of evaluation indicators, we will pursue a balance among reliability, new CO₂ storage demands, and data availability.

2. Framework of the Evaluation Method

2.1. Identification of the Evaluation Objects. A potential reservoir block for CO₂-EOR storage is usually surrounded by different geological features, such as caprocks and faults. These features as a whole compose a network that determines the sealing ability of the seal system (Figure 2). A reservoir for CO₂ storage is usually deeper than 800 m underground, and more than one set of caprocks are positioned over the reservoir. The overlying caprock layer is usually specified as a leakage controlled layer, and it actually determines the scope of the sealing system that must be evaluated. The engineering target in this project requires a lack of direct CO₂ penetration into the caprock so that the injected CO₂ cannot leak through the caprock and to the upper reservoirs. Therefore, only the directly overlying caprock-fault system (composed of the caprock and the faults) associated with the reservoir for CO₂ storage will be evaluated in this paper (Figure 2).

CO₂-EOR risk assessments have tended to use risk scenarios, particularly scenarios related to wellbores, large faults, and an unspecified leaking caprock [26]. Figure 2 shows a conceptual model of a typical system that includes a reservoir, caprocks, and faults for CO₂-EOR storage. The sealing effectiveness of the system depends on the sealing ability of all components as shown in Figure 2(A)–(E). Therefore, the components must be assessed during the site evaluation

FIGURE 2: Conceptual model of caprock-fault system for CO₂-EOR storage.

stage. The caprocks are usually geologically cut by the faults and form several configurational relationships. Three types of configurational relationships have been identified: embedding type, lower broken type, and broken-through type [27, 28]. The embedding type refers to direct caprocks that are only partly penetrated by the fault (Figure 2(A)). The lower broken type refers to a direct caprock that has been cut through by a fault, although the overlying caprock has not been reached (Figure 2(B)). The broken-through type refers to a direct caprock and its overlying caprocks that have been cut through by a fault (Figure 2(C)).

The matching types between caprocks and faults can also be characterized by the relationship between the fault throw and the thickness of the direct caprock. The following three matching types have been defined: intact top seal type, seal connected type, and seal apart type [27]. The intact top seal type (Figure 2(E)) corresponds to an embedded type when the top of the direct caprock is not penetrated by faults. The seal connected type refers to a direct caprock that has been cut through by a fault but the throw is less than the thickness of the direct caprock. The seal apart type refers to a direct caprock that has been cut through by a fault but the throw is greater than the thickness of the direct caprock (Figure 2(D)).

2.2. Indicator System and Evaluation Criteria. The sealing effect of a caprock-fault system for CO₂-EOR storage depends mainly on the sealing ability of the caprocks and faults [29]. The sealing mechanisms for CO₂ storage are similar to that for hydrocarbons and include the capillary sealing mechanism, overpressure sealing mechanism, concentration sealing mechanism, and synergetic sealing mechanism composed of two or more sealing mechanisms [21]. Therefore, breakthrough pressure (or displacement pressure) and caprock overpressure are necessary indicators for evaluating the sealing effect of caprocks. In this paper, the two indicators will be merged as one indicator, that is, frontier displacement

work described in Appendix. As a structural characteristic, the thickness of a caprock has no direct relationship with the breakthrough pressure, although it has been confirmed to have an outstanding sealing effect. The frontier displacement work can be calculated by the values of the thickness, breakthrough pressure, and overpressure of the caprock with the formula (A.3) in Appendix. In addition, permeability, shale content, and other caprock parameters are usually chosen as evaluation indicators. Liu [30] concluded a positive correction between permeability and porosity that was used to assess the sealing effect of caprocks. A fault can either be a seal or a leak depending on specific factors of the fault. In past decades, knowledge on fault sealing properties has been accumulated by the oil and gas industry, and these data could be directly applied when evaluating the sealing properties of CO₂-EOR storage. The following two types of fault seals have been recognized: juxtaposition seals and fault rock seals [31]. Juxtaposition seals originate from differences in the lithology and petrophysical properties (porosity, permeability, capillary pressure, etc.) of different rocks juxtaposed between the hanging wall and the footwall. Typical methods of evaluating the sealing properties of juxtaposition seals mainly include stratigraphic juxtaposition methods (e.g., the Allan map [32] and triangle juxtaposition diagram [33]) and clay smear indices. Compared with the stratigraphic juxtaposition methods, triangle juxtaposition diagram primarily focuses on the architecture of the fault juxtapositions, the stratigraphic units, and the fault geometry. The clay smear index methods emphasize the amount of clay that has been smeared along the fault planes. These methods include the Clay Smear Potential (CSP), Shale Smear Factor (SSF), and Shale Gouge Ratio (SGR). According to their definitions, these indicators are dependent on specific parameters, such as the shale bed thickness, distance from the source bed, the fault throw, and the shale layer thickness. The CSP and SSF estimate the fault sealing properties by considering the continuity of smearing

TABLE 1: Indicators and ranking system for a caprock-fault system for CO₂-EOR storage [27, 30, 37–40].

I	II	III Specific indicators	Very Good 5	Good 4	Normal 3	Poor 2	Very Poor 1
Fault caprock sealing system	Caprock	Displacement work (MPa·m)		>6300	2100~6300	350~2100	<350
		Porosity (%)		<5	5~10	10~15	>15
		Permeability (mD)		<0.1	0.1~1.87	1.87~10	>10
		Shale content (%)		>75	75~50	50~25	<25
		Well density (/10 km)	0	1~2	3~5	5~10	>10
	Fault	Fault activity time		Tranche	Syngenetic	Multiperiod	
		Configuration relationship between fault extension and caprock		Embedded type	Lower broken type	Broken- through type	
		Configuration relationship between fault throw and direct caprock thickness		Intact top seal type	Seal connected type	Seal apart type	
		Fault dip angle (°)		≤45	45~75	>75	
		Fault lateral displacement work (MPa·m)		>30	2.5~30		<2.5
		Fault vertical displacement work (MPa·m)		>6300	2100~6300	350~2100	<350
		Fault lateral permeability (mD)		<0.001	0.001~0.0187	0.0187~0.1	>0.1
		Fault vertical permeability (mD)		<0.001	0.001~0.0187	0.0187~0.1	>0.1
		Fault tightness coefficient	>1				<1
		Shale smear factor	<4		4~7		>7
		Clay smear potential	>35		15~35		<15
		Shale gouge ratio	>0.5		0.3~0.5		<0.3

of shale/mudstone beds, whereas the SGR calculates the average mixture of clays likely to be present at different points on a fault [31]. Compared with juxtaposition seals, where the fault is usually treated as a single plane, fault rock seals refer to faults as a fault zone composed of a series of fault planes and fault rocks. Therefore, the fault zone is similar to a thin caprock with high heterogeneity. Therefore, many caprock sealing indicators (permeability, capillary threshold pressure, etc.) could be used to evaluate the sealing properties of fault rock in the fault zones. The petrophysical properties of fault rocks are affected by many factors, the most important of which involve geostresses, subsurface temperatures, and their historical tendencies. Occasionally, these factors or their derived parameters have been selected as evaluation indicators of fault sealing properties, and they typically include differential displacement pressures between the caprock and the reservoir [34], the slip and offset of the formation lithology [29], and the fault tightness coefficient [35]. In many practical evaluations, the vertical and lateral sealing properties of faults might have different roles in specific projects and must be evaluated separately [36]. In addition, it is worth noting that although we strive to choose independent indicators, however, some of them in Table 1 might be intrinsically connected and actually not independent. Therefore, the indicators in Table 1 might be redundant. This is inevitable to some extent because, according to the current knowledge, we cannot get the exact

quantitative relationship between these possible redundant indicators.

In the evaluations for specific engineering objectives, a comprehensive evaluation approach that uses multiple indicators, including redundant indicators, is widely adopted ([41, 42]) because a single indicator cannot characterize the sealing properties of a system with such a high degree of complexity and uncertainties. According to the objective of this study, we designed a system of multiple indicators considering the geometry, juxtaposition characteristics, and petrophysical properties of the caprock or faults (Table 1). Each of the indicators is classified into five grade levels, scoring, respectively, 1, 2, . . . , 5, which can be used to produce a comprehensive evaluation result in the next section.

2.3. Weighted Comprehensive Evaluation. To represent the sealing effectiveness of the caprock or the fault, the multiple indicators in Table 1 need to be synthetically integrated, which will be done with the idea similar to analytic hierarchy process (AHP). Hierarchical method was used to compute the weight of each indicator/criterion. AHP is applied with its extension to create weights for quantitative, expert opinion, and sensory panel data (listed in Table 2). The indicators/criteria adopted for evaluating the sealing ability of the caprock and faults are listed in Table 2, and the detailed evaluation method is similar to that described in Bachu [41]. To evaluate a specific part k , a monotonically decreasing numerical function $S_{i,j}$ (score)

TABLE 2: Scores and weights assigned to the various criteria and classes.

Class I	Class II	Criteria	Index i	Scores					Weight $\bar{w}_i$
				$j = 5$	$j = 4$	$j = 3$	$j = 2$	$j = 1$	
Caprock fault sealing system	Caprock	Displacement work	1		15	7	3	1	0.14
		Porosity	2		9	7	3	1	0.06
		Permeability	3		15	7	3	1	0.06
		Shale content	4		13	5	3	1	0.03
		Well density	5	15	9	7	3	1	0.02
		Fault active time	6		9	5	1		0.01
		Configuration relationship between fault extension and caprock	7		9	5	1		0.05
	Fault	Configuration relationship between fault throw and direct caprock thickness	8		9	5	1		0.05
		Fault dip angle	9		7	5	1		0.05
		Fault lateral displacement work	10		9	5		1	0.11
		Fault vertical displacement work	11		9	5		1	0.11
		Fault lateral permeability	12		9	7	5	1	0.03
		Fault vertical permeability	13		9	7	5	1	0.03
		Fault closed coefficient	14	15				1	0.11
		Shale smear factor	15	15		7		1	0.02
		Clay smear potential	16			7		1	0.02
		Shale gouge ratio	17	15		7		1	0.02

is assigned to indicator i according to its corresponding grade level j as determined in Table 1 (j from 5 to 1 indicates the best to the worst grade in terms of suitability for a particular criterion). The scores can be continuous or discrete, that is, they can be assigned to all five grades or only a portion of the grade levels of the corresponding criterion. Because the function S_i has different ranges of values for each criterion i , comparisons between different indicators of sealing effectiveness may be difficult. Therefore, a normalized value must be used for different indicators as in

$$P_i^k = \frac{S_{i,j} - S_{i,1}}{S_{i,n} - S_{i,1}}, \quad (1)$$

where $S_{i,j}$ is the specific score value for criterion i ; $S_{i,1}$ is the function score value under the least favourable class conditions for criterion i ; $S_{i,n}$ is the value under the most favourable class condition; the normalized value $P_i = 0$ represents the least favourable class; and the normalized value $P_i = 1$ represents the most favourable class.

The effect of parameterization and normalization pertains to the transformation of various site characteristics into dimensionless variables between 0 and 1. Considering the weight factor of each criterion, a synthetical score R^k can be obtained as follows:

$$R^k = \sum_{i=1}^i \bar{w}_i P_i^k, \quad \sum_{i=1}^i \bar{w}_i = 1, \quad (2)$$

where $\bar{w}_i$ is the weight factor from Table 2, and it is used to estimate the impact degree of a corresponding criterion.

2.4. Application Steps of the Method. In practical evaluation work, a preliminary characterization of a candidate site is necessary and the fundamental geological and physical parameters are required to be prepared by lab tests or geophysical prospecting. Next, the target caprocks or faults of the candidate site are discretized into small pieces, and the evaluation parameters involved in Tables 1 and 2 could be obtained for each piece. In other words, the evaluation work is actually done for each piece and therefore the evaluation result will be a scoring or ranking distribution of the whole candidate site. The case study in the latter part of this paper will follow the evaluation process.

3. Target Site

3.1. Site Geology. The Shengli Oilfield branch company includes 65 oil fields and 2 gas fields, and it covers an aerial extent of approximately 2117 km² [43]. Almost 90% of the oil reserves lie at depths ranging from 950 m to 3200 m underground. The candidate target site is the Gao89-Fan142 district, which is located in the northern Zhenglizhuang Oilfield of the Dongying sag and the central Jinjia-Zhenglizhuang-Fanjia structure belt. The target site consists of the G899 block, G89-1 block, G891 block, F143 block, and F142 block as shown in Figure 3. The strata of the target site (from top to bottom) are the Pingyuan formation of the Quaternary system, the Minghuazhen formation and Guantao formation of the upper Tertiary system, the Dongying formation of the lower Tertiary system, and the 1st, 2nd, 3rd, and 4th

FIGURE 3: The target area (G89-F142 area) for CO₂-EOR storage and the distribution of faults.

Erathem	Era	System period	Formation	Stage age	Subsegment	Depth	Rock formation	Lithologic characteristic	Reservoir-cap nature
Cenozoic	Neogene	Guantao Ng				1000		Thin sand-shale interbedded	Reservoir
						1200			
	Paleogene	Dongying Ed				1400		Primarily composed of thick sandstone with a pure mudstone top of approximately 50 m	Reservoir
						1600	F2	Oil shale	Regional caprock
		Shahejie Es		Es1		1800		Grey mudstone	
				Es2	Es2s	1800			
					Es2x	1800			
					Es3s	2000		Primarily composed of thick sandstone	Reservoir
					Es3m	2200	F4	Mudstone deposits	
					Es3x	2200	F5	Mudstone deposits in southern work area with thick bodies and a small range	Partial caprock
					Es4cs	2400	F3		
					Es4cx	2600	F21		
					Es4x	2800	F19	Oil shale mudstone	Regional caprock
						2800		Cream mudstone and oil shale	
						3000		Thin sand-shale interbedded	Reservoir
			Kongdian Ek			3000			

FIGURE 4: The strata of the target site.

members of the Shahejie formations and Kongdian formation in Cenozoic Erathem (Figure 4). In the blocks, five main sets of oil-bearing series have been found via exploration: Ed, ES1, ES2, ES3, and ES4. Among these series, the Shahejie ES4S formation, which is the main oil-bearing series, is buried at

a depth of 2700–3200 m and the thickness of the strata is approximately 120–170 m. The lithology of the formation is mainly grey and light grey mudstone with thin sandstone. The Shahejie ES3 formation is a direct caprock of ES4S reservoir, and its lithology is mainly dark grey mudstone.

TABLE 3: Geostress data of the target area.

Well	Core depth (m)	Geostresses			Stress gradient (MPa/m)				
		Direction (°)	Size (MPa)						
		σ_H	σ_h	σ_v	σ_H	σ_h	σ_v	σ_H	σ_h
G892-3	3170	71.23	161.23	72.69	61.97	47.97	0.0229	0.0195	0.0151
G892-X8	3225	70	160	71.80	82.37	56.12	0.0223	0.0255	0.0174
G893	3281	118	208	73.95	88.67	57.67	0.0225	0.0271	0.0176

The target area is a southeast high, northwest low monoclinal structure with a strata dip angle of approximately $4\sim 8^\circ$. The structure is divided into many terraces by a series of parallel faults running northwest and trending northeast. The largest structural gap can reach 500~700 m. According to strata comparisons and seismic interpretations, fault F1 extends upward to the Guantao formation; F2 extends upward to the ES1 formation; F3, F4, F6, and F7 mainly extend upward to the ES3M formation; F5 extends upward to the ES2 formation; and the other faults mainly extend to the ES3X formation. Approximately 26 faults intersect with the direct caprock as shown in Figure 3.

3.2. Current Geostresses. Geostresses and fault sealing properties are closely correlated, and geostress variations significantly affect the fault sealing effectiveness [44]. Therefore, the geostress data must be obtained to calculate the fault surface stress for the evaluation indexes. Current geostress characteristics of the target area have been obtained from a variety of sources, like the empirical formula of geostresses, measured geostress data, and so on.

The target area is located in the Bohai Bay basin, and the three principal stresses all increase with depth. When the depth is greater than a certain value, the three principal stresses will satisfy $\sigma_H > \sigma_v > \sigma_h$; thus, the vertical stress σ_v represents the intermediate principal stress. In the oil fields of the eastern region of China, the vertical stress σ_v is approximately equal to the lithostatic stress of the overlying rock formations. The Dongying sag is located in a district of medium tectonic stress controlled by plate tectonic movement. The hydraulic fracturing data of the Dongying sag show that the cracks caused by the oil well fracturing are mainly vertical cracks. Li [45] investigated the current geostress field of the 3rd Shahejie formation in the Dongying sag based on numerical modelling and found that the direction of the current maximum horizontal principal stress is approximately $NE280^\circ$ with the stress values ranging from 50 to 65 MPa, and the direction of the minimum principal stress is approximately $NE10^\circ$ with the stress values ranging from 35 to 50 MPa. The geostresses of the southern and eastern parts of Dongying sag are larger, and smaller stresses appear to occur along the north-western edges of the Boxing depression. Lower stresses occur in the fault zone belt. Moreover, because the 3rd Shahejie formation in the Dongying sag is under abnormally high formation pressure, the minimum horizontal principal stress in the sag is significantly higher than that of the surrounding formations.

Limited measured geostress data are available for the target area, and the latest measured data are listed in Table 3. To the authors' knowledge, no studies have focused on the geostress distribution in the target area; however, some measured data and research on the neighbouring regions could provide a partial supplement and reference for our research work. These data are listed in Table 4. In addition, the Geological Institute of the National Seismological Bureau recommended the following regression formula to estimate the geostress data for the Shengli Oilfield:

$$\begin{aligned}
 \sigma_H &= -22.58 + 0.034H, \\
 \sigma_h &= -11.65 + 0.022H, \\
 \sigma_v &= (0.021 \sim 0.022) H,
 \end{aligned} \tag{3}$$

$H \in [1300, 3300] \text{ m}.$

Wang [49] also studied the geostress of the L112 region in Chunliang and suggested the following approximate estimation formula:

$$\begin{aligned}
 \sigma_H &= 0.03731H - 21.6655, \\
 \sigma_h &= 0.02955H - 23.8529, \\
 \sigma_v &= 0.02335H + 1.36759,
 \end{aligned} \tag{4}$$

where H is the depth, m; σ_H is maximum principal stress, MPa; σ_h is minimum principal stress, MPa; and σ_v is the vertical principle stress, MPa.

4. Results and Analysis

4.1. Evaluation Parameter Values. Figures 5–9 show values of some key parameters of the caprock. The parameters of the faults will be detailed in a subsequent section. Figure 5 shows the contour map of the effective thickness of the target caprock, which has strong regularity. In the south, the caprock is thin, and, in the north, the caprock is thick. The caprock is especially thick near wells G899, G89-24, and F142-3, with an average thickness of approximately 540 m and a maximum thickness of up to 590 m. The region near wells F142-2-8 and F142-8-2 also presents considerable caprock thicknesses. Starting at the positions of the two wells, the thickness of the caprock increases gradually, and the minimum value is approximately 450 m. Figure 6 shows the distribution of the mudstone displacement pressure ranging from 0 to 24 MPa in the ES3X region of the Shahejie formation. The

TABLE 4: Measured geostress data in the region near the target area.

Blocks	Well number	Well section /depth (m)	σ_H (MPa)	σ_v (MPa)	σ_h (MPa)	Maximum principal stress's direction N E (°)	Note
Fanjia	Fan8-511	2866~2874	—	66	43.6	89.3	
	Fan10-513	2870~2894	60.6	66.3	46.1	82.7	
	Fan17-17	2867~2872	57.9	65.9	46.1	80	
	Fan15-8	3013~3076	71.6	70	52	123	
	Fan12-511	2866~2877	67.6	66.2	51.2	82	[46]
	Fan19-720	3136.3~3156.1	76.4	72.4	56.4	138	
	Fan22-724	3144~3167	83.2	72.6	58.6	175	
	Fan24	2815~2825	66.2	64.9	49.6	100	
	Fan18-720	3142~3146	68.2	72.3	53.4	145	
	Fan23	3150~3155	73.5	72.5	58.1	143.3	
	Fan26	2980~3020	68	71.1	45	91.2	
	Fan10	2914~2935	67	66.6	46	87.6	
	Fan162	2644.5~2652.0	59.5	63.5	46.5	107	
Bonan		3100	66	68	44	85	[47]
Fanjia		3000	66.7	68	45.8	100	
Yingli		3100	110–120	68	59–62	100	
Shanjiasi		2600	78	68	44	100	
Changwei		2400	66	54	45	80	
Niuzhuang		3250	91	68	66	105	
Binnan		2400	66	66	45	80	
Shengtuo		2100	58	—	44	90	
Gao89	G89-1		76.41		47.35	NE69.0	[48]
	G89-7		72.47		55.77	NE53.3	
Chun107	C97-6		—	—	49.64	—	
	C97-7		75.59		53.27	NE97.5	
	L112-32		78.03		50.79	NE128.6	
	L112-8		83.00		55.8	NE103.0	
	L9-3		—	—	—	NE145.5	
L112	L112-12	2676.6~2701	81.64	64	54.26	102.6	
	L112-8	2717~2750	82.64	65	51.89	103.6	
	L112-61	2789.5~2818.6	79.07	66	52.39	151.0	[49]
	L112-32	2722.4~2764.4	78.03		53.79	128.6	
	L112-43	2715.3~2759	80.38		52.43	132.9	
	L112-45	2729.5~2776.8	82.60		52.70	127.4	

displacement pressure gradually increases from the centre of wells G892-X4, G89-1, and F142-8-2 outwards. Figure 7 shows the distribution of the formation pressure in the range of 0 to 8 MPa. The formation pressure is large in the eastern part of well F143-8 and the northern part of wells F143-X9, F142-2-4, and F142-3-9, which present values that are all greater than 4 MPa, whereas in the remaining areas, the pressures are less than 4 MPa. Figure 8 shows the porosity distribution of the caprock, which gradually decreases from the centres of wells G891-10, G899-X2, and G89 outwards. The porosity gradually increases in a local area with a “Λ” shape at the eastern part of wells F142-1 and F142-11 and the west part of wells F142-11-2

and F142-16-2, and the maximum porosity is up to 24%. Figure 9 shows the frontier displacement work of the caprock calculated using the formulas (A.1)–(A.3). The distribution characteristics are similar to that of the displacement pressure of caprock in Figure 6.

The calculation results of the fault properties are shown in Table 5. Most of the fault activities ceased prior to the deposition of ES2. Faults F1 and F2 stopped growing at the late stage of the Guantao group, and the configuration relationship between F1, F2, and the caprock is the double break type. Therefore, faults F1 and F2 are active faults, and CO₂ might leak to the Guantao formation through the two faults.

4.2. Evaluation Results and Analysis. In Section 4.1, we determined all the primary parameter values as iso-values and spatial layers in the GIS tool for the target caprock-fault system

FIGURE 7: Formation pressure distribution in the target area.

FIGURE 8: Caprock porosity distribution in the target area.

(Figures 5–9, Table 5). Spatial layers representing indicates were converted into 50 m × 50 m grid squares (or segments). Then using methodology presented in Section 2.3. and the spatial analysis functions of the GIS tool, we obtained the weighted comprehensive score for each grid square. Higher scores were correlated with a higher sealing effectiveness. Thus, the sealing effectiveness distributions for all segments

of all the caprocks and faults were determined, and these distributions were used to define the sealing effectiveness of the whole caprock-fault system as shown in Figure 10. We classified the evaluation results into 5 grade levels, that is, Bad, Medium, Good, Better, and Best. Table 6 shows the area percentage assigned to each grade level. Figure 10 shows the evaluation results for the integral caprock and the faults.

FIGURE 9: Frontier displacement work distribution of the caprock in the target area.

FIGURE 10: Evaluation results of the sealing effectiveness of the target formations and faults (middle and lower Shahejie formation, including three sections in G89-F142).

TABLE 5: Fault property sheet.

Fault name	Activity stopping time	Relationship between the fault lateral extension and caprock thickness	Largest fault dip angle (°)	Vertical permeability (10^3 mD)	Fault rock thickness (m)	Minimum displacement pressure (MPa)	Minimum formation pressure (MPa)	Lateral displacement work	Lateral permeability (10^{-7} mD)	Closed coefficient	Upthrown SGR (%)	Upthrown SSF	Downthrow SGR (%)	Downthrow SSF
F1	The late Guantao	Broken through type	62	1	1.02	19.61	31.600	25348.24	8.1	1.903	0	0.76	/	/
F2	The late Guantao	Broken through type	49	1	1.04	18.302	29.797	10203.58	2.4	1.987	0	0.33	25-35	7
F3	ES3M	Embedded type	52	1	1.03	17.724	29.059	7278.321	1.7	1.988	0	0.22	24-32	5.5
F4	Before the depositing of ES2	Embedded type	41	1	1.03	16.872	27.896	10447.25	9.5	2.007	0	0.33	25-45	4
F5	Before the depositing of ES2	Embedded type	48	1	1.03	16.42	27.304	15459.13	4.2	1.879	0	0.54	15-20	9
F6	Before the depositing of ES2	Embedded type	49	1	1.03	18.632	30.250	15209.75	1.7	1.983	0	0.43	10-15	8
F7	Before the depositing of ES2	Embedded type	52	1	1.02	19.729	31.827	8020.887	4.0	1.977	0	0.22	10-18	2.4
F8	Before the depositing of ES2	Embedded type	46	1	1.03	18.757	30.609	6981.568	1.3	1.922	0	0.22	18-32	8.7
F9	Before the depositing of ES2	Embedded type	47	1	1.03	20.025	32.342	7405.984	2.0	1.927	0	0.22	20-32	2

TABLE 5: Continued.

Fault name	Activity stopping time	Relationship between the fault lateral extension and caprock thickness	Largest fault dip angle (°)	Vertical permeability (10^{-3} mD)	Fault rock thickness (m)	Minimum displacement pressure (MPa)	Minimum formation pressure (MPa)	Lateral displacement work	Lateral permeability (10^{-7} mD)	Closed coefficient	Upthrown SGR (%)	Upthrown SSF	Downthrow SGR (%)	Downthrow SSF
F10	Before the depositing of ES2	Embedded type	52	1	1.01	19.44	30.723	10641.43	3.2	2.100	0	0.33	25–40	7.2
F11	Before the depositing of ES2	Embedded type	55	1	1.02	19.331	31.241	8582.552	1.0	1.928	0	0.26	15–25	7.5
F12	Before the depositing of ES2	Embedded type	45	1	1.03	16.15	26.665	3330.498	1.1	3.147	0	0.11	22	6.2
F13	Before the depositing of ES2	Embedded type	44	1	1.02	15.627	26.259	2961.856	5.0	2.337	0	0.11	28–30	5.2
F14	Before the depositing of ES2	Embedded type	45	1	1.03	17.167	28.283	5656.751	2.8	1.992	0	0.17	18–26	6.7
F25	The end of ES3X deposit	Embedded type	41	1	1.03	16.962	28.040	3182.196	1.2	2.062	0	0.28	16–20	7.5
F15	The end of ES3X deposit	Embedded type	40	1	1.03	18.55	30.137	8951.203	2.0	1.763	25–35	0.75	32–44	0.75
F21	The end of ES3X deposit	Embedded type	48	1	1.03	16.825	27.834	3157.941	1.5	2.165	32	2	32	2

TABLE 6: Comprehensive grading of the sealing effectiveness of the caprock-fault system.

Caprock-fault seal classification	Bad	Medium	Good	Better	Best
Score	<0.56	0.56~0.65	0.65~1.45	1.45~1.61	>1.61
Area percentage	1.59%	2.63%	14.89%	37.00%	43.55%

Figure 10 shows that the green areas representing the integral caprocks without disturbances in the northwest present integral caprocks that have almost the best sealing ability. In these areas, the porosity and the well density are very small, whereas the frontier displacement work is quite large. The distribution characteristics of the caprock sealing ability are consistent with that of the caprock porosity. In the region with the “Λ” shape lying between the wells F142-1 and F142-11 and the wells F142-11-2 and F142-16-2, the positions that have porosity ranging from 10% to 20% and 6% to 10% also present “Good” and “Better” sealing effectiveness, respectively.

The sealing ability of most faults in the target area is “Good.” The sealing ability throughout F1, F9, F22, and F28 is “Good”; the sealing ability throughout F12 and F12-N is “Bad”; and the sealing ability of F2, F5, F19, F6, and F11 ranges from “Medium” to “Good.” Thus, F2, F5, F19, F6, and F11 appear to have different sealing abilities, which might be caused by the properties of the caprock surrounding the faults. Li [27] considered that the vertical sealing ability of fault F1 is worse than that of F2 based on the fault properties and configuration relationship between the caprock and the faults. In this paper, the sealing ability of fault F1 is better than that of F2, although F1 and F2 have the same activity period and cut-through type. The sealing ability of the remaining faults is classified as “Better.”

The area classified as “Good” accounts for approximately 70.55% of the total target area, whereas the area classified as “Bad” accounts for approximately 1.59% and is located near the fault crossings (i.e., throughout F12 and F12-N and local positions within F2, F5, F6, and F11). The area classified as “Medium” sealing capacity accounts for 2.63% of the total area and is affected by the caprock porosity, and these areas are mainly distributed in faults F25, F14, and F4, which present porosities of more than 10%. More attention should be paid to these positions of injection wells planned in this area. Larger frontier displacement work corresponds to a better sealing capacity. The sealing ability of a caprock-fault system is affected by the porosity of the caprock. Caprock-fault systems with good sealing ability often appear in the following areas: where the allocation relationships between the regional seals and the vertical fault extensions are the embedded type and lower broken type; where the allocation relationships between the fault throw and the direct seal thickness are the intact top seal type and the seal connected type (without the seal apart type); and where the fault dip is between 40° and 65°.

Figure 11 shows the sealing capacity of five blocks. The sealing capacity of the G89-1 and G891 blocks ranges from “Medium” to “Good,” and they are suitable for CO₂-EOR storage. The sealing capacity of the F142 block is “Medium” to “Good” overall except at the western end of F6, which is “Bad”

and not suitable for CO₂-EOR storage. The sealing ability of the head of the northeast extension direction of fault F11 in the G899 block is “Bad,” but the remainder is suitable for CO₂-EOR storage. Fault F2 as the boundary line between F143 block and G899 block, and also the boundary line between the G899 block and G89-1 block, has the sealing ability level “Bad”; therefore, the adjacent area of fault F2 is not suitable for CO₂-EOR storage.

5. Conclusions

- (1) A new framework for evaluating the sealing effectiveness of a caprock-fault system for CO₂-EOR storage was developed considering specific site characteristics. The method is a weighted ranking system with multiple indicators. In the method, caprocks and faults are considered as elements of the whole sealing system defined as “caprock-fault system.”
- (2) Additional indicators are involved in the method, such as the newly proposed parameter, frontier displacement work. The sealing mechanism of the caprock and faults as well as the configuration relationship between the caprock and faults were considered in the evaluation method.
- (3) The method was used to evaluate the sealing effectiveness of the G89 block in the Shengli Oilfield, which presents many faults. A preliminary evaluation showed that higher scores corresponded with better sealing capacity of the caprock-fault system. Sealing systems classified as “Good” account for 70.55% of the total area, and they are mainly located in areas with large frontier displacement work, small porosity, and small well density. Sealing systems classified as “Bad” account for only 1.59% of the total area, and they are located at the tail and the head of the southwest extension direction of faults F12 and F2 and parts of F5, F19, F6, and F11. The sealing effectiveness of most regional caprock is classified as “Good.”
- (4) The sealing effectiveness of fault F1 is better than that of F2, although F1 and F2 have the same activity period and cut-through type. This result is inconsistent with the results presented in existing studies. Thus, more attention should be focused on these two faults.
- (5) The sealing effectiveness of the G89-1 and G891 blocks is “Medium” and “Good,” respectively, and the two blocks are suitable for CO₂-EOR storage. The overall sealing effectiveness of most parts of the F142 block is also “Medium” to “Good,” although at the western end of F6, it is classified as “Bad.” Therefore, this block is not suitable for CO₂-EOR storage. The sealing

FIGURE 11: Sealing capacity of five blocks in the target area.

effectiveness of the head along the northeast extension direction of F11 in the G899 block is classified as “Bad,” although the remainder is suitable for CO₂-EOR storage. The sealing effectiveness of fault F2, which is the boundary line of the F143 block and G899 block (also the boundary line of the G899 block and G89-1 block), is classified as “Bad”; therefore, the regions near the F2 border are not suitable for CO₂-EOR storage.

- (6) The evaluation parameters and methods in this research are essentially static because we do not consider the disturbances from CO₂-EOR storage production. Therefore, the evaluation method involved in this paper might be especially suitable for site selection prior to injection.

Appendix

Frontier Displacement Work

Frontier displacement work considers the formation pressure (pore pressure), caprock displacement pressure, and caprock thickness. The formation pressure and caprock displacement pressure represent the overpressure sealing and capillary sealing, respectively [21]. The top edge of the caprock is considered as the controlled leakage point and the critical state of the leading edge of the flow. We consider a conceptual model of CO₂ leaking through a caprock with a thickness H , as shown in Figure 12. The leakage process is actually a flooding

FIGURE 12: CO₂ flooding through caprock.

process of CO₂ displacing saline water in the caprock. The caprock in the model is uniform and divided hypothetically into N representative element volumes (REV)s.

Assume the initial formation pressure of the caprock is P and the fluid gravity is not considered. We tested the sealing capacity of the caprock under the assumption that the fluid

injected slowly from the bottom of the caprock will overcome the formation pressure, capillary resistance, and drainage caprock pore water during the process of gradual upward migration. As shown in Figure 12(a), the injected fluid (i.e., CO₂ in this study) will overcome the displacement pressure of the REV-1 unit (red) and remain in a critical equilibrium state after the REV-1 unit becomes full of CO₂. The force diagram of the top edge of the REV-1 unit is shown in Figure 12(b).

To keep the fluid migrating slowly until it reaches the top of REV-2, we increase the injection pressure P_I until the leading edge of the fluid at the top of REV- N reached equilibrium. The process by which the fluid slowly advances and drains the caprock pore water on each REV is called quasi-static displacement. The fluid frontier has the following equation at each REV:

$$P_I = P_p + P_d. \quad (\text{A.1})$$

In the quasi-static displacement process, the work done by the fluid pressure on a unit area is

$$W = \int_0^H P_I dl, \quad (\text{A.2})$$

which is called specific displacement work (Pa·m) or simply referred to as displacement work through the paper.

Displacement work reflects the resistance of the formation pressure and displacement pressure as well as the influence of the flow path. Therefore, this value reflects the ease of draining fluid from the caprock and can be used as a measured index of the caprock sealing ability. If the pore pressure and displacement pressure of the formation are uniform in the process of CO₂ injection, the injection pressure P_I is constant. These indicators can be simplified directly as follows:

$$W = P_I H = (P_p + P_d) H, \quad (\text{A.3})$$

where P_p is the caprock formation pressure (the pore pressure (MPa) is obtained by Wang's method [52]); and P_d is the caprock displacement pressure (MPa). The breakthrough pressure measured by Liu [30] is used to determine the relationship between the displacement pressure and acoustic time and the relationship between the displacement pressure and the depth to calculate the caprock displacement pressure; and the caprock thickness (m) is frequently obtained by combining the seismic and well information.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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