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Research Article

Mesoscale Assessment of CO_2 Storage Potential and Geological Suitability for Target Area Selection in the Sichuan Basin

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In China, south of the Yangtze River, there are a large number of carbon sources, while the Sichuan Basin is the largest sedimentary basin; it makes sense to select the targets for CO_2 geological storage (CGUS) early demonstration. For CO_2 enhanced oil and gas, coal bed methane recovery (CO_2-EOR, EGR, and ECBM), or storage in these depleted fields, the existing oil, gas fields, or coal seams could be the target areas in the mesoscale. This paper proposed a methodology of GIS superimposed multisource information assessment of geological suitability for CO_2 enhanced water recovery (CO_2-EWR) or only storage in deep saline aquifers. The potential per unit area of deep saline aquifers CO_2 storage in Central Sichuan is generally greater than 50×10^4 t/km^2 at $P50$ probability level, with Xujiahe group being the main reservoir. CO_2 storage potential of depleted gas fields is 53.73×10^8 t, while it is 33.85×10^8 t by using CO_2-EGR technology. This paper recommended that early implementation of CGUS could be carried out in the deep saline aquifers and depleted gas fields in the Sichuan Basin, especially that of the latter because of excellent traps, rich geological data, and well-run infrastructures.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) noted in its fifth assessment report that climate change is more serious than the original understanding, and perhaps more than 95% of it is caused by human behavior [1]. In China, south of the Yangtze River, there are a large number of carbon sources; among that about 104.58 Mt CO_2 are discharged in Sichuan Province and Chongqing City mainly from cement and thermal power plants [2]. Therefore, as the largest sedimentary basins in Southern China, the Sichuan Basin covers about 20×10^4 km^2, with its craton basic structure, thick marine carbonate, and clastic sedimentary strata, and has great significance in analyzing mesoscale potential and geological suitability for CO_2 geological utilization and storage technologies (CGUS), including CO_2 enhanced oil, gas, coal bed methane, shale gas and water recovery (CO_2-EOR, EGR, ECBM, ESGR, and EWR), CO_2 enhanced geothermal systems, and uranium leaching (CO_2-EGS and EUL). Furthermore, CO_2 geological storage technologies include depleted oil or gas fields, unmineable coal seams, and deep saline aquifers CO_2 storage [3].

Evaluation of CO_2 storage potential is required to assess the contribution towards the reduction of CO_2 emissions. The Carbon Sequestration Leadership Forum (CSLF) and US Department of Energy (USDOE) both proposed the standards and methodologies for CO_2 storage capacity estimation and site selection and also the atlas [4–9], which provided the basic methodologies. Some researchers developed the methodologies or key parameters to evaluate the CO_2 storage potential or site selection [10, 11], and Goodman et al. [12] provided a detailed description of the USDOE's methodology for CO_2 storage potential evaluation. In China, Zhang et al. [13] first carried out a preliminary assessment of the national scale potential of CO_2 geological storage

in depleted oil and gas fields, unmineable coal seams, and deep saline aquifers. Subsequently, Liu et al. [14] and Li et al. [15] carried out evaluation of the potential of CO_2 geological storage in depleted natural gas fields and deep saline aquifers, respectively. Guo et al. [16] evaluated the national scale potential of CO_2 geological storage in depleted oil and gas fields, unmineable coal seams, and deep saline aquifers in 417 onshore and offshore sedimentary basins supported by China Geological Survey (CGS) and evaluated the suitability for prospective selection in the macroscale. As the CGUS methodologies are paid more and more attention, Li et al. [17] preliminary evaluated CO_2 geological storage potential of CO_2-EOR, EGR, and ECBM. ACCA21 [3] first evaluated the national scale potential of CGUS, and Wei et al. [18] developed the methodology of potential assessment of CO_2 geological utilization and storage in the macroscale in China.

From the view of spatial scale and time scale, the mesoscale corresponds to target between basin and site which needs more geological survey for CCUS demonstration or industrialization in the short term, generally before 2030 according to carbon reduction target of China. Therefore, because of the large area and complicated geology different from abroad, the methodologies and parameters of potential evaluation of CGUS should be more suitable for geology in the Sichuan Basin.

2. Methodology

In the mesoscale, oil and gas fields and CBM fields under production could be the target areas for CO_2 geological utilization or storage. However, for deep saline aquifer CO_2 geological storage or CO_2-EWR, the assessment of potential and geological suitability for target area selection should follow the order of candidate prospective area to target area, because of fast changing lithology and strong heterogeneity in terrestrial sedimentary formations and also the different distribution of aquifers in lateral and vertical direction. Based on the detailed studies of reservoirs and caprocks in sedimentary basins and the basic requirements for geological safety, the candidate prospective areas in the Sichuan Basin should be selected first, and then potential and geological suitability assessment could be carried out for target area selection next.

2.1. Method of Assessment of CO_2 Geological Utilization and Storage Potential

2.1.1. Depleted Oil Fields CO_2 Storage and CO_2-EOR

(1) Depleted Oil Fields CO_2 Storage. The method of assessment of CO_2 storage potential of CO_2-EOR is as follows [12]:

$$G_{CO_2} = \frac{\text{OOIP}}{\rho_{\text{oil}}} \cdot B \cdot \rho_{CO_2} \cdot E_{\text{oil}}, \tag{1}$$

where G_{CO_2} is CO_2 geological storage potential; OOIP is the proven original oil reserves in place of existed oil and gas fields presented by Ministry of Land and Resources of China (MLR), in accordance with the research scale in this paper; ρ_{oil} is oil density at standard atmospheric pressure; B is oil volume factor; ρ_{CO_2} is CO_2 density at reservoir temperature and pressure conditions (according to Berndt Wischnewski formula); E_{oil} is storage efficiency (or effective coefficient), recommend as 75% by Li et al. [17] based on the largest oil production rate of most depleted oil fields in China and the possible amount of CO_2 could be injected.

Table 1: The value of EXTRA with different API gravity.

EXTRA (%)	API
5.3	<31
1.3 (API—31) + 5.3	31 ≤ API ≤ 41
18.3	>41

Table 2: Four EOR cases with different depth/pressure and API gravity.

Depth	API	P_{LCO_2} (%)	P_{HCO_2} (%)
<2000	>35	100	0
	≤35	66	33
>2000	>35	33	66
	≤35	0	100

(2) CO_2-EOR. The method of CO_2 geological storage potential assessment of CO_2-EOR is as follows [19]:

$$G_{CO_2\text{-EOR}} = \frac{\text{OOIP}}{\rho_{\text{oil}}} \cdot B \cdot E_{\text{oil}} \cdot \text{EXTRA} \cdot \left(P_{LCO_2} \cdot R_{LCO_2} + P_{HCO_2} \cdot R_{HCO_2}\right), \tag{2}$$

$$\text{API} = \left(\frac{141.5}{S_g}\right) - 131.5, \tag{3}$$

where $G_{CO_2\text{-EOR}}$ is storage potential of CO_2 by using CO_2-EOR technology; EXTRA is the proportion of extra recovery to OOIP (Table 1); P_{LCO_2} is the lowest probability of oil recovery (Table 2); P_{HCO_2} is the highest probability of oil recovery (Table 2); $R_{LCO_2} = 2.113\ \text{t/m}^3$; $R_{HCO_2} = 3.522\ \text{t/m}^3$; S_g is specific gravity; other parameters are the same as formula (1).

2.1.2. Depleted Gas Fields CO_2 Storage and CO_2-EGR

(1) Depleted Gas Fields CO_2 Storage. USDOE [12] and CSLF [5] have the same assumptions for assessments of both CO_2-EGR storage potential and CO_2-EOR storage potential. Therefore, the calculation formulas are basically the same:

$$G_{CO_2} = \frac{\text{OGIP}}{\rho_{\text{gasstd}}} \cdot B \cdot \rho_{CO_2} \cdot E_{\text{gas}}, \tag{4}$$

Table 3: The values of R_{CO_2/CH_4} and C of different types of coal (USDOE, 2003).

Types of coal	R_{CO_2/CH_4}	C
Lignite	10	1.00
Noncaking coal	10	0.67
Weakly caking coal	10	1.00
Long flame coal	6	1.00
Gas coal	3	0.61
Fat coal	1	0.55
Coking coal	1	0.50
Lean coal	1	0.50
Meager coal	1	0.50
Anthracite	1	0.50

Table 4: Storage efficiency of unmineable coal seams [12].

P_{10}	P_{50}	P_{90}
21%	37%	48%

where OGIP is the proven original natural gas reserves in place, similar to OOIP; ρ_{gasstd} is gas density under standard atmospheric pressure; B is natural gas volume factor; E_{gas} is storage efficiency (effective coefficient), 75% [17]; other parameters are the same as formula (1).

(2) CO_2-EGR. Whether the feasibility of CO_2-EGR technique is possible or not, we could evaluate the storage potential of CO_2 using the following formula:

$$G_{CO_2\text{-EGR}} = \frac{\text{OGIP}}{\rho_{gasstd}} \cdot B \cdot \rho_{CO_2} \cdot E_{gas} \cdot C, \quad (5)$$

where $G_{CO_2\text{-EGR}}$ is CO_2 geological storage potential by using CO_2-EGR technology; C is reduction coefficient, compared with depleted gas storage, Li et al. recommend it as 63% [17]; other parameters are the same as formula (4).

2.1.3. Unmineable Coal Seams CO_2 Storage and CO_2-ECBM

(1) Unmineable Coal Seams CO_2 Storage. The formula to calculate the storage potential is as follows:

$$G_{CO_2} = G_{CBM} \cdot R_{CO_2/CH_4} \cdot \rho_{CO_2 std} \cdot E_{coal}, \quad (6)$$

where G_{CBM} is coal bed methane reserves (there is only prospective reserves proposed by MLR, less credible than the oil and gas reserves); R_{CO_2/CH_4} is the absorption capacity ratio of CO_2 and CH_4 in coal seams; E_{coal} is storage efficiency (effective coefficient); other parameters are the same as formula (4).

The values of R_{CO_2/CH_4} and E_{coal} were proposed by USDOE (2003) and Goodman et al. [12] as shown in Tables 3 and 4.

Table 5: CO_2 storage efficiency coefficients E_{saline} at regional scales [12].

Lithology	P_{10}	P_{50}	P_{90}
Clastics	1.2%	2.4%	4.1%
Dolomite	2.0%	2.7%	3.6%
Limestone	1.3%	2.0%	2.8%

(2) CO_2-ECBM. The formula to calculate the storage potential of CO_2-ECBM is as follows:

$$G_{CO_2\text{-ECBM}} = G_{CBM} \cdot R_{CO_2/CH_4} \cdot \rho_{CO_2 std} \cdot E_{coal} \cdot C, \quad (7)$$

where $G_{CO_2\text{-ECBM}}$ is CO_2 geological storage potential by using CO_2-ECBM technology; C is recovery coefficient of different types of coal; other parameters are the same as formula (6).

2.1.4. Deep Saline Aquifers CO_2 Storage and CO_2-EWR. The calculation formulas of CO_2-EWR and the only geological storage in saline aquifers technology are the same as follows:

$$G_{CO_2} = A \cdot h \cdot \varphi_e \cdot \rho_{CO_2} \cdot E_{saline}, \quad (8)$$

where A is reservoir distribution area; h is reservoir thickness; φ_e is saline aquifer average effective porosity; E_{saline} is storage efficiency (effective coefficient), shown in Table 5; other parameters are defined above.

2.2. Method of Suitability Assessment for Saline Aquifers Storage Target Selection

2.2.1. Mathematical Model

(1) GIS Superimposed Multisource Information Assessment Technology. Superimposed multisource information assessment technology is an integrated method of processing multisource geological data. Based on the two-dimensional space determined by geographical coordinates, the unity of the geographical coordinates within the same region but with different information, that is, the so-called spatial registration, is achieved, which is performed by using geographic information software (ArcGIS or MapGIS).

(2) Mathematical Model. The selected candidate prospective areas undergo the GIS spatial analysis into grids of 1000 m × 1000 m. The thematic information map prepared for each factor is screened by key veto factors. Thus, the single factor unfit to carry out CO_2 geological storage is identified to abandon the unsuitable grid for deep saline aquifer CO_2 storage.

Table 6: Index system for geological suitability assessment to select suitable targets for deep saline aquifer CO_2 storage.

Level one index	Weight	Level two index	Weight	Level three index	Weight	Good	General	Poor	Key veto factor
Reservoir conditions and storage potential	0.50	Characteristic of the best reservoir	0.60	Lithology	0.07	Clastic	Mix of clastic and carbonate	Carbonate	
				Single layer thickness h/m	0.11	≥ 80	$30 \leq h < 80$	$10 \leq h < 30$	<10
				Sedimentary facies	0.36	River, delta	Turbidity, alluvial fan	Beach bar, reef	
				Average porosity φ/%	0.20	≥ 15	$10 \leq \varphi < 15$	$5 \leq \varphi < 10$	<5
				Average permeability k/mD	0.27	≥ 50	$10 \leq k < 50$	$1 \leq k < 10$	<1
		Storage potential	0.40	Storage potential per unit area G (10^4 t/km^2)	1.00	≥ 100	$10 \leq G < 100$	<10	
Geological safety	0.50	Characteristic of the main caprock	0.62	Lithology	0.30	Evaporites	Argillite	Shale and dense limestone	
				Thickness h/m	0.53	≥ 100	$50 \leq h < 100$	$10 \leq h < 50$	<10
				Depth D/m	0.11	$1000 \leq D \leq 2700$	<1000	>2700	
				Buffer caprock above the main caprock	0.06	Multiple sets	Single set	None	
		Hydrodynamic conditions	0.24	Hydrodynamic conditions	1.00	Groundwater high-containment area	Groundwater containment area	Groundwater semicontainment area	Groundwater open area
		Seismic activity	0.14	Peak ground acceleration	0.50	<0.05 g	0.05 g, 0.10 g	0.15 g, 0.20 g, 0.30 g	≥ 0.40 g
				Development degree of fractures	0.50	Simple	Moderate	Complex	Within 25 km of active faults

Then, GIS spatial analysis and evaluation are carried out using formula (9).

$$P = \sum_{i=1}^{n} P_i A_i \quad (i = 1, 2, 3, \ldots, n). \tag{9}$$

Here, P is suitability scores of unit for CO_2 geological storage; n is the total number of evaluation factors; P_i is given point of the factor i; A_i is index weight of the factor i.

Single metric suitability rating is as follows: "good": 9 points, "general": 5 points, and "poor": 1 point. The evaluation result suitability rating is as follows: "highly suitable": value range $7 \leq P \leq 9$, "suitable": $5 \leq P < 7$, "less suitable": $3 \leq P < 5$, and "unsuitable": $1 \leq P < 3$.

2.2.2. Index System for Geological Suitability Assessment. As shown in Table 6, the index system for geological suitability has three hierarchies. The index weights at all levels are determined using the Analytic Hierarchy Process (AHP) [20, 21].

The assessment indexes are described detailed in the following.

(1) Characteristic of the Best Reservoir

Depth. Only if the theoretical storage depth is more than 800 meters can CO_2 enter the supercritical state, normally low than 3500 meters.

Lithology. According to the existing commercial-scale CO_2 geological storage projects (e.g., [22–24]), reservoir characteristics of oil and gas fields in China [25], and the engineering verification by the Shenhua CCS demonstration project in the Ordos Basin in China [26], clastic reservoirs are generally better than carbonate reservoirs.

Single Layer Thickness. Because of terrestrial sedimentary facies in most formations in onshore basins of China, it is difficult to find the large thick aquifers for CO_2 storage similar as Sleipner project in Norway. The minimum single layer thickness of reservoirs recommended in this paper is 10 m.

Sedimentary Facies. Most Cenozoic sedimentary basins in China are terrestrial sedimentary formations. The main part of the reservoir is the deltaic sand body, followed by the turbidite sand and alluvial fan glutinite body and finally the sand beach dams and a small amount of reef.

Porosity and Permeability. Low porosity and permeability is a special feature in terrestrial sedimentary oil and gas reservoirs and saline aquifers in China. Generally, for both the clastic and carbonate rock reservoirs, the porosity should be greater than or equal to 5% and permeability should be greater than or equal to 1 mD (e.g., [27–30]).

(2) Characteristic of the Main Caprock

Lithology. The most common caprocks of oil and gas fields in China are argillite (mudstone and shale) and evaporites (gypsum and rock salt), followed by carbonate rocks (marl, argillaceous dolomite, compact limestone, and dense dolomite) and frozen genesis caps. Sometimes there are local chert layers, seams, dense volcanic rocks, and intrusive rock caps.

Thickness. There are certain relationships between cap thickness and the size and height of the reservoir. With the combination of existing cap thickness grading standards [30] and considerations of the differences between CO_2 and oil and gas, the reference criteria for grading the classification of CO_2 geological storage cap thickness can be specified. The minimum thickness of CO_2 geological storage caprocks recommended in this paper is 10 m.

Burial Depth. The cap type is argillaceous rocks. The diagenesis has different effects on the performance of the caprock at different stage [31]. When the burial depth of argillaceous rocks is less than 1000 m, the diagenetic degree is poor and the sealing mainly relies on the capillary pressure. The porosity and permeability are good but with poor plasticity. At the burial depth of 1000–2700 m, the diagenesis is enhanced; mineral particles inside the argillaceous rock become more compacted; the porosity and permeability deteriorate; the plasticity increases; the capillary flow capacity declines; sealing ability improves; and there is abnormal sealing pressure. When the burial depth is greater than 2700 m, it is equivalent to the tightly compacted stage of the Argillite. The diagenesis is boosted further; the plasticity decreases and fragility increases; with the increase in the abnormal pressure, microcracks appear on the argillaceous rocks; and capillary sealing ability deteriorates.

The "Buffer Cap" above the Main Caprock. When the CO_2 breaks through the main cap, the "buffer cap" above the main cap has to provide a certain sealing capability to reduce or prevent the escape of CO_2.

(3) Geological Safety

Hydrodynamic Conditions. Ye et al. [32] divided the effect of hydrogeological conditions controlling coalbed methane into three categories: hydraulic transport dissipation effect, hydraulic seal effect, and hydraulic block effect. The more closed the hydrogeological conditions are, the more favorable they are for CO_2 geological storage. Basin lots with complex geological structure and powerful water alternating are not suitable CO_2 geological storage candidate prospective areas due to the high degree of hydrogeology and strong groundwater activities.

Peak Ground Acceleration. The GB 18306-2001 "The Peak Ground Acceleration Zoning in China" shows the Chinese seismic zonation map, its technical elements, and user provisions. It also applies to the CO_2 geological storage construction project. The greater the peak ground acceleration is, the more unfavorable it is for CO_2 geological storage. In general, the peak ground acceleration should be less than 0.40 g. Besides, active faults are not only CO_2 leakage pathways but also cause damage to the strata continuity, resulting in CO_2

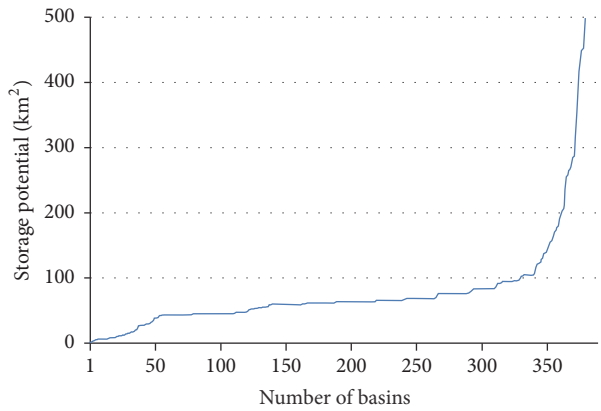

Figure 1: The statistical profile of CO_2 geological storage potential per square kilometer of 390 onshore basins in China.

leakage through the caprock. According to the GB 17741-2005 "Project site seismic safety evaluation" [33], the identification of the capable fault has to be made within a 5 km range of the first class venues and epitaxy. For seismic safety evaluation, the near-field region should be extended to a radius of 25 km range. Therefore, areas within 25 km of the active faults are inappropriate as the candidate prospective areas.

Development Degree of Fractures. CO_2 could leak by tectonic pathways including faults, fractures, and ground fissures (e.g., [28, 34–36]). Due to the complexity of geological structure and faults development in the Sichuan Basin, the qualitative assessment is based on the faults development and the existing seismic data. The more complex the fault system is, the more unfavorable it is for CO_2 geological storage. In addition, there have been more frequent seismic activities in the Sichuan Basin in recent years.

(4) Storage Potential per Unit Area. Guo (2014) evaluated the national scale potential of CO_2 geological storage in deep saline aquifers of 390 onshore basins in China supported by China Geological Survey. As shown in Figure 1, the potential of CO_2 geological storage in deep saline aquifers in most of the sedimentary basins is 50×10^4–100×10^4 t generally, and a small part of the basins are less than 10×10^4 t or more than 100×10^4 t.

3. Candidate Prospective Areas for CO_2 Geological Utilization and Storage

The fine forming conditions of the reservoir mediums for oil, gas, and CBM make them possible that the existing oil and gas fields under production are the mesoscale candidate prospective areas or target areas in the short future. Because of no official basin-scale data available, the CO_2 storage potential of other CO_2 geological utilization technologies is not discussed further in this paper.

3.1. Geology

3.1.1. Geostructure. As shown in Figure 2 [37], the current geostructure of the Sichuan Basin consists of the Southeast Sichuan fold belt, Central Sichuan low uplift, and Northwest Sichuan depression.

Table 7: Proven OGIP of 27 natural gas fields in the Sichuan Basin.

Gas fields	OGIP/10^8 m^3
Puguang	4050.79
Guang'an	1355.58
Hecuan	1187.06
Datianchi	1067.55
Xinchang	843.02
Luojiazhai	797.36
Moxi	702.31
Wolonghe	408.86
Weiyuan	408.61
Tieshanpo	373.97
Dukouhe	359
Bajiaochang	351.07
Luodai	323.83
Qiongxi	323.25
Qilibei	282.21
Baimamiao	268.72
Dachigan	258.71
Gaofengchang	227.26
Qilixia	225.48
Hebaochang	222.12
Tieshan	187.82
Zhongba	186.3
Majing	175.58
Xindu	175.32
Chongxi	136.35
Fuchengzhai	103.3
Jiannan	100.25

3.1.2. Stratigraphy. The Sichuan Basin sedimentary strata are complete, with a total thickness of 6000–12000 m. Only the Permian and the younger strata are considered in this paper, as follows from old to new:

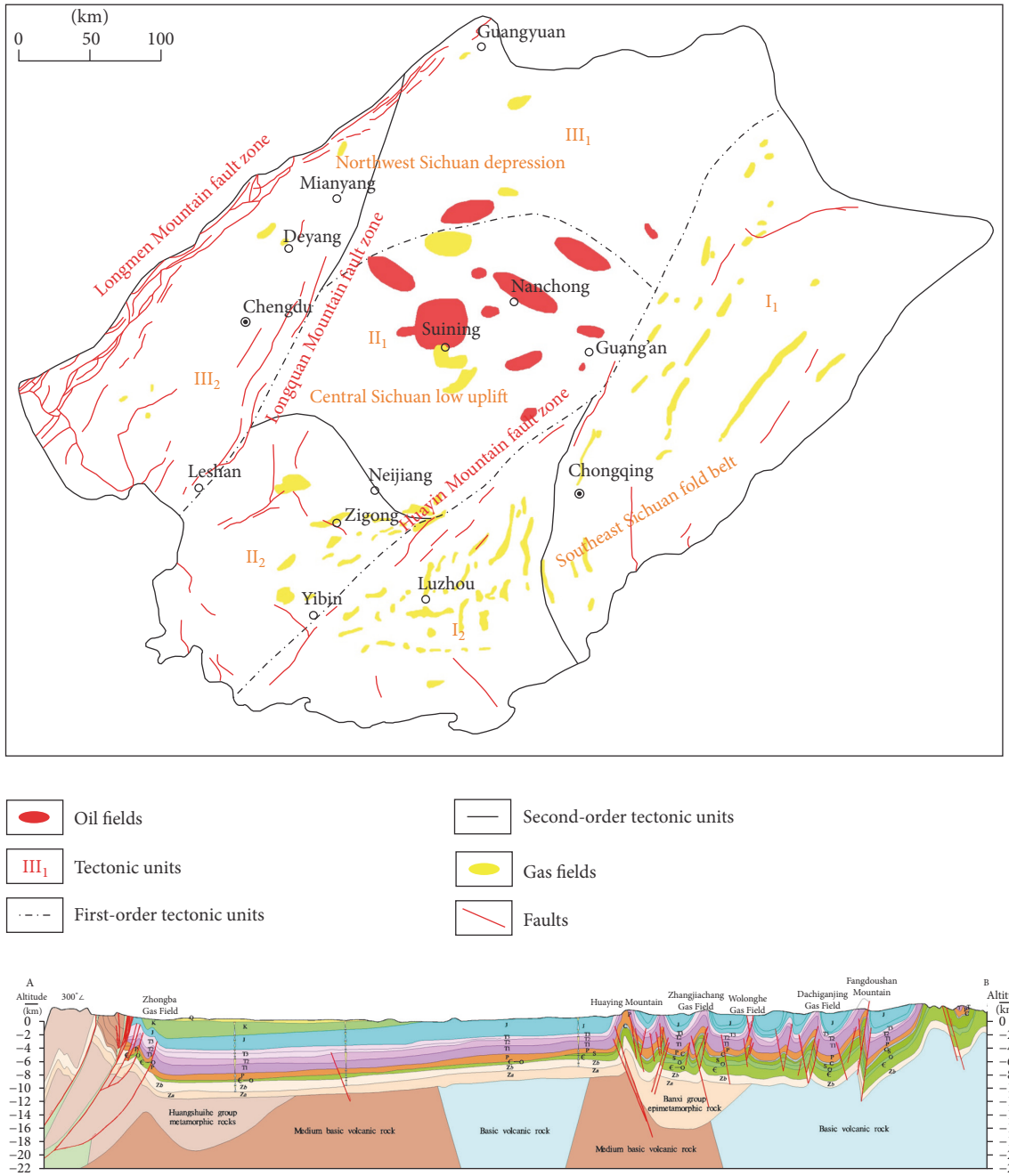

FIGURE 2: Sichuan Basin geological structure unit zoning map. There are three first-order tectonic units in the Sichuan Basin, that is, the Southeast Sichuan fold belt, the Central Sichuan low uplift, and the Northwest Sichuan depression. The Southeast Sichuan fold belt consists of the high steep fold belt in Eastern Sichuan (I1) and the low steep bottom fold belt in Southern Sichuan (I2); the Central Sichuan low uplift is composed of the flat fold belt in Central Sichuan (III1) and the low steep fold belt in Southwestern Sichuan (II2); the Northwest Sichuan depression consists of the low-lying fold belt in Northern Sichuan (III1) and the low steep fold belt in Western Sichuan (III2).

(1) The Permian: Liangshan group (P_1l), Qixia group (P_2q), Maokou group (P_2m), Longtan group (P_3l), and Changxing group (P_3c).

(2) The Triassic: Feixianguan group (T_1f), Jialing Group (T_1j), Leikoupo group (T_2l), Tianjingshan group (T_2t), Ma'antang group (T_3m), Xiaotangzi group (T_3t), and Xujiahe group.

(3) The Jurassic: Ziliujing group (J_1z), Qianfoya group (J_2q), Shaximiao group (J_2s), Suining group (J_3s), and Penglaizhen group (J_3p).

(4) The Cretaceous (K) and the Quaternary (Q).

3.1.3. Hydrodynamic Condition. The Sichuan Basin is essentially an artesian basin dominated by Permian and Triassic

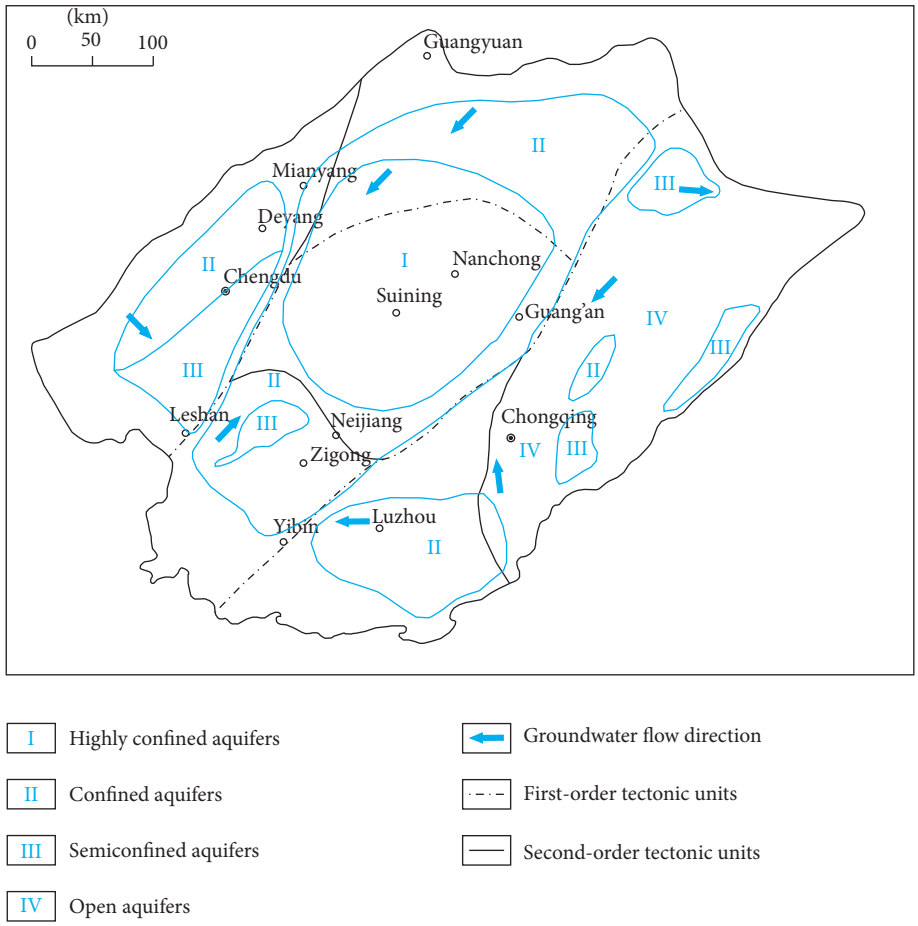

Figure 3: Hydrodynamic conditions in the Sichuan Basin. The groundwater activities are very strong in the peripheral target exposure area. In contrast, the groundwater activities inside the basin are relatively weak, with better hydrogeological confinement. On the edge of the mountain around the Sichuan Basin and the eastern fold belt experiencing infiltration of fresh water due to the complex structure and strong water alternating.

strata. The upper Jurassic and Cretaceous formations are mostly a large set of terrestrial clastic sedimentary rocks with red sandstones and mudstones throughout the basin. They are extremely thick with poor permeability, generally low in moisture, but exceedingly uneven, which could be good caprocks for the reservoirs below them. The lower upper Triassic Xujiahe consists of sandstones and shale, and the sandstone may be good aquifers for CO_2 geological storage due to its huge thickness. The lower and middle Triassic and Permian carbonate rocks are the main saline aquifers, in which Triassic carbonate rocks often form alternate layers with evaporites. Therefore, an aqueous rock series based on many stacked white aquifers is formed in the Sichuan Basin (Figure 3).

3.1.4. Geological Safety. There are many late Quaternary active faults on the boundary of the Sichuan Basin; for example, the Longmenshan fault zone in Northwestern Sichuan has experienced more intense activity in recent years. It is the induced fracture of the "5.12" Wenchuan 8.0 earthquake. The Lushan 7.0 earthquake on April 20, 2013, is another devastating earthquake that followed the Wenchuan 8.0 earthquake nearly five years later. It is also closely linked with the Longmenshan fault belt.

However, the crust in the Central and Eastern Sichuan Basin is more stable. Historical earthquakes with magnitude above 6 mainly took place in Western Sichuan and Southwestern Sichuan Basin. And the peak ground acceleration zoning according to the GB 18306-2001 "The Peak Ground Acceleration Zoning in China" is shown in Figure 4.

3.2. Oil and Gas Fields. The Sichuan Basin has abundant natural gas resources, mainly in Eastern Sichuan, but a relatively small amount of oil resources. The petroleum geological reserves in the Sichuan Basin amount to 4.38×10^8 t, and only 0.75×10^8 t of proven OOIP in Central and Northern Sichuan flat structure area [38].

By the end of 2008, the Ministry of Land and Resources of China (MLR) announced 125 gas fields in the Sichuan Basin (Figure 1), and the total amount of proven OGIP is 17225.02 $\times 10^8$ m^3. Among them, there are 27 medium to large-sized confirmed gas fields with OGIP exceeding 100×10^8 m^3, of

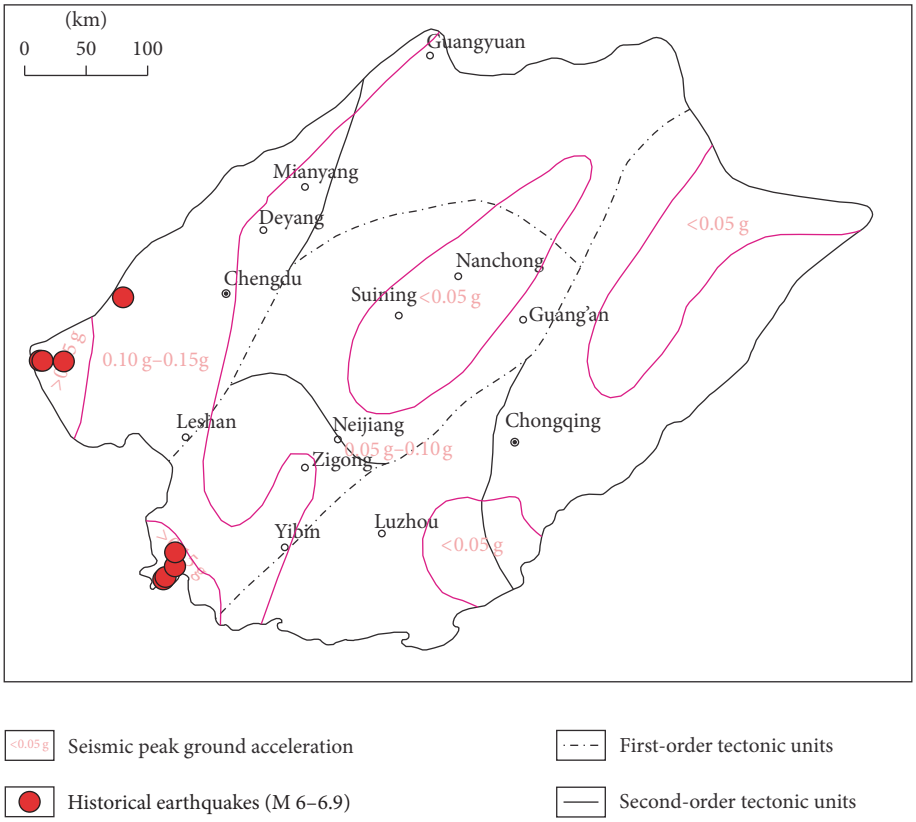

Figure 4: Seismic peak ground acceleration and large historical earthquakes in the Sichuan Basin. The peak ground acceleration is less than 0.10 g in most parts of the Sichuan Basin. Only in the western margin of the Sichuan Basin, the peak ground acceleration is larger than 0.15 g.

which the total natural gas reserves are 15092.68×10^8 m^3, accounting for 87.6% of the total proven OGIP in the basin (Table 7).

3.3. Unmineable Coal Seams. The CBM geological reserves in the Sichuan Basin amount to 3471.40×10^8 m^3 in Sichuan province and Chongqing city, 5084.57×10^8 m^3 in Southern Sichuan province and Northern Guizhou province, respectively, from 1000 to 2000 meters depth [39]. Among these, the coalfields in Southern Sichuan province are the most abundant, accounting for 82% of the province's total resources.

3.4. Deep Saline Aquifers. Compared with oil fields, gas fields, and unmineable coal seams, the analysis of geological conditions for saline aquifers CO_2 geological storage is much more complex. The CO_2 geological storage candidate prospective area for deep saline aquifers CO_2 storage was selected from the map projection on the ground of all potential underground CO_2 reservoirs. In addition, the hydrodynamic and geological safety conditions must be studied to delineate the candidate prospective areas.

3.4.1. Candidate Prospective Area Delineation Standards. As mentioned above, this report presents the delineation standards of the CO_2 geological storage candidate prospective areas shown in Table 8. Further potential and suitability assessments can be carried out for target area selection.

Table 8: Veto over key factors of CO_2 geological storage candidate prospective areas delineation.

Key factors	Veto
Reservoir conditions	
Layer thickness	<10 m
Porosity	<5%
Permeability	<1 mD
Hydrogeological conditions	
Formation water salinity	<3 g/L
Groundwater hydrodynamic condition	Groundwater zone
Geological safety conditions	
Active faults	<25 km
Peak ground acceleration	≥0.40 g

3.4.2. Vertical Reservoir Cap Combination and Candidate Prospective Areas Distribution. The reservoirs for deep saline aquifer CO_2 storage consist of the Permian, the lower Triassic carbonates, and upper Triassic and Jurassic clastic reservoirs (Figure 5). The reservoir space includes carbonate karst pores and cracks and clastic pores and cracks. Overall, all reservoirs

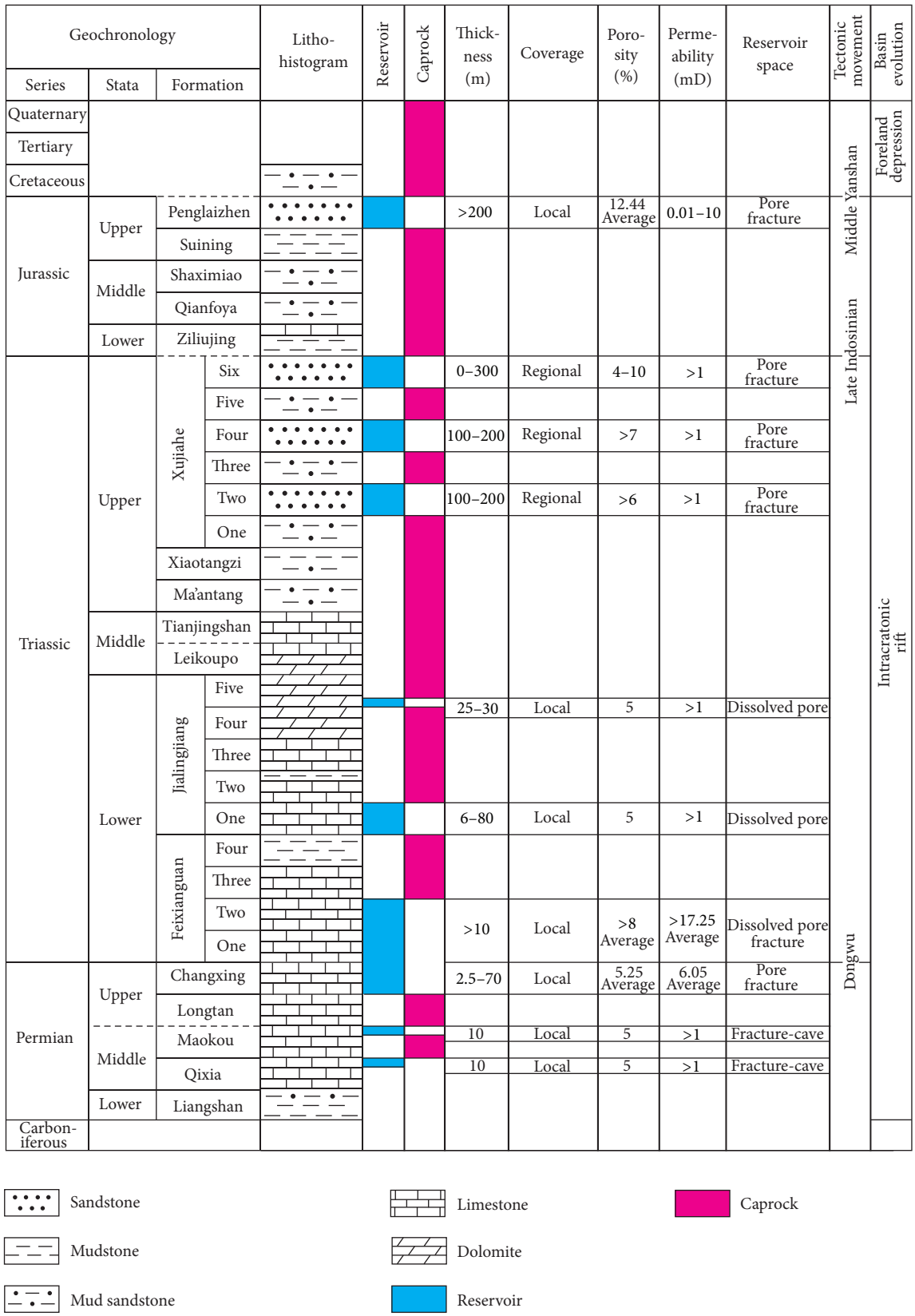

FIGURE 5: CO_2 geological storage vertical reservoir cap combination in the Sichuan Basin. There are nine sets of reservoirs in the Sichuan Basin, and the section four of Xujiahe group is the primary reservoir with large thickness and area, which almost cover the whole basin.

Table 9: Storage potential of CO_2 geological storage in depleted oil fields.

Tectonic unit	OOIP/10^8 t	Oil density (kg/m^3)	B (—)	Reservoir pressure/Mpa	Oil temperature/°C	ρ_{CO_2} (kg/m^3)	E_{oil}	$G_{CO_2}/10^8$ t
Central Sichuan flat structure area	0.58	850	1.18	21.26	64.42	712.63	0.75	0.57
Northern Sichuan flat structure area	0.17	850	1.18	21.26	64.42	712.63	0.75	0.17

Table 10: CO_2-EOR geological storage potential in the Sichuan Basin.

Tectonic unit	API	EXTRA (%)	P_{LCO_2} (%)	P_{HCO_2} (%)	E_{oil}	$G_{CO_2\text{-EOR}}/10^8$ t
Central Sichuan flat structure area	34.97	10.46	33	66	0.75	0.16
Northern Sichuan flat structure area	34.97	10.46	33	66	0.75	0.05

in the Sichuan Basin have poor physical properties, with ultra-low porosity and low permeability. Comparing with the natural gas fields in the Sichuan Basin, these reservoirs for CO_2 storage have better caprock conditions too. For example, the extensive deposits of gypsum rocks in the Leikoupo phase and the widely developed dark mudstone in the Lower Jurassic can provide good sealing conditions for the underlying reservoirs.

(1) The Permian. The reef flat facies on the top of Qixia group form a good reservoir through dolomitization, with favorable reservoir conditions (P_2q) [40]. Part of them form the natural gas reservoirs, with a thickness of approximately 10 m. Similar to the Qixia group, the Maokou group (P_2m) is a fracture-cave type of reservoir. Changxing group (P_3c) reservoirs are pore type and fracture-pore type. The porosity is generally 2.03%–15.85%, with an average value of 5.25%; the permeability is less than 1000 mD, with an average value of 6.05 mD. The reservoir thickness is large, with a monolayer thickness of 0.5–5 m and a single well cumulative thickness of 2.5–70 m [41].

(2) The Triassic. The Feixianguan group (T_1f) is similar to the Changxing group. The quality and distribution of the reef beach reservoir are mainly controlled by sedimentary facies and diagenesis. The evaporative platform oolitic dolomite reservoir is mainly distributed in Northeast Sichuan, with a monolayer thickness of 1.5–15 m and total thickness of 20–50 m. The porosity ranges from 2% to 26.8%, on the average of 8.29%; and the permeability is less than 1160 mD, with an average value of 59.73 mD. The porosity of the open platform edge oolitic dolomite reservoir is 2.05%–22.62%, on the average of 8.42%, and the permeability is less than 410 mD with an average value of 17.25 mD. The reservoir monolayer thickness is generally 0.5–6 m, and the total thickness is 10–45 m typically.

The favorable Jialingjiang reservoir facies are the platform interior shoal and the platform margin shoal facies. For example, section five of Jialingjiang reservoirs consists of limestone and dolomite, with a thickness of 25–30 m, of which approximately 60% is the porosity layer, and the average of the porosity is 5%, with the highest value reaching 18%.

The sandstone aquifers in section two, section four, and section six of Xujiahe formation could be reservoirs for CO_2 geological storage, composed of residual intergranular pore, intergranular dissolved pore, and fracture. The sand ratio of the sandstones is greater than 70% in 80% generally. In addition, the porosity of section four is higher than section two and section six, usually between 5%–10%, while the porosity of sandstones in section two and section is less than 7% generally.

Figure 6 shows the candidate prospective areas in the Sichuan Basin in the Sichuan Basin for deep saline aquifer CO_2 storage based on geology study.

4. Results

4.1. Potential

4.1.1. Depleted Oil Fields CO_2 Storage and CO_2-EOR. The primary CO_2-EOR prospective areas in the Sichuan Basin are located in the flat tectonic area in Central and Northern Sichuan Basin. As shown in Tables 9 and 10, the CO_2 geological storage potential of storage in depleted oil fields is only 0.74×10^8 t, while the storage potential is about 0.21×10^8 t by using CO_2-EOR technology.

4.1.2. Depleted Gas Fields CO_2 Storage and CO_2-EGR. The CO_2 geological storage potential of depleted gas fields is 53.73×10^8 t. By using CO_2-EGR technology, the Sichuan Basin gas fields could achieve CO_2 geological storage of 33.85×10^8 t. Among that 27 large and medium gas fields have the greatest potential, with the possibility of achieving a CO_2 geological storage capacity of 42.39×10^8 t in depleted gas fields, while the storage potential is about 26.70×10^8 t by using CO_2-EGR technology.

4.1.3. Unmineable Coal Seams CO_2 Storage and CO_2-ECBM. The Sichuan Basin has abundant coal bed methane resources. As shown in Table 11, the total CO_2 geological storage

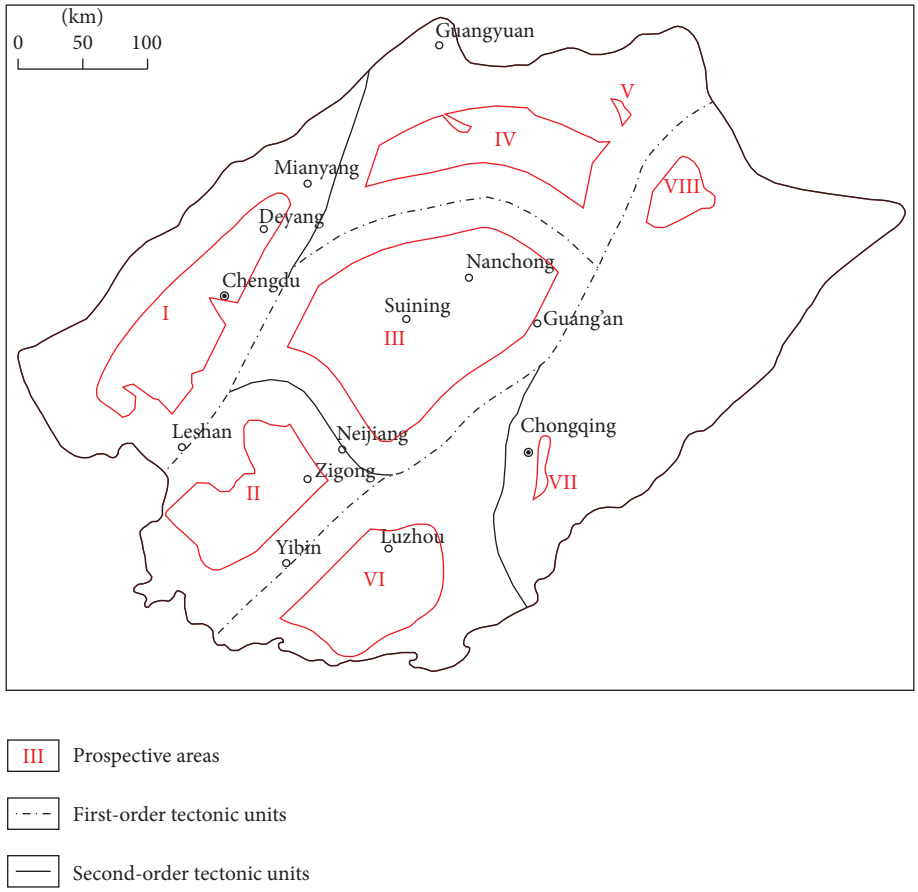

Figure 6: Candidate prospective areas in the Sichuan Basin. There are eight candidate prospective areas in the Sichuan Basin for deep saline aquifer CO_2 storage which cover more than 5×10^4 km^2 and mainly locate in Central Sichuan Basin (districts II–V). Only district I is in Northwestern Sichuan. The candidate prospective areas (districts VI–VIII) in Eastern Sichuan are relatively small due to the effects of formation depth, geological safety, and hydrogeological conditions.

Table 11: Storage potential of CO_2 in unmineable coal seams and CO_2-ECBM in the Sichuan Basin.

Area	$G_{CBM}/10^8$ m^3	Types of coal	R_{CO_2/CH_4}	C	$\rho_{CO_2 std}$ (kg/m^3)	$G_{CO_2}/10^8$ t	$G_{CO_2\text{-ECBM}}/10^8$ t
Southern Sichuan and Northern Guizhou	5084.57	Mainly anthracite	1	0.50	1.977	3.72	1.86
Sichuan and Chongqing	3471.40	Mainly coking coal and lean coal	1	0.50	1.977	2.54	1.27

potential of unmineable coal seams can vary in the range from 3.55×10^8 t to 8.12×10^8 t (6.26×10^8 t on the average), while the storage potential of CO_2-ECBM technology is half of the unmineable coal seams CO_2 geological storage.

However, the coal bed methane in the Sichuan Basin proposed by Ministry of Land and Resources (MLR) is just the theoretical geological reserves in place but not proven reserves, so the reliability of potential of unmineable coal seams and CO_2-ECBM is much lower than depleted oil and gas fields CO_2 storage and CO_2-EOR and CO_2-EGR.

4.1.4. Deep Saline Aquifers CO_2 Storage or CO_2-EWR. The total CO_2 geological storage potential in deep saline aquifers varies in the range of 77.81×10^8 t to 262.08×10^8 t (154.20×10^8 t on the average). However, the main CO_2 geological reservoirs are sections two, four, and six of Xujiahe formation, with the storage potential of 71.98×10^8 t to 245.95×10^8 t (143.98×10^8 t on the average), that is, approximately 93.37% of the total storage potential.

According to the statistics of the structural position, the total expected storage potential in Central Sichuan is the largest, reaching 89.26×10^8 t on the average. The total expected storage potentials in Western Sichuan and Eastern Sichuan are 45.68×10^8 t and 19.27×10^8 t on the average, respectively. The potential per unit area is shown in Figure 7.

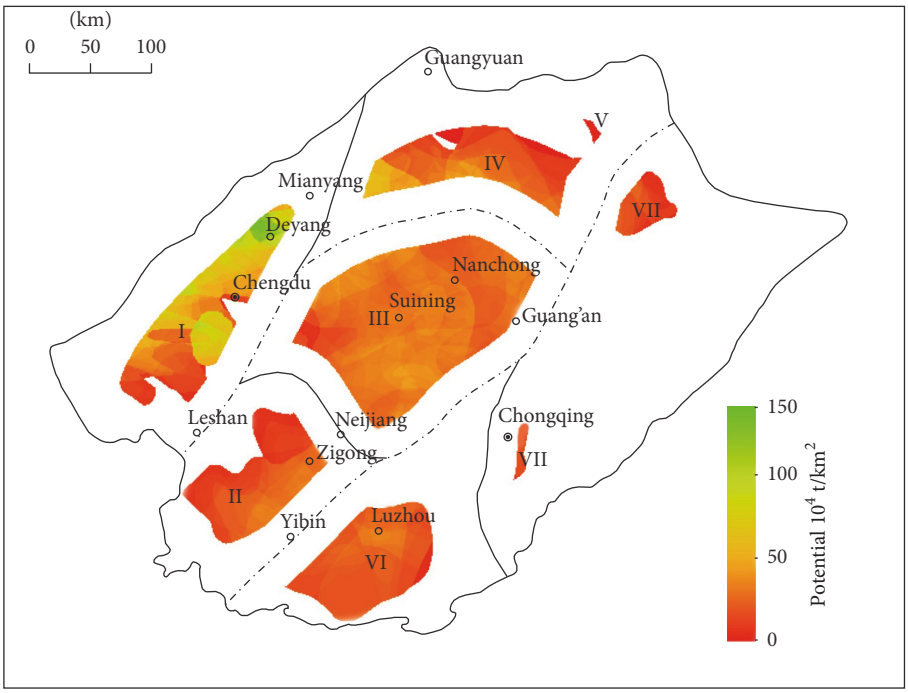

Figure 7: Storage potential per unit area for each prospective area. Due to the large stratigraphic thickness and many reservoir layers, the storage potential per unit area in most depressions in Northwestern Sichuan is quite large, with the largest up to 140×10^4 t/km^2, at $P50$ probability level. The storage potential per unit area in Central Sichuan is generally greater than 50×10^4 t/km^2, at $P50$ probability level.

Table 12: Geological suitability assessment information of the main reservoir distribution area (within section four of Xujiahe formation).

Level one index	Level two index	Level three index	Distribution information of the main reservoir in Xujiahe section 4	Geological information outside of Xujiahe section 4 distribution
Reservoir conditions and storage potential	Reservoir geological characteristics	Lithology	Clastic	Mix of clastic and carbonate
		Thickness/m	≥80	<30
		Sedimentary facies	River, delta	Beach bar, reef
		Average porosity/%	GIS partition processing	<10
		Average permeability/mD	<10	<10
	Storage potential	Storage potential per unit area (10^4 t/km^2)	GIS partition processing	GIS partition processing
Geological safety	Cap geological characteristics	Lithology	Argillite	Argillite
		Thickness/m	≥100	≥100
		Main cap depth	1000–2700	1000–2700
		Buffer cap above main cap	Multiple sets	Multiple sets
	Hydrodynamic conditions	Hydrodynamic conditions	GIS partition processing	GIS partition processing
	Seismic activity	Peak ground acceleration	GIS partition processing	GIS partition processing
		Fracture development	GIS partition processing	GIS partition processing

The main reservoir is the section four of Xujiahe formation, and the main cap is the lower Jurassic strata. The GIS partition processing must be carried out separately for the prospective areas within and outside of section four of Xujiahe formation. The geological information outside of section four of Xujiahe formation is from the best value of other eight reservoirs.

Table 13: Storage potential results in this paper compared with studies before.

CCUS	Study scales	Authors	Results before (10^8 t)	Basic data
CO_2 geological utilization				
CO_2-EOR	National	ACCA 21, 2014		MLR, 2010
	National	Wei, 2015		
	Target	*This paper*	*0.21*	
CO_2-EGR	National	ACCA 21, 2014		MLR, 2010
	National	Wei, 2015		
	Target	*This paper*	*26.70*	
CO_2-ECBM	National	ACCA 21, 2014		MLR, 2009
	National	Wei, 2015		
	Target	*This paper*	*3.13*	
CO_2 geological storage				
Depleted oil fields	National	Zhang, 2005		
	Basin	Li, 2009	0.20	Li, 2002
	National	ACCA 21, 2014		MLR, 2010
	Basin	Guo, 2014	Unpublished	
	National	Wei, 2015		
	Target	*This paper*	*0.74*	
Depleted gas fields	National	Zhang, 2005		
	National	Liu, 2006	10.14	900~3500 m Recoverable reserves [25]
	Basin	Li, 2009	10.50	
	National	ACCA 21, 2014		MLR, 2010
	Basin	Guo, 2014	Unpublished	
	National	Wei, 2015		
	Target	*This paper*	*42.39*	
Unmineable coal seams	National	Zhang, 2005		
	National	ACCA 21, 2014		MLR, 2009
	Basin	Guo, 2014	Unpublished	
	National	Wei, 2015		
	Target	*This paper*	*6.26*	
Deep saline aquifers	National	Zhang, 2005		
	National	Li, 2006	64.07	
	National	Li, 2009		
	National	ACCA 21, 2014		
	Basin	Guo, 2014	Unpublished	
	National	Wei, 2015		
	Target	*This paper*	*154.20*	*Further geological study*

4.2. Target Areas for Deep Saline Aquifers CO_2 Storage

4.2.1. Data. On the basis of systematic analysis of the deep saline aquifer CO_2 geological storage cap, through the geological suitability evaluation index system, the superimposed multisource information evaluation was successively carried out using ArcGIS software. The basic information is shown in Table 12. As mentioned in Section 3.4.2, the main reservoir in the Sichuan Basin is the section four of Xujiahe formation.

4.2.2. Target Areas. As shown in Figure 8, most prospective areas are suitable for CO_2 geological storage. The suitable areas could be used as the target areas for CO_2 geological storage. By further ground suitability evaluation and social economic surveys, some project sites can be identified from those target areas for large-scale saline aquifers CO_2 geological storage.

5. Discussion and Conclusions

5.1. Discussion. The purpose of this paper is not only to evaluate the mesoscale potential of different CCUS technologies but also select the suitable target areas for early demonstration in the Sichuan Basin. On the basis of geology study, the CO_2 storage potential of CO_2-EOR, CO_2-EGR, CO_2-ECBM, and saline aquifer CO_2 storage technologies was first evaluated comprehensively. Compared with the

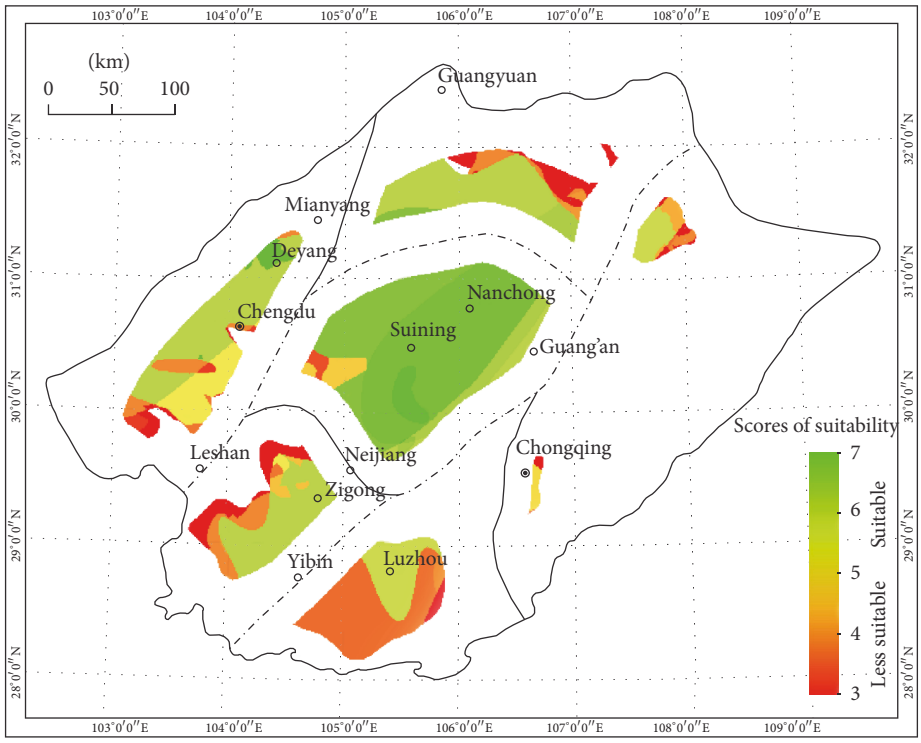

Figure 8: Assessment results of CO_2 geological storage suitability (suitable area is the "target area"). Most prospective areas in the Sichuan Basin are suitable for CO_2 geological storage, which could be the "target areas" for CO_2 geological storage. The main reservoirs in the Central Sichuan Basin are sections two, four, and six of Xujiahe formation with large thickness and good physical properties. They are far from the basin boundary faults, with weak hydrodynamic and good geological safety conditions.

similar studies before, the study scale in this paper is more detailed especially for CO_2 storage in deep saline aquifers, which is based on further geological study of reservoirs, seals, hydrogeology, and geological safety. The basic data for potential assessment are from MLR, PetroChina, and other authorities; thus the potential results are more credible, and more in accordance with geology. Table 13 shows the storage potential results in this paper compared with studies before.

5.2. Conclusions. Taking the low technical application levels of CO_2-EWR and CO_2-EGR into account, it is recommended that deep saline aquifers and depleted gas fields CO_2 geological storage in the Sichuan Basin could be early demonstrated, especially that of the latter because of excellent traps, rich geological data, and well-run infrastructures.

5.2.1. Deep Saline Aquifers CO_2 Geological Storage. For deep saline aquifers CO_2 geological storage, based on the consideration of deep saline aquifer CO_2 geological storage mechanism and geology of the Sichuan Basin, this paper proposes the study order of "prospective areas" to "target areas" and a new GIS superimposed multisource information evaluation method of geological suitability for target selection. The index system of geological suitability assessment for target selection is appropriate for multiple tectonics, facies, and reservoirs, to evaluate the suitability of prospective areas to select suitable target areas. The GIS superimposed multisource information evaluation results show that most areas are suitable for CO_2 geological storage, and only some local peripheral areas are not suitable for CO_2 geological storage. The areas selected through geological suitability assessment can be used as target areas for CO_2 geological storage.

The geology in Central Sichuan provides the best conditions, and the storage potential per unit area in Central Sichuan is generally greater than 50×10^4 t/km^2, at $P50$ probability level, with Xujiahe group is the main reservoir. However, deep saline aquifers CO_2 geological storage could only be used in the future due to its lack of other economic benefits, high investment, and multiple barriers in the short term.

5.2.2. Depleted Gas Fields CO_2 Geological Storage. In the mesoscale, gas fields under exploration or exploitation can be used as target areas for depleted gas fields CO_2 geological storage. The MLR has announced that there are 125 gas fields in the Sichuan Basin and 27 medium to large-sized confirmed gas fields among them. There are many gas reservoirs or traps becomes depleted, which provide a great chance for early demonstration first for the CO_2 resources located in the Sichuan Basin. Even in the long run, the depleted gas fields could be the main reservoirs for CO_2 geological storage in the Sichuan Basin.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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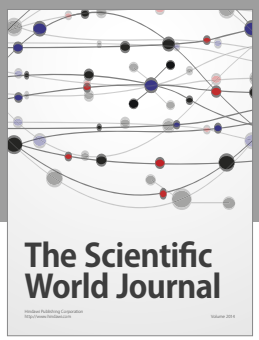

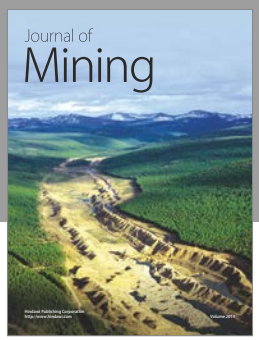

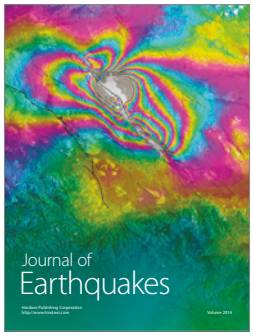

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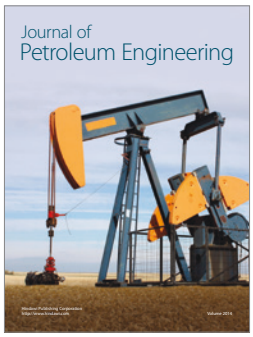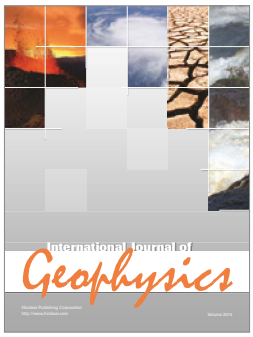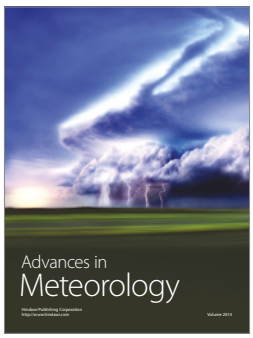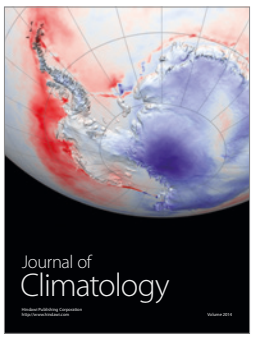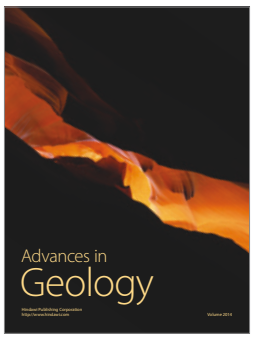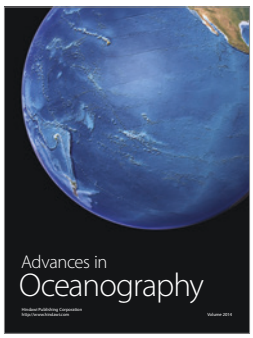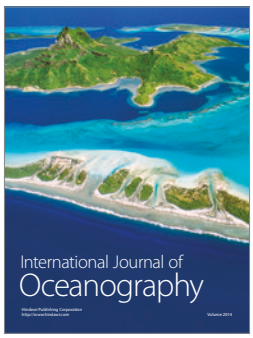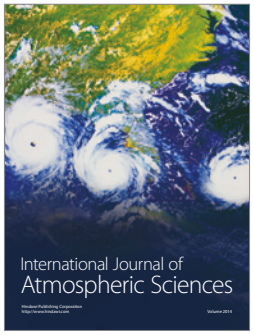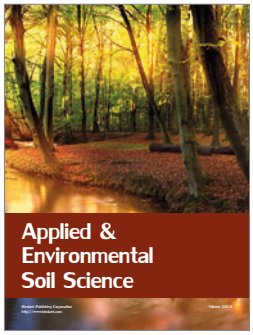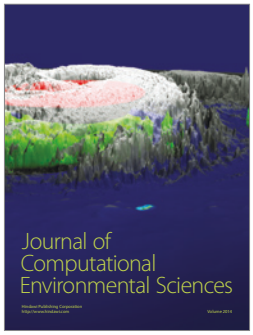
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