Journal of Applied Mathematics and Physics, 2014, 2, 1009-1021
Published Online October 2014 in SciRes. http://www.scirp.org/journal/jamp
http://dx.doi.org/10.4236/jamp.2014.211115

CO_2 Geological Storage Suitability Assessment of Sichuan Basin

Jijiao Fan, Jianqiang Guo, Senqi Zhang, Xiaofeng Ji

Center for Hydrogeology and Environmental Geology Survey, CGS, No.1305, Qiyi Middle Road, Baoding, 071051, Hebei Province, China
Email: jiaxiaofengdaxia@163.com, gjq@vip.163.com, senqizhang@126.com

Received August 2014

Abstract

The paper chooses the secondary tectonic units of Sichuan Basin as the evaluation object, and considers regional crustal stability conditions, basic geological conditions, reservoir and cap rock conditions, storage potential conditions, geothermal conditions, research degree and potential resources conditions, social and economic conditions as first-level indexes. Based on collected data and a comprehensive analysis of 16 level-two indexes and 9 level-three indexes, and with the application of comprehensive index method, the conclusions regarding the suitability partition of the secondary tectonic units of Sichuan Basin are as follows: Central Sichuan low-flat structural belt is highly suitable for carbon dioxide geological storage, West Sichuan low-slope structural belt is relatively suitable, and SW low-slope structural belt is unsuitable for carbon dioxide geological storage, South Sichuan low-slope structural belt is relatively unsuitable, whereas East Sichuan high-slope faulted fold belt, and North Sichuan low-flat structural belt are fairly suitable for carbon dioxide geological storage. Based on the above, with a comprehensive analysis of corresponding hydrographic and geological conditions, and at the same time considering the non-covered oil or gas resources and the buried structure, six CO_2 geological target formations are identified, including lower Jurassic Ziliujing Group, upper Triassic Xujiahe Group, middle Triassic Leikoupo Group, lower Triassic Jialingjiang Group and Feixianguan Group, and lower Permian Qixia Group. This paper provides an important guidance and reference for the selection criteria of CO_2 geologic storage sites in Sichuan Basin.

Keywords

Suitability Evaluation, Sichuan Basin, Geological Storage of Carbon Dioxide, Tectonic Unit

1. Introduction

With the establishment of operational targets regarding controlling greenhouse gas emissions, as well as the appropriate policy measures and actions put forward by the State Council, Chinese enterprises with high energy consumption and high carbon dioxide emissions are facing tremendous pressure to reduce emissions. To alleviate the pressure and to develop the green and low-carbon economy, some companies start to focus on carbon dioxide capture and storage by taking some actions.

How to cite this paper: Fan, J.J., Guo, J.Q., Zhang, S.Q. and Ji, X.F. (2014) CO_2 Geological Storage Suitability Assessment of Sichuan Basin. *Journal of Applied Mathematics and Physics*, **2**, 1009-1021. http://dx.doi.org/10.4236/jamp.2014.211115

China CO_2 emissions are approximately 8 billion tonnes per year. Therefore Chinese government and companies are playing an increasingly prominent role in assessment and development of CCS technologies. The activities in China include indigenous research and development, collaborative research with international entities, learning from other countries through knowledge sharing, and development of demonstration or full-scale projects. Between 2010 and 2012, China has carried out carbon dioxide geological storage potential evaluation and suitability assessment, and has finished CO_2 geological storage suitability assessment at both regional and basin-scales [1]-[5]. Potential and suitability assessment of CO_2 geological storage was divided into five stages, with each stage focusing on a smaller scale area and increasing the level of precision for the storage capacity estimate (**Figure 1**). The first stage is regional-scale, and the study object is individual basin, the second stage is basin-scale, and the study object is the first or second tectonic units, and so on until completion of the injection-scale assessment. The "target scale" serves as a transition between the basin-scale and site-scale stages. For this article, the basin scale research was based compilation of existing maps, development of some new maps, and calculation of storage capacities. In general, the capacity assessment was conducted using methodologies published under the Carbon Sequestration Leadership Forum (CSLF) as presented in [6]. The suitability assessment was conducted by other professors work [7]-[10]. Based on technical requirements of the project "national CO_2 geological storage potential evaluation and suitability assessment" implemented between 2010 and 2012, this paper carried out the basin-scale assessment in Sichuan Basin.

CPI constructed the first domestic 10,000 ton level "CO_2 capture and liquefaction plant" for their coal-fired power plant named Shuanghuai Plant in Hechuan Town (**Figure 2**) in November, 2009. The Hechuan Town located in the Chongqing Province in Sichuan Basin.The primary objective is to determine the feasibility for storage of about 100,000 tons per year CO_2. In addition, consideration is also given to the expansion to about 1,000,000 tons per year as the future target [11]. During mid-2012, our team was selected by Battelle to assist them in geologic storage assessment.

2. Study Area and Carbon Emission

Sichuan Basin is located in Sichuan-Chongqing area, between 28˚ - 32˚40′ north latitude and 102˚30′ - 110˚ east longitude, with a total area of 260,000 km^2. Sichuan Basin, one of the four largest basins in China, is also called Bashu Basin, Xinfeng Basin or Purple (Red) Basin. The outline of Sichuan Basin is of rhombus shape,

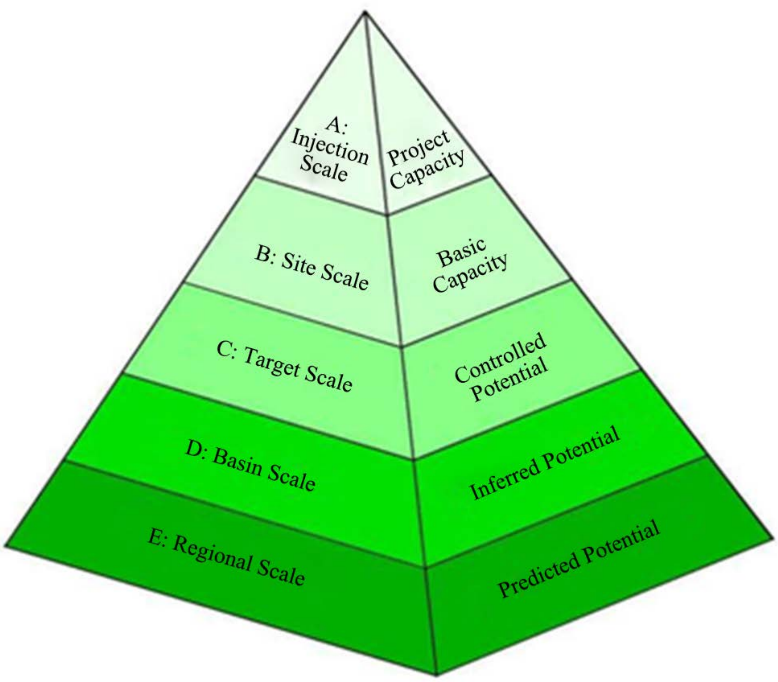

Figure 1. Stages of CO_2 geological storage assessment in China.

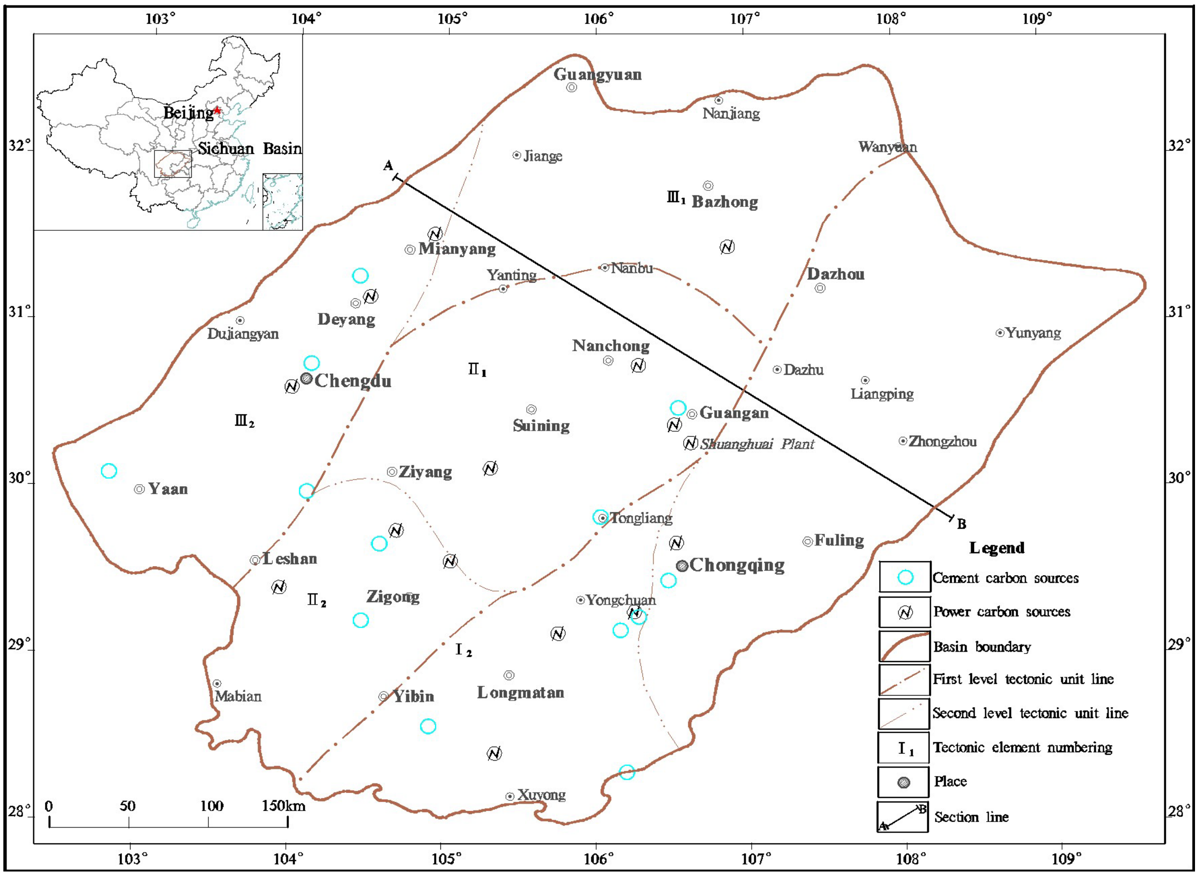

Figure 2. Location of the Sichuan Basin and carbon sources.

containing the east part of Sichuan Province, most of Chongqing and the junction zone of three provinces: Hubei, Guizhou and Yunnan. Considering its geographical variations, Sichuan Basin can also be divided into three parts: Chengdu Plain in the west of Sichuan, hilly areas in the middle, and parallel ridge-valley region in the eastern Sichuan.

The Sichuan Basin is the most important gas-producing basin in China, the amounts of natural gas resources are the largest in China, accounting for about one-fourth of The total national gas production. It is also one of the most important heavy industrial zones in China, having a large number of CO_2 emission sources such as power plants, cement production plants, and steelworks. The main sources of carbon emissions are the two provincial capitals (Chengdu and Chongqing) and the fourteen large cities (Ya'an, Meishan, Leshan, Ziyang, Zigong, Luzhou, Yinbi, Suining, Nanchong, Guangan, Mianyang, Bazhong, Dazhou and Guangyuan). Four parameters (emission amount of power plants and cement production plants of Chengdu and Chongqing) have been collected to assess the amount of carbon emission in the Sichuan Basin. Chongqing and Sichuan' results are of the same order of 10^8 t magnitude according to China statistics yearbooks of 2008a (National Bureau of Statistics of China, 2008). The economic circle can be divided into Chengdu centered Western Sichuan economic zone (Western Sichuan economic belt), Chongqing centered Chuanjiang economic zone (Chuanjiang economic belt) and Nanchong centered North-Central Sichuan economic zone. Compared with the experimental, the total carbon emission is referring to the energy consumption related to economic development and GDP. Along with economic growth and people's energy consumption demand increase, the carbon emission amount must be a rising tendency. It is one of the most rapidly developing areas with large energy consumption and CO_2 emission, carbon capture and storage is probable and urgently needed.

3. Evaluation Method

China's CO_2 geological storage suitability at basin scale could be classified as 7 first-level evaluation indexes:

(1) regional crustal stability conditions, (2) basic geological conditions, (3) reservoir and cap-rock conditions, (4) potential conditions of storage, (5) geothermal geological conditions, (6) research degree and resource potential conditions, and (7) socio-economic conditions (**Table 1**). and 16 second-level indexes (**Table 1**) and 9 third-level indexes (**Table 2**, **Table 3)**, and as shown at with 5 levels for each index as 9, 7, 5, 3 and 1, representing conditions of highly suitable, suitable, generally suitable, unsuitable and highly unsuitable (**Tables 1-3**). The synthetical index for each secondary tectonic unit could be calculated according to the following formula [12]:

$$P = \sum_{i=1}^{n} P_i T_i$$

where, P represents the synthetical index of CO_2 geological storage suitability within second-order tectonic units in the basin;

P_i represents a given index of the i^{th} evaluation factor, and here P_i has values of 9, 7, 5, 3, or 1 as assigned as a evaluation result of each index through comparing with ranking conditions listed in **Table 1-3**, as described in chapter 4, that is, The indices of P_i is given by professors group according to existing information.

T_i represents the weight of the i^{th} index, which is given by professors group according to their experience value.

Table 1. Carbon dioxide geological storage suitability evaluation system.

Index layers	Weight	**Evaluation Index sub-layers**	Weight	**Highly suitable**	**Relatively suitable**	**Fairly suitable**	**Relatively unsuitable**	**unsuitable**
Crustal Stability	0.37	Crustal Stability	0.370	Stable	Basically stable	Slightly unstable	Less stable	unstable
Basic Geological Condition of tectonic unit	0.07	Area/km^2	0.033	$S > 10000$	$5000 < S \le 10000$	$500 < S \le 5000$	$100 < S \le 500$	$S < 100$
		Sedimentary Depth/m	0.033	$H > 3500$	$2500 < H \le 3500$	$2500 < H \le 1500$	$1500 < H \le 800$	$H < 800$
Seal and Reservoir	0.22	Seal	0.078	highly suitable	suitable	possible	unlikely	unsuitable
		Reservoir stratum	0.078	highly suitable	suitable	possible	unlikely	unsuitable
		Combination	0.067	Regional seal, Independent seal	Regional seal, self-reservoir and self-seal	Local seal, Independent seal	Local seal, self-reservoir and self-seal	NO
Predicted potential	0.16	Predicted potential/10^{8}t	0.094	$M > 50$	$25 < M \le 50$	$0.5 < M \le 25$	$0.02 < M \le 0.5$	$M < 0.02$
		Predicted potential per area/(10^{4}t·km^{-2})	0.063	$m > 200$	$100 < m \le 200$	$50 < m \le 100$	$1 < m \le 50$	$m < 1$
Geothermal Geology	0.12	Geothermal gradient/ [°C·(100 m)$^{-1}$]	0.049	$G < 2.0$	$2.0 < G \le 3.0$	$3.0 < G \le 4.0$	$4.0 < G \le 5.0$	$G > 5$
		Geothermal heat flow value(mW·m^{-2})	0.049	$q < 54.5$	$54.5 < q \le 65$	$65 < q \le 75$	$75 < q \le 85$	$q > 85$
		Land Surface Temperature/°C	0.025	$t < -2$	$-2 < t \le 3$	$3 < t \le 10$	$10 < t \le 25$	$t > 25$
Research Degree and Resources Potential	0.04	Exploration Degree	0.022	Development	High	General	Low	No
		Data supply	0.011	Full, reliable data	Less full data	General full data	Not sufficient data	No data
		Resources potential	0.004	large	Relatively large	General	Relatively less	less
Social & Economic Condition	0.02	Population density (Person/km^2)	0.013	$P < 50$	$50 < P \le 100$	$100 < P \le 200$	$200 < P \le 1000$	$P > 1000$
		Land use types	0.009	Desert, land no using	Grassland	Woodland	Arable land	Settlements waterbody
		Score		9	7	5	3	1

Table 2. Reservoir ranks.

Reservoir	Evaluation Index	Weight	Highly suitable	Relatively suitable	Fairly suitable	Relatively unsuitable	Unsuitable
First reservoir	lithology	0.25	Clastic rocks	Mixed clastic and carbonate	carbonate	Magmatic rock, metamorphic rocks, salt dome etc. Special reservoir	No
	depth	0.15	$1500 \le H \le 2000$	$2000 < H \le 2500$	$2500 < H \le 3000$	$3000 < H \le 3500$	$H > 3500$
	Porosity (%)	0.3	$\varphi \ge 25$	$20 \le \varphi < 25$	$10 \le \varphi < 20$	$5 \le \varphi < 10$	$\varphi < 5$
	Permeability ($\times 10^{-3}\ \mu m^2$)	0.3	$K \ge 1000$	$500 \le K < 1000$	$50 \le K < 500$	$1 \le K < 50$	$K < 1$
Second reservoir stratum	Same to First reservoir						
…							

Table 3. Seal ranks.

Seal	Evaluation Index	Weight	Highly suitable	Relatively suitable	Fairly suitable	Relatively unsuitable	Unsuitable
First seal	Lithology	0.2	Gypsum, mudstone, calcilutite	Mudstone contain aleurite, sand	Arenaceous, siltstone mudstone	Argillaceous sandstone, Argillaceous siltstone	Shale, compact limestone
	The distribution of continuity	0.25	continuous, steady	more continuous, more steady	Middle	Poorer continuous, poorer steady	discontinuous
	thickness of single layer	0.1	$h \ge 20$	$10 \le h < 20$	$5 \le h < 10$	$2.5 \le h < 5$	$h < 2.5$
	gross thickness	0.2	$h \ge 300$	$150 \le h < 300$	$100 \le h < 150$	$50 \le h < 100$	$h < 50$
	permeability	0.25	$K < 0.001$	$0.001 \le K < 0.01$	$0.01 \le K < 0.1$	$0.1 \le K < 1$	$K > 1$
Second seal	Same to First seal						
…							

T_i of every level indexes satisfy the condition:

$$1 = \sum_{i=1}^{n} T_i$$

n represents the total number of evaluation factors, and here $n = 9$ for third-level indexes, $n = 16$ for second-level indexes and $n = 7$ for first-level evaluation indexes.

The results of synthetical index scores P of individual are in the range of [1] [9], to make the results distributes more average between [0, 1], the synthetical index scores P are normalized according to:

$$P_{i,i=1\sim6} = \frac{P_{i,i=1\sim6} - \min P_{i,i=1\sim6}}{\max P_{i,i=1\sim6} - \min P_{i,i=1\sim6}}$$

As a result of this process, each second-order tectonic units in Sichuan basin being screened and ranked by **Table 4**.

4. The Analysis of Suitable Conditions

4.1. Geologic Structure

The interior Sichuan Basin is divided into six second-level tectonic units, including East Sichuan high-slope faulted fold belt, South Sichuan low-slope structural belt, Central Sichuan low-flat structural belt, SW low-slope structural belt, North Sichuan low-flat structural belt, North Sichuan low-flat structural belt and West Sichuan low-slope structural belt, with corresponding area and deposition thickness shown in **Table 5** [13].

Table 4. Comparison table of number range of P value and evaluation result.

Evaluation Result	Highly suitable	Relatively suitable	Fairly suitable	Relatively unsuitable	unsuitable
Number Range of P	0.8, 1	0.6, 0.8	0.4, 0.6	0.2, 0.4	0, 0.2

Table 5. Tectonics units in Sichuan Basin.

No	Second-level tectonic units	Area (km^2)	Deposition thickness (m)
I_1	East Sichuan high-slope faulted fold belt	50,000	10,000
I_2	South Sichuan low-slope structural belt	26,000	8000
II_1	Central Sichuan low-flat structural belt	37,000	9000
II_2	Southwestern low-steep fold belt	21,000	7000
III_1	North Sichuan low-flat structural belt	34,000	12,000
III_2	West Sichuan low-slope structural belt	32,000	10,000

4.2. Regional Crustal Stability

According to Yang X.'s research results [14], for the available seismic network record between1970 and 2010, the number of earthquakes with ML ≥ 2.0 in Sichuan Basin and its periphery is 33646, and the number of earthquakes with ML ≥ 2.0 in Sichuan Basin is 9058. The number of earthquakes with focal depth record and with ML ≥ 2.0 in this basin is 4271, where in the shallowest one is 1 km, the deepest one is 60 km and the majority is within the range of 5 - 30 km, belonging to shallow-focus earthquake. According to the research of Zhang J. *et al.*, the occurrence of the next earthquakes with eight magnitudes in Sichuan should be between 2041 and 2042 [15], and it is substantially sufficient for the carbon dioxide storage field to run for 30 years.

According to GB18306-2001 [16], the map of Chinese seismic peak acceleration, it can be seen that seismic peak acceleration values from eastern high and steep fold belt are less than or equal to 0.05 g, values from southern low-steep fold belt are 0.05 g, values from middle gentle fold belt are less than 0.05 g, values from southwestern low-steep fold belt are within the range of 0.05 g and 0.1 g, values from northern low-steep fold belt was 0.05 g, and values from western low-steep fold belt are within the range of 0.1 g and 0.2 g. Overall, the central and eastern basin area has the highest stability level.

The large-magnitude earthquake with magnitude 8.0 occurred in Sichuan Wenchuan on May 12, 2008, with its significant influence along the Yingxiu-Beichuan fault zone to Ningqiang County in Shaanxi of Qingchuan fault zone [17]·

A comprehensive analysis showed that the crust stability conditions for carbon dioxide geological storage in Sichuan Basin is relatively high in Central Sichuan low-flat structural belt, but the rest area, including East Sichuan high-slope faulted fold belt, South Sichuan low-slope structural belt, North Sichuan low-flat structural belt, SW low-slope structural belt and West Sichuan low-slope structural belt is unsuitable for carbon dioxide geological storage.

4.3. Reservoir-Cap Combination of CO_2 Geological Storage

Sichuan Basin is an Artesian Basin consisting of Permian and Triassic strata. The first set of regional seal covering the whole basin is Jurassic Shaximiao Group, whereas the second set is Suining Group and Penglaizhen Group. According to field survey, shale content in Shaximiao Group is more than 50%. The Suining Group mainly consists of brown-red mudstone and sandy mudstone with siltstone thin layer. Penglaizhen mainly consists of gray and sandy mudstone, as well as multiple layers of marl and siltstone. These two sets of covering caps are relatively stable [18].

Jurassic is distributed in southeast plateau area, middle gentle uplift, and northwest depressions of Sichuan Basin. Some strata are missing in East Sichuan high-slope faulted fold belt, South Sichuan low-slope structural belt and SW low-slope structural belt except for the middle and lower part. Considering the risk of leakage, only the lower part of Jurassic Ziliujing Group is considered as carbon dioxide geological storage site. Specifically, the lenticular sand body of lower part of Jurassic Ziliujing Group is considered as the exact site for carbon dioxide geological storage.

Water alternating phenomenon is strong around mountains at the edge of the basin or at the eastern separated file fold anticline area. Since it is the infiltration type of fresh water in these places, they are not appropriate for carbon dioxide storage. By contrast, the ancient sealed water with sedimentary origin is found in the deep part of Triassic strata, and this is the right place for carbon dioxide geological storage [19].

According to the research of Wang J. [20] the average porosity of reservoir matrix of fractured sandstone in Sichuan Basin is about 4%, the average porosity of carbonate matrix is less than 2%, and the average porosity of the porous carbonate reservoir is within the range of 4% and 6%, with permeability more than 1 md. By contrast, sandstone porosity is approximately 4.5%, with permeability less than 0.01 md. Therefore, it could be concluded that the distribution of the porosity and permeability in Sichuan Basin is $5 \leq \varphi < 10$ and $K < 1$, which represents less suitable and unsuitable conditions, respectively.

According to Zhang K. [21], based on thickness values of storage reservoirs in Sichuan Basin derived from corresponding contour maps and the areas of different tectonic unit, the volume of secondary tectonic units could be obtained, among which eastern high and steep fold belt accounts for 25.21%, northern low-steep fold belt accounts for 21.25%, western low-steep fold belt accounts for 17.09%, southern low-steep fold belt accounts for 7.56%, southwestern low-steep fold belt accounts for 8.99%, and middle gentle fold belt accounts for 19.9%.

A comprehensive analysis of reservoir-cap in Sichuan basin shows that East Sichuan high-slope faulted fold belt is relatively unsuitable for carbon dioxide geological storage. By contrast, North Sichuan low-flat structural belt, West Sichuan low-slope structural belt, South Sichuan low-slope structural belt and SW low-slope structural belt are relatively suitable, and Central Sichuan low-flat structural belt is the best place for carbon dioxide geological storage.

4.4. Geothermal and Geological Conditions

Geothermal gradient between middle gentle fold belt and SW low-slope structural belt in Sichuan Basin is relatively high, ranging from 24 to 30˚C/km. The geothermal gradient of Weiyuan tectonic zone is more than 30˚C/km. The geothermal gradient between East Sichuan high-slope faulted fold belt and North Sichuan low-flat structural belt gradually decreases to 20˚C/km. Also, the geothermal gradient of the outer edge of the northeastern Sichuan is as low as 16˚C/km. On both sides of Central Sichuan low-flat structural belt and West Sichuan low-slope structural belt, the geothermal gradient is maintained around 20˚C/km. The piedmont fractured developed in northeastern Sichuan could lead to the downward infiltration of groundwater, which would future cause the reduction of local geothermal gradient so that it is much lower than the average level.

Terrestrial heat flow values in Sichuan Basin are within the range of 35.4 and 68.8 mw/m^2, with the average value as 53.2 mw/m^2, which is similar with low heat flow characteristics of other typical cratonic basins all over the word. As to the aspect of regional distribution, terrestrial heat flow is obviously affected by the base structure. Terrestrial heat flow values of uplift area are within the range of 60 and 70 mw/m^2, values of depression area are below 60 mw/m^2, and values could be even less than 40 mw/m^2 near the leading edge of the fold belt of Daba Mountain, which is located in the northeastern Sichuan [22].

According to annual average temperature statistics of the Sichuan Basin, Chongqing, Yibin and Chengdu between 1997 and 2005, the derived average temperature in Sichuan Basin is 17.9˚C. Specifically, the average temperature in East Sichuan high-slope faulted fold belt or South Sichuan low-slope structural belt is 18.6˚C, the average temperature in Central Sichuan low-flat structural belt or southwestern low-steep fold belt is 18.3˚C, and the average temperature in North Sichuan low-flat structural belt or western low-steep fold belt is 16.8˚C [23].

A comprehensive analysis of geothermal geological conditions in Sichuan basin shows that East Sichuan high-slope faulted fold belt, South Sichuan low-slope structural belt, Central Sichuan low-flat structural belt and West Sichuan low-slope structural belt is relatively suitable for carbon dioxide geological storage. By contrast, SW low-slope structural belt and North Sichuan low-flat structural belt are not suitable for carbon dioxide storage purpose.

4.5. Storage Potential Conditions

When CO_2 geological storage potentials in deep saline aquifers are calculated, it is necessary to consider the volume of the aquifer, saturation of CO_2 trapped after formation water countercurrent, porosity of saline aquifer, density of CO_2 under the conditions of formation water, the density of the initial formation water and the solubility of CO_2 in saline aquifers [6].

According to the distributed area and thickness of the reservoir described in 4.3, the reservoir volume of every reservoir located 800 m depth below in every secondary tectonic unit could be calculated, and the evaluation of D grade inferred potential of CO_2 geological storage in deep saline aquifers of secondary tectonic units in Sichuan Basin is shown in **Table 6**.

Based on parameters of CO_2 geological storage potentials in deep saline aquifers, grade D constructive potentials of CO_2 geological storage in every secondary tectonic unit of Sichuan Basin could be calculated, among which storage potentials of East Sichuan high-slope faulted fold belt reach the maximum value and account for 27.55% of the total storage capacity of deep saline aquifers. Also, storage potentials of West Sichuan low-slope structural belt account for 15.62% of the total storage capacity. Storage potentials of Central Sichuan low-flat structural belt account for 20.33% of the total storage capacity. Storage potentials of SW low-slope structural belt account for 7.48% of the total storage capacity. Storage potentials of North Sichuan low-flat structural belt account for 22.30% of the total storage capacity. By contrast, storage potentials of South Sichuan low-slope structural belt have the minimum value and account for 6.72% of the total storage capacity. Storage potentials and per unit area storage potentials of the secondary tectonic units of Sichuan Basin are $0.5 < M \leq 25$ and $1 < m \leq 50$, respectively.

A comprehensive analysis indicates that storage potential conditions of the secondary tectonic units in Sichuan Basin are generally suitable.

Table 6. Evaluation of D grade inferred potential of CO_2 geological storage in deep saline aquifers of secondary tectonic units in Sichuan Basin.

Type of storage Tectonic unit	Saline aquifers	East Sichuan high-slope faulted fold belt	South Sichuan low-slope structural belt	Central Sichuan low-flat structural belt	SW low-slope structural belt	North Sichuan low-flat structural belt	West Sichuan low-slope structural belt
D grade inferred potential of residual gas mechanism ($\times 10^6$t)	Jurassic Ziliujing Formation	383.97	175.95	219.77	128.80	227.79	208.00
	The Upper Triassic Xujiahe Formation	455.83	226.34	276.64	135.26	280.94	312.00
	The Middle Triassic Leikoupo Formation	939.60	0.00	2433.17	988.01	1556.56	2273.52
	The Middle Triassic Jialing River Formation	5972.84	1144.29	2852.89	864.51	3097.99	2614.89
	The lower Triassic Feixianguan Formation	3127.35	1144.29	2093.66	864.51	3769.42	796.26
	Lower Permian Qixia Formation	-	-	-	-	-	142.10
	total	10879.58	2690.86	7876.14	2981.10	8932.70	6346.77
Grade inferred potential of dissolution mechanism ($\times 10^6$t)	Jurassic Ziliujing Formation	28.49	14.70	14.76	11.83	8.95	8.93
	the Upper Triassic Xujiahe Formation	19.04	10.64	15.50	6.99	11.04	13.40
	The Middle Triassic Leikoupo Formation	18.12	0.00	293.64	51.09	28.26	57.43
	The Middle Triassic Jialing River Formation	443.16	53.81	222.78	44.71	121.79	112.31
	The lower Triassic Feixianguan Formation	182.02	53.81	117.31	44.71	263.27	15.79
	Lower Permian Qixia Formation	-	-	-	-	-	3.59
	total	690.82	132.97	663.98	159.34	433.31	211.45
Total ($\times 10^6$ t)		11570.40	2823.83	8540.12	3140.43	9366.01	6558.22

4.6. Research Levels and Resource Potentials

The exploration of Sichuan basin could be considered as under a developmental state. Each secondary tectonic unit has its own drilling well control system so that the suitability assessment could be done based on the information of local resource potentials. According to the latest resource evaluation results of 2002, oil resources are only founded in the middle, eastern and northern blocks of Sichuan basin, among which the middle block of the basin has the highest level of oil storage, accounting for 48% of total oil storage. By contrast, the eastern and northern blocks of Sichuan basin have 29% and 23% of total oil storage, respectively. By contrast, gas resources are found in all six blocks of the basin, among which the eastern block has the highest level of gas storage, accounting for 43.26% of total gas storage. For other blocks, gas storage from the highest to the lowest level is in the order of western block (23.46%), middle block (12.43%), northern block (9.65%), southwestern block (6.22%) and southern block (4.98%) [24].

A comprehensive analysis reveals that both the Central Sichuan low-flat structural belt and the East Sichuan high-slope faulted fold belt are highly suitable in terms of research levels and resource potentials of the secondary tectonic units. Similarly, North Sichuan low-flat structural belt is relatively suitable, and West Sichuan low-slope structural belt is fairly OK. By contrast, South Sichuan low-slope structural beltand SW low-slope structural belt are unsuitable.

4.7. Social and Economic Conditions

According to the national standard *Land Use Classification* [25], remote sensing technique has been applied to Sichuan basin in order to better understand current land use status, with land use status of six secondary tectonic units shown in **Table 7**.

According to relevant report [26], the statistics of population density within different secondary tectonic units could be derived. The density of eastern high and steep fold belt is 350 persom/km^2, the density of southern low-steep fold belt is 335 person/km^2, the density of middle gentle fold belt is 490 person/km^2, the density of southwestern low-steep fold belt is 418 person/km^2, the density of North Sichuan low-flat structural belt is 275 person/km^2, and the density of West Sichuan low-slope structural belt is 591 person/km^2.

5. A Comprehensive Evaluation

The partition evaluation results of Sichuan Basin second-grade structural units' suitability is as shown in **Figure 3**, **Table 8** and **Table 9**. The subsurface reservoirs are Lower Jurassic Ziliujing Formation, Upper Triassic Xujiahe Formation, Middle Triassic system Leikoupo Formation, Lower Triassic system Jialingjiang Formation and Feixianguan Formation, and the Qixia Formation in the lower part of Permian System. There is a risk of leakage in Huanyin fault zone in the reservoir of Lower Jurassic Ziliujing Formation, Upper Triassic systems Xujiahe Formation and Triassic system Leikoupo formation, but due to the impact of the Longmenshan and Huanyin thrust fault smearing, the reservoir of Lower Triassic Jialingjiang Formation, Feixianguan Formation and the lower part of Permian Qixia Formation have a sealing effect for the goal reservoir to some extent (**Figure 4**).

Table 7. Descriptions of land use area in Sichuan Basin.

Tectonic units	Agricultural acreage (km^2)	Settlement (km^2)	Woodland (km^2)	Water body (km^2)	Bare land (km^2)
East Sichuan high-slope faulted fold belt	27124.3	152.5	21518	742.7	
South Sichuan low-slope structural belt	14945.8	32.9	11600.8	515.1	162.5
Central Sichuan low-flat structural belt	35242.9	49.6	335.1	1268.9	
SW low-slope structural belt	14928	80.2	5926.4	371.5	133.5
North Sichuan low-flat structural belt	22782.7	27.8	10761.4	392.4	
West Sichuan low-slope structural belt	17445.9	250.2	12869.9	1699.8	902.3

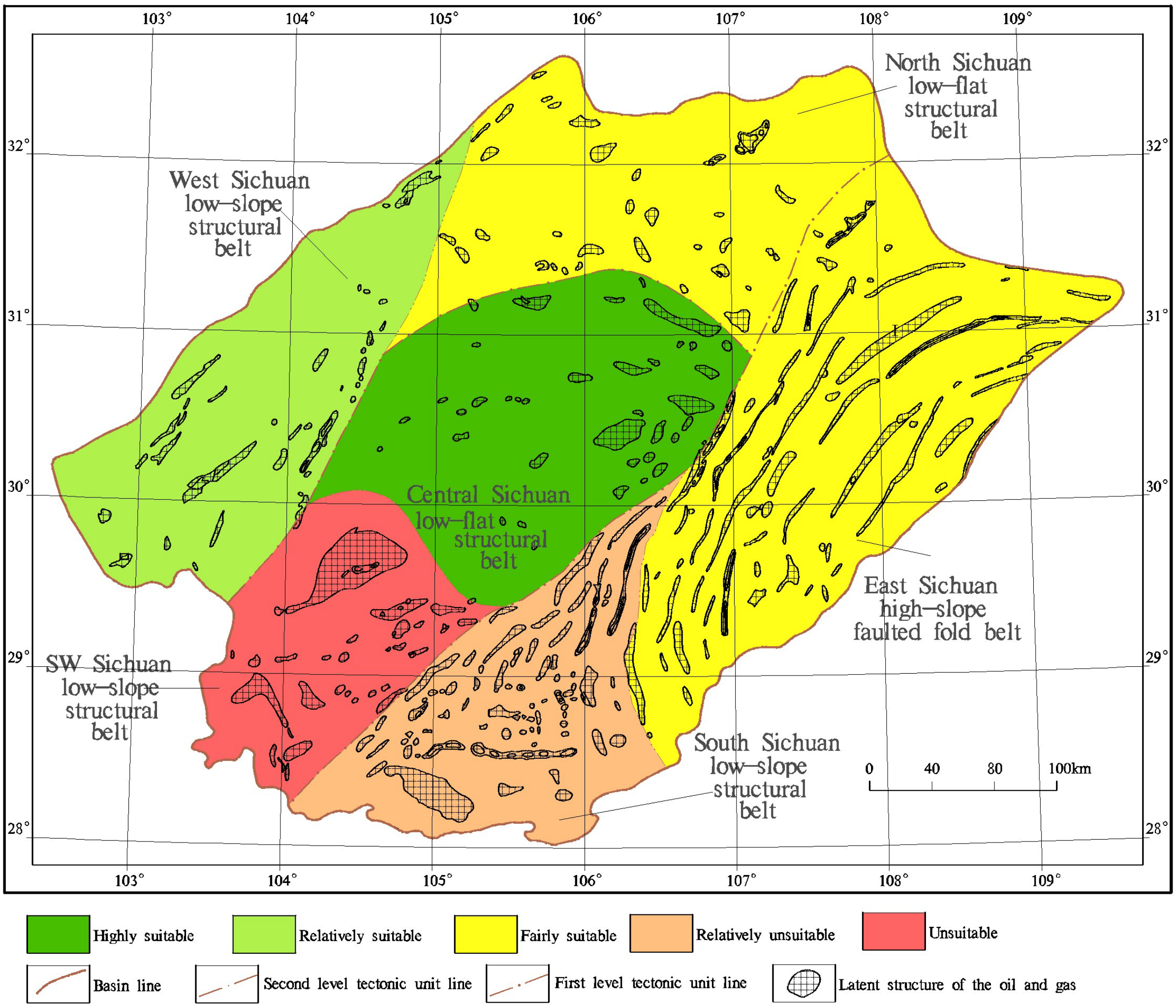

Figure 3. Map showing of a comprehensive evaluation result.

Table 8. P value and Evaluation result table.

Tectonic units	P value	Normalization result	Evaluation result
West Sichuan low-slope structural belt	5.24	0.079	Relatively suitable
SW low-slope structural belt	5.06	0.000	Unsuitable
South Sichuan low-slope structural belt	5.79	0.320	Relatively unsuitable
East Sichuan high-slope faulted fold belt	6.03	0.425	Fairly suitable
North Sichuan low-flat structural belt	6.42	0.596	Fairly suitable
Central Sichuan low-flat structural belt	7.34	1.000	Highly suitable

Fractured water-bearing formation of Carbonate rock is mainly developed in the east side of hanging wall in the Huanyin mountains fault, and the carbonate rock fissure cave water outcrops in the form of spring. The leaking of the fault spring in the west side are mainly far away from the fault, having nothing to do with the deep fault; and west side part which is near the fault, have no spring water dew point [27] [28]. It can be inferred that the footwall of the west side of Huanyin mountains fault has good water-blocking properties, and can produce fault sealing effect, so it is good for deep saline aquifers geological storage of carbon dioxide. Therefore, it can be determined that as for reservoir of the Lower Triassic Jialingjiang Formation, Feixianguan Formation

Table 9. Sichuan Basin geological storage of carbon dioxide suitability evaluation results.

Weight of first level	Index layer	Indicator	Weight of Second level	East Sichuan high-slope faulted fold belt			South Sichuan low-slope structural belt			Central Sichuan low-flat structural belt		
				Decription	Assignment	Index value	Decription	Assignment	Index value	Decription	Assignment	Index value
0.33	stability	stability	1	Less	3	0.99	Less	3	0.99	stable	7	2.31
0.27	Basic geology	Area (km^2)	0.5	50000	9	1.22	26000	9	1.22	37000	9	1.22
		sediment depth (m)	0.5	10000	9	1.22	8000	9	1.22	9000	9	1.22
0.04	research degree and resource potential	exploration degree	0.75	developing	9	0.27	developing	9	0.27	developing	9	0.27
		Data support	0.13	Completed, reliable	7	0.04	Completed, reliable	7	0.04	Completed, reliable	7	0.04
		coal/oil gas resource	0.12	plenty	3	0.01	plenty	3	0.01	plenty	3	0.01
0.02	socio-economy	population density	0.86	transition region	5	0.09	Core densely district	1	0.02	Core densely district	1	0.02
		condition of land use	0.14	Woodland, farmland	5	0.01	Residential & Transport	1	0.00	Residential & Transport	1	0.00
0.06	Thermal geology	Surface temperature (˚C)	0.14	18.6	3	0.03	18.6	3	0.03	18.3	3	0.03
		Terrestrial heat flow ($mW \cdot m^{-2}$)	0.14	50	9	0.08	50	9	0.08	70	5	0.04
		Geothermal gradient [$˚C \cdot 100\ m^{-1}$]	0.71	2-2.5	7	0.30	2.5-3	7	0.30	2.5-3	7	0.30
0.1	Inferred storage potential	Total (10^8 t)	0.83	115.7	9.0	0.75	28.2	7.0	0.58	85.4	9.0	0.75
		Unit (10^4 t/km^2)	0.17	23.1	3	0.05	10.9	3	0.05	23.1	3	0.05
0.17	Reservoir and cap-rock	Reservoir condition	0.43	20.9	5	0.37	21.2	5	0.37	17	3	0.22
		cap-rock conditions	0.43	6.7	7	0.51	6.7	7	0.51	8.2	9	0.66
		Reservoir and cap-rock conditions	0.14	regional, mainly independent	5	0.12	regional, mainly independent	5	0.12	regional	9	0.21
comprehensive index					6.03			5.79			7.34	

Weight of first level	Index layer	indicator	weight of Second level	SW low-slope structural belt			North Sichuan low-flat structural belt			West Sichuan low-slope structural belt		
				Decription	assignment	Index value	Decription	assignment	Index value	Decription	assignment	Index value
0.33	stability	stability	1	Not stable	1	0.33	Less	3	0.99	Not stable	1	0.33
0.27	basic geology	Area (km^2)	0.5	21000	9	1.22	34000	9	1.22	32000	9	1.22
		sediment depth (m)	0.5	7000	9	1.22	12000	9	1.22	10000	9	1.22
0.04	research degree and resource potential	exploration degree	0.75	developing	9	0.27	developing	9	0.27	developing	9	0.27
		Data support	0.13	Completed, reliable	7	0.04	Completed, reliable	7	0.04	Completed, reliable	7	0.04
		coal/oil gas resource	0.12	plenty	3	0.01	less	1	0.00	plenty	3	0.01
0.02	socio-economy	Population density	0.86	Core densely district	1	0.02	sparsely	9	0.15	Core densely district	1	0.02
		condition of land use	0.14	Residential & Transport	1	0.00	Woodland, farmland	5	0.01	Residential & Transport	1	0.00
0.06	Thermal geology	Surface temperature (˚C)	0.14	18.3	3	0.03	16.8	3	0.03	16.8	3	0.03
		Terrestrial heat flow ($mW \cdot m^{-2}$)	0.14	70	5	0.04	50	9	0.08	70	9	0.08
		Geothermal gradient [$˚C \cdot 100\ m^{-1}$]	0.71	3 - 3.5	5	0.21	1.5 - 2	9	0.38	2 - 2.5	7	0.30
0.1	Inferred storage potential	Total (10^8 t)	0.83	31.4	3.0	0.25	93.7	9.0	0.75	65.6	9.0	0.75
		Unit (10^4 t/km^2)	0.17	15.0	3	0.05	27.5	3	0.05	20.5	3	0.05
0.17	Reservoir and cap-rock	Reservoir condition	0.43	26.8	9	0.66	24.7	7	0.51	17.6	3	0.22
		cap-rock conditions	0.43	6.7	7	0.51	6.7	7	0.51	5.8	7	0.51
		Reservoir and cap-rock conditions	0.14	regional	9	0.21	regional	9	0.21	regional	9	0.21
comprehensive index					5.06			6.42			5.24	

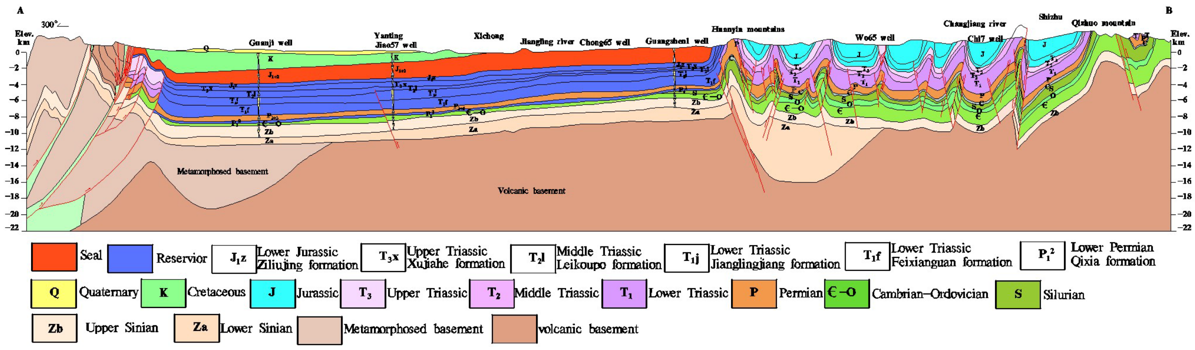

Figure 4. Geological profile across the basin along the line A-B in **Figure 2** (Blue formations indicate the saline aquifers and red formation are the caprock seal).

and Lower Permian Qixia Formation, the gently fold belt reservoir in the middle part of Sichuan can be used as geological goal targets. As for the reservoir of Lower Jurassic Ziliujing formation, Upper Triassic Xujiahe formation, and Triassic system Leikoupo Formation, where exists the risk of leakage in Huanyin mountains fault zone, the furthest areas from structure unit boundary faults zone should be selected for the best.

6. Discussion

Since the secondary tectonic units within the basin are considered as research objects, the scope of corresponding evaluation objects are narrowed to some extent. However, to achieve the goal that the storage of carbon dioxide reaches the ultimate state, *i.e.*, the mineralized storage state, a completely enclosed space is required strictly. Regarding the closed space issues, the smearing effect displayed by the fault rupture of Huanyin mountain just has a sealing function theoretically for the lower Triassic Jialing group, Feixianguan and lower Permian Qixia Formation reservoir, but its closed fracture feature is very complex and deserves more in-depth analysis.

For the six geological targets determined preliminarily, borehole data should be used to analyze the sedimentary microfacies of these six targets located at different geological layers. For area with less borehole data available, microfacies analysis should be applied in order to establish the physical model of geological targets and carry out corresponding numerical simulation work.

7. Conclusions

The suitability assessment of the secondary tectonic units in Sichuan Basis shows that middle gentle fold belt is relatively suitable. Eastern high and steep fold belt, southwestern low-steep fold belt and North Sichuan low-flat structural belt are quite unsuitable, and western and southwestern low-steep fold belts are unsuitable.

The underground reservoirs of six geological targets include lower Jurassic Ziliujing Group, upper Triassic Xujiahe Group, middle Triassic Leikoupo Group, lower Triassic Jialingjiang Group, lower Triassic Feixianguan Group and lower Permian Qixia Group.

References

[1] Fan, J., Jia, X. and Zhang, S. (2011) Methods and Assessments of CO_2 Geological Storage Potentials and Suitability. *Hydrogeology and Engineering Geology*, **38**, 108-112. (in Chinese)

[2] Fan, J., Zhang, S. and Zheng, B. (2011) CO_2 Geological Storage Potentials and Map Compilation Method for Suitability Assessment. *Hydrogeology and Engineering Geology*, **38**, 101-105. (in Chinese)

[3] Guo, J., Zhang, S. and Diao, Y. (2011) Site Selection Technology and Engineering Methods for Deep Saline Aquifer CO_2 Geological Storage. *Jilin University* (*Earth Science Edition*), **41**, 1084-1091. (in Chinese)

[4] Diao, Y., Zhang, S. and Guo, J. (2012) Selection and Evaluation of Deep Saline Aquifer Sites for Carbon Dioxide Geological Storage. *Rock and Soil Mechanics*, **33**. (in Chinese)

[5] Zhang, S., Guo, J. and Diao, Y. (2012) Selection Methods for Deep Saline Aquifer CO_2 Geological Storage Sites at Large Scale. *Chinese Geology*, **38**, 1640-1651. (in Chinese)

[6] Bachu, S., Bradshaw, J., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N.P. and Mathiassen, O-M. (2007) CO_2 Storage Capacity Estimation: Methodology and Gaps. *International Journal of Greenhouse Gas Control*, **1**, 430-443.

http://dx.doi.org/10.1016/S1750-5836(07)00086-2

[7] Bachu, S. (2003) Screening and Ranking of Sedimentary Basins for Sequestration of CO_2 in Geological Media. *Environmental Geology*, **44**, 277-289. http://dx.doi.org/10.1007/s00254-003-0762-9

[8] Oldenburg, C.M. (2008) Screening and Ranking Framework for Geologic CO_2 Storage Site Selection on the Basis of Health, Safety, and Environmental Risk. *Environmental Geology*, **54**, 1687-1694. http://dx.doi.org/10.1007/s00254-007-0947-8

[9] Doughty, C., Freifeld, B.M. and Trautz, R.C. (2008) Site Characterization for CO_2 Geologic Storage and Vice Versa: The Frio Brine Pilot, Texas, USA as a Case Study. *Environmental Geology*, **54**, 1635-1656. http://dx.doi.org/10.1007/s00254-007-0942-0

[10] Meyer, R. and May, F. (2008) Regional Search, Selection and Geological Characterization of a Large Anticlinal Structure, as a Candidate Site for CO_2-Storage in Northern Germany. *Environmental Geology*, **54**, 1607-1618. http://dx.doi.org/10.1007/s00254-007-0939-8

[11] Gupta, N. and Cumming, L. (2013) Assessment of Carbon Dioxide Storage Sichuan Basin, Hechuan, China. Draft Final Report.

[12] Xu, J., Ma, Z., Zhang, T. and Zhu, H. (2005) Fuzzy Indexes for Geological Environment Quality Evaluation in Bohai area, Shandong Province. Coastal Engineering Geological Environment and Urban Development, 262. (in Chinese)

[13] Li, G. and Lu, M. (1988) Atlas of Chinese Petroliferous Basins. Petroleum Industry Press. (in Chinese)

[14] Yang, X.K. (2012) Tectonic and Sedimentary Basin Evolution and Suitability Assessment of Carbon Dioxide Geological Storage Sites in China. (in Chinese).

[15] Zhang, J. and Huang, Ch. (2009) Sichuan Earthquake Hazard Risk Analysis. *Tropical Geography*, **29**, 280-284. (in Chinese)

[16] Hu, Y. (2001) GB18306-2001 "Chinese Ground Motion Parameter Zoning Map" Publicizing Materials. Standard Press of China. (in Chinese)

[17] Peng, H., Ma, X. and Jiang, J. (2009) Fault Stress Measurement and Stability Assessment in Northern Longmen Shan fault of Green River. *Geomechanics*, **15**, 114-130. (in Chinese)

[18] Wang, M., Bao, C. and Xiao, M.D. (1989) Petroleum Geology of China (Volume Ten)(in Chinese), Sichuan Oil and Gas District.

[19] Lin, T. and Chen, S. (2008) Exploration and Development Prospect of Underground Brine in Sichuan. *Salt Lake Research*, **16**, 1-7. (in Chinese)

[20] Wang, J. (2004) Sichuan Petroleum Geology. *Petroleum Geology*, **26**, 115-120. (in Chinese)

[21] Zhang, K. and Zhang, S. (2007) Research on the Deposition in Sichuan Basin. (in Chinese).

[22] Xu, M., Zhu, C. and Tian, Y. (2011) Basin Borehole Temperature Measurements and Current Geothermal Features. *Geophys*, **54**, 1052-1060. (in Chinese)

[23] Fei, Y. (2007) The Change of Temperature Trends in Sichuan within Fifty Years. *Plateau Mountain Meteorology Research*, **27**, 21-22. (in Chinese)

[24] Ma, Y., Cai, X. and Zhao P. (2010) Distribution Patterns and Exploration Methods of Medium-Sized Gas Fields in Sichuan Basin. *Petroleum Technology*, **31**, 347-354. (in Chinese)

[25] 2007 GB T. Land Use Classification Criteria, 2007. (in Chinese)

[26] National Bureau of Statistics in 2010, the Sixth National Census Data Bulletin. China National Bureau of Statistics, Beijing, 2011. (in Chinese)

[27] Chen, X.M. (1977) Chongqing Amplitude (H-48-23) 1/20 000 Regional Hydrogeological Investigation Report.

[28] Xie, Y.X. (1981) Guang'an Amplitude (H-48-17) 1/20 000 Regional Hydrogeological Survey Report.