Geological Suitability and Capacity of CO_2 Storage in the Jiyang Depression, East China

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Abstract

Carbon dioxide Capture and Storage (CCS) is an effective technology to reduce carbon dioxide (CO_2) emissions in China. In this paper, the authors considered storage opportunities offered by oil reservoirs and deep saline aquifers in the Jiyang Depression, East China. Based on detailed geological analysis and assessment of CO_2 storage suitability, the Dongying Sag and Linyi-Shanghe areas of the Huimin Sag within the Jiyang Depression appear promising for CO_2 storage. Following more detailed characterization, the 2nd member and 3rd member of the Shahejie Formation located in these two areas appear the most promising for CO_2 storage. Within the areas identified as having potential for storage, 55 primary and 62 secondary recommended storage units were defined, with a total theoretical capacity of 5.02×10^8 tonnes (t) CO_2. This represents storage of CO_2 emissions from large–scale sources in the Jiyang Depression for more than 30 years at current emission rates.

Keywords: CO_2, CO_2 storage, CCS, Jiyang Depression, potential

1 Introduction

As a developing country, fossil fuels dominate energy consumption in China. Smog, which results from fossil fuel combustion, is frequently an issue for major cities in China and has attracted attention from all over the world. At the 21st Conference of the Parties to the UN Framework Convention on Climate Change (COP21), China pledged that CO_2 emissions would peak by around 2030 or sooner. Carbon dioxide Capture and Storage (CCS), a highly effective technology capable of large-scale reduction of emissions from fossil fuels, will be essential in reducing CO_2 emissions [1]. According to the new Five-Year Plan (2016-2020) of the Ministry of Industry and Information Technology of the People's Republic of China, the Chinese government will develop CCUS (Carbon dioxide Capture, Utilisation and Storage) demonstration plants in high-emission industries (chemical, cement, steel etc.) and reduce the CO_2 emissions per unit of industrial added value by 22% within the next five years.

Chinese researchers have carried out many case studies of CO_2 storage in important hydrocarbon-bearing basins of China [2-10]. However, few assessments consider the Jiyang Depression. This structure is one of the most important sedimentary basins in China as it is geographically large with multiple potential reservoir and seal formations and the Shengli Oilfield (the third largest oil field in China) is located here. After more than 50 years of hydrocarbon exploration and development, the Jiyang Depression is deemed to have CO_2 storage potential, as depleted hydrocarbon reservoirs and deep saline formations offer potential CO_2

storage options that are widely considered in similar assessments in a number of countries [11].

The geological setting, including reservoir properties, potential seals, hydrogeology, formation temperature and pressure conditions, and regional crustal stability were analysed in this study. The scoring system uses 43 weighted criteria. The results of this storage site evaluation are presented here.

2 Geological Setting

2.1 Regional geology

The Jiyang Depression lies at latitude 37° to 38°, and longitude 116°40’ to 119°; and has an area of 26,500 km^2. It lies in the south of the Bohai Bay Basin and is surrounded by several geological uplifts and depressions. The metamorphic basement of the Jiyang Depression formed during the Archeozoic Eon (Fig. 1).

The depression itself is a fault-bounded basin, developed through several stages: slow uplift during the Paleozoic Era, strong folding during the Permian to Triassic periods, rifting during Jurassic to Cretaceous times, syn-rift extension and subsidence during the Paleogene Era and post-rift subsidence during the Neogene and Quaternary Eras [12, 13].

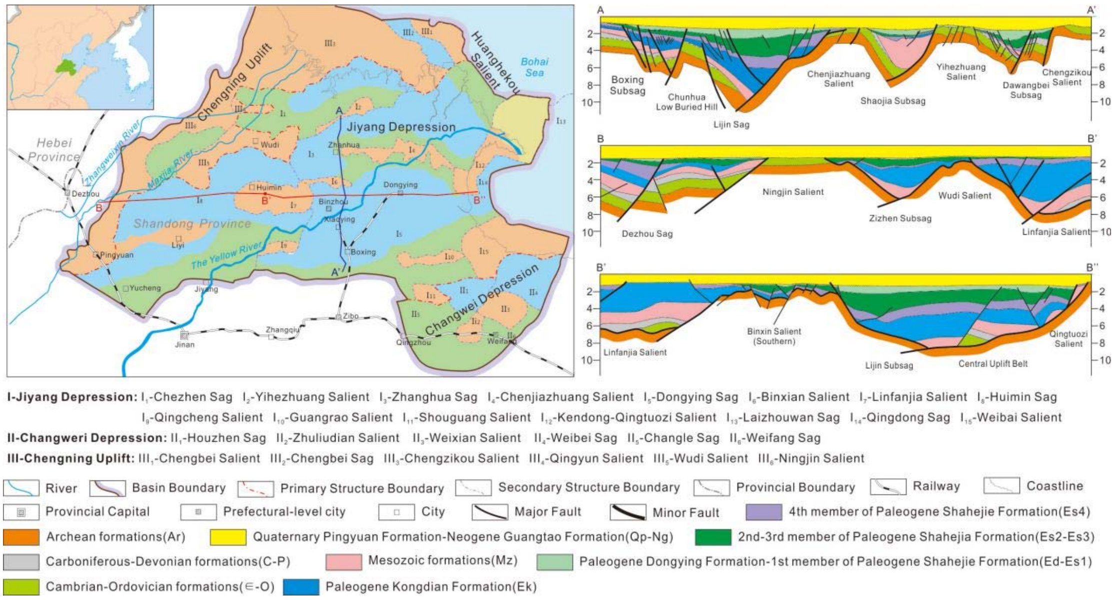

Figure 1. Geological structure of the Jiyang Depression (The map and cross sections were modified from Li, Gy et al (2002) [14].)

2.2 Sedimentary geology

Based on available core, seismic and geophysical log data, the Cenozoic strata have a thickness of more than 10,000 m in the Jiyang Depression. The thickness of Paleogene sediments is greatest in the center of the depression, reaching about 7,000 m and decreasing towards the edges. In some areas, Paleogene sediments are entirely missing due to erosion. The Quaternary and upper Neogene sediments are 1,000 to 2,000 m thick and are present across the whole depression. Cenozoic strata contain mature source rocks and ideal seals and reservoirs for hydrocarbons, which has enabled the formation of large oilfields (Fig. 2).

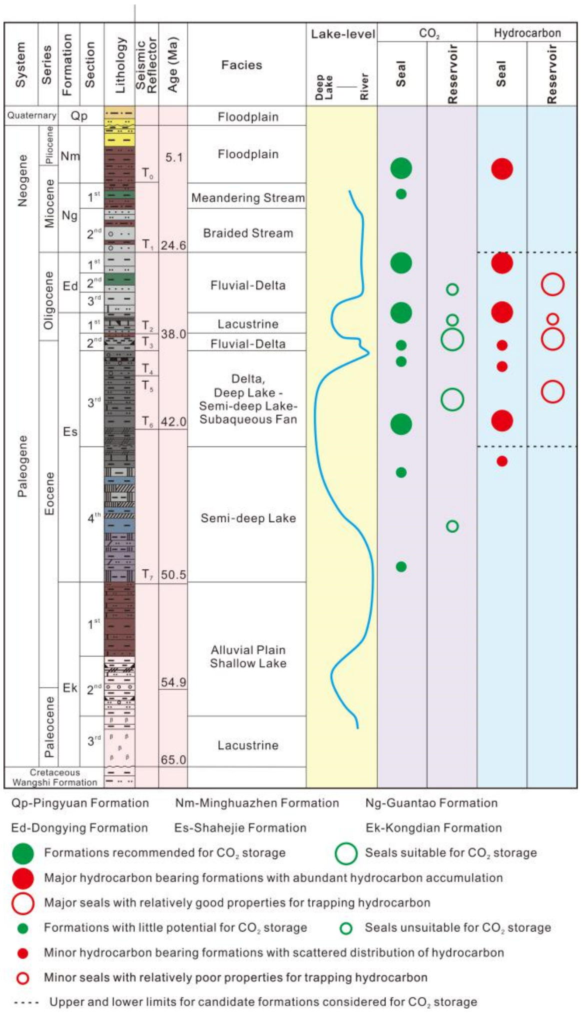

Figure 2. Stratigraphic column of the Jiyang Depression. (The sizes of red/green circles under column 'seal' indicate the expected ability of seals to trap hydrocarbon or injected CO_2; the sizes of red/green circles under column 'reservoir' indicate the assessed suitability and potential for hydrocarbon accumulation or CO_2 storage; please see section 3.2 and 3.3 for detail)

3 Potential storage area in Jiyang Depression

3.1 Candidate formations

In general, 800m is considered the shallowest depth suitable for CO_2 storage as CO_2 should be in a dense state [15, 16]. Based on geophysical log data, the Neogene

Guantao Formation (Ng) is present across the whole depression at depths greater than 800 m, with a few exceptions at the southeast edge. The base of the Guantao Formation is the seismic reflection T1 and second-order sequence boundary Tsb1 [17] in Figure 2. The base of this formation is also important in terms of structure and hydrogeology; across this boundary, hydrodynamic conditions, regional structural characteristics and tectonic stress field clearly change. The base of the Guantao Formation seems a reasonable upper limit for candidate formations for CO_2 storage in the Jiyang Depression.

Due to large-scale hydrocarbon exploration and development, formations above 4000 m depth have been studied and described fully in previous studies. However, since reservoirs are absent below 4000 m, detailed data of formations below this depth are not available. Therefore, the authors used 4000 m as the lower limit of candidate CO_2 storage formations for the purposes of this study. Between these two limits, the Dongying Formation (Ed) and the Shahejie Formation (Es) were chosen for assessment.

3.2 Reservoirs

There are several sedimentary facies present in the Jiyang Depression. For the candidate formations identified above, the depositional facies are mainly nearshore subaqueous fan, turbidite fan, fan delta, shallow lake, lake shore and beach-barrier deposits [18]. The lithology of the Dongying and Shahejie formations is mainly sandstone with medium grain sorting and sphericity, and low maturity.

Several reservoirs are present in the Dongying and Shahejie formations (Fig. 3). For the reservoirs in the same formation but different parts of the depression, the physical properties, such as porosity and permeability are usually variable, which needs to be taken into consideration when selecting potential storage sites. The most promising reservoir is located in the 2nd member of the Shahejie Formation (Es2). Across the depression this formation has a maximum thickness of 500 m, porosity of 13.3~33.7%, permeability of 13.3~32000mD and depth of about 2000 m. The formation mainly comprises multiple sandstone layers and sandy mudstone strata.

The physical properties of the 3rd member of Shahejie Formation (Es3) vary with depth. Minimum porosity and permeability in the formation are 12.4% and 4 mD respectively, while the maximum are 35.35% and 11000 mD. The lithology of the formation comprises pebbly sandstone, siltstone, sandstone intercalated with mudstone, and oil shale. The 3rd member of the Shahejie Formation generally has a total thickness of 250 - 1500m; but in some parts of the depression, this formation is absent or classic reservoirs are not developed (Fig. 3).

Potential storage reservoirs are also found in the Dongying Formation and the 4th member of Shahejie Formation (Es4). Across the Jiyang Depression, the Dongying Formation contains alternating beds of sandstone and mudstone, with a porosity 17.59~35.2% and permeability 192~5500 mD. Although the maximum thickness is more than 600 m, in some parts of the depression, the formation is absent due to erosion at relatively shallow depths (Fig. 3). The upper part of the 4th member of the Shahejie Formation contains limestone and bioclastic limestone, providing an additional opportunity to store CO_2. In the uplifted part of the Jiyang Depression, the depth of the 4th member of the Shahejie Formation is greater than 2500 m, while in the sag part of the depression it usually lies at depths greater than 3000 m or even 5000 m, so in some places it is below the lower depth limit suggested for CO_2 storage in the Jiyang Depression.

Across the Jiyang Depression, the 1st member of the Shahejie Formation (Es1) is dominated by mudstone. Only scattered reservoirs are found amongst continuous mudstones, these reservoirs have average porosity of 14.9-35.9% and permeability of 16.05-5500 mD. This member is not considered ideal for CO_2 storage since the reservoirs are small and scattered.

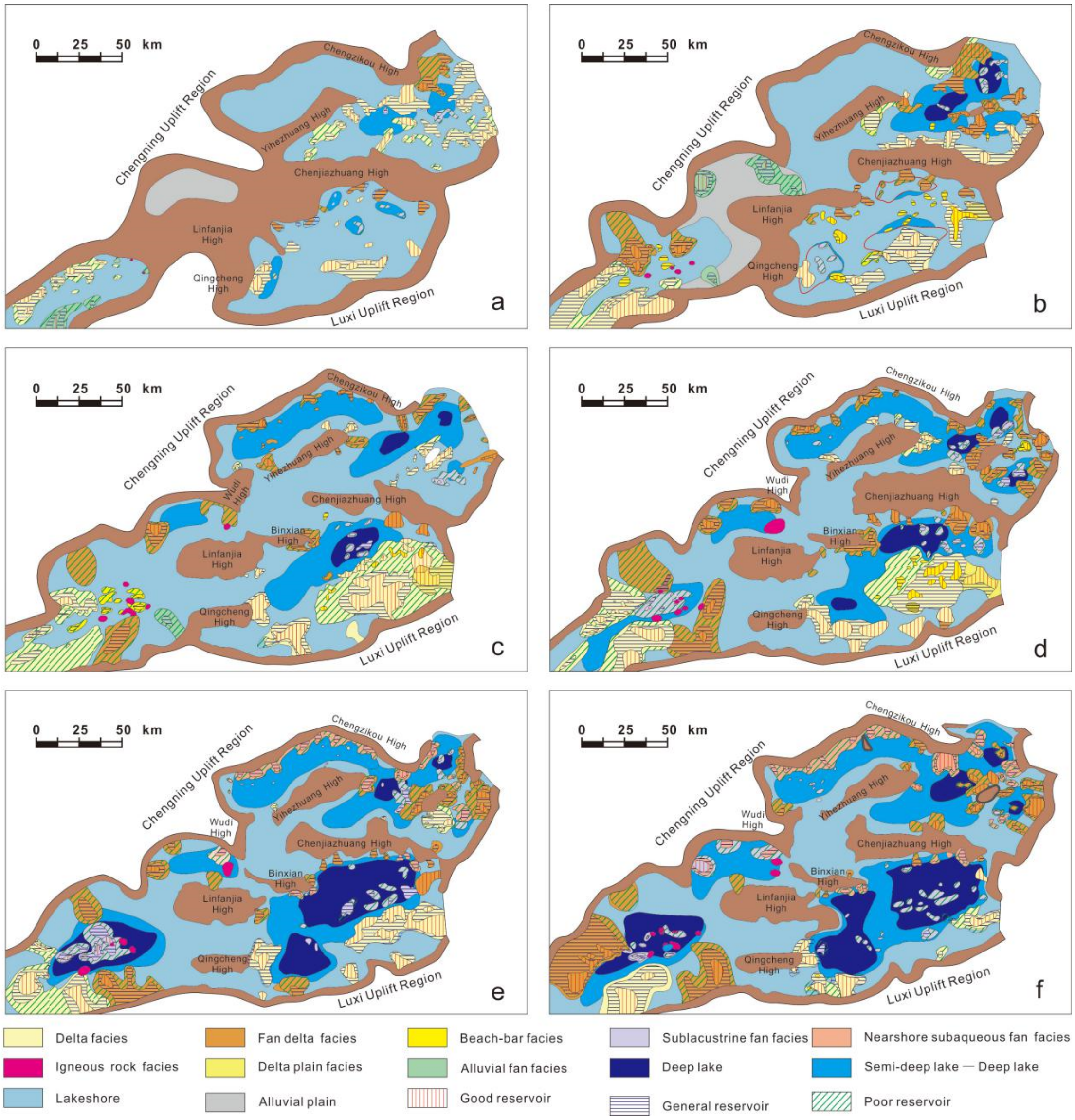

Figure 3. The distribution of sedimentary facies and reservoirs in the Jiyang Depression (a. Lower Es3 formations; b. Middle Es3 formations; c. Upper Es3 formations-Lower Es2 formations; d. Upper Es2 formations-Es1 formations; e. Ed3 formations-Ed2 formations; f.Ed1 formations) [17]

3.3 Seals

As the Dongying Formation (Ed) and the Shahejie Formation (Es) were chosen for assessment, the seals under consideration in the Jiyang Depression comprise thick mudstone layers in the upper Guantao Formation (Ng), mudstone and shale layers in the 1st member of the Shahejie Formation; and mudstone and gypsum layers in the 3rd and 4th members of the Shahejie Formation.

The mudstones of the Guantao Formation are present across the whole Jiyang Depression, without absence or breaks and thus constitute the regional seal that covers all the underlying formations. Although the porosity is relatively high (>20% in some areas), the net thickness of mudstone layers is quite large (Table 1). With increasing formation depth, the disconnection of mudstone seals begins to appear in the uplifted parts of the depression; while in the sag parts the mudstone is continuous (Fig. 4), where the porosity of seals is low (5-20%) and ultra-low (<5%). The measurement of displacement pressure and sealed gas column height also indicate that all the seals have sufficient sealing ability for gas (Table 1). Moreover, the 2nd and 3rd members of the Shahejiang Formation contain the most important natural gas reservoirs of the Jiyang Depression, and also some natural CO_2 reservoirs [21, 22], which offers supplementary evidence that these seals would be expected to prevent gases from escaping, including CO_2.

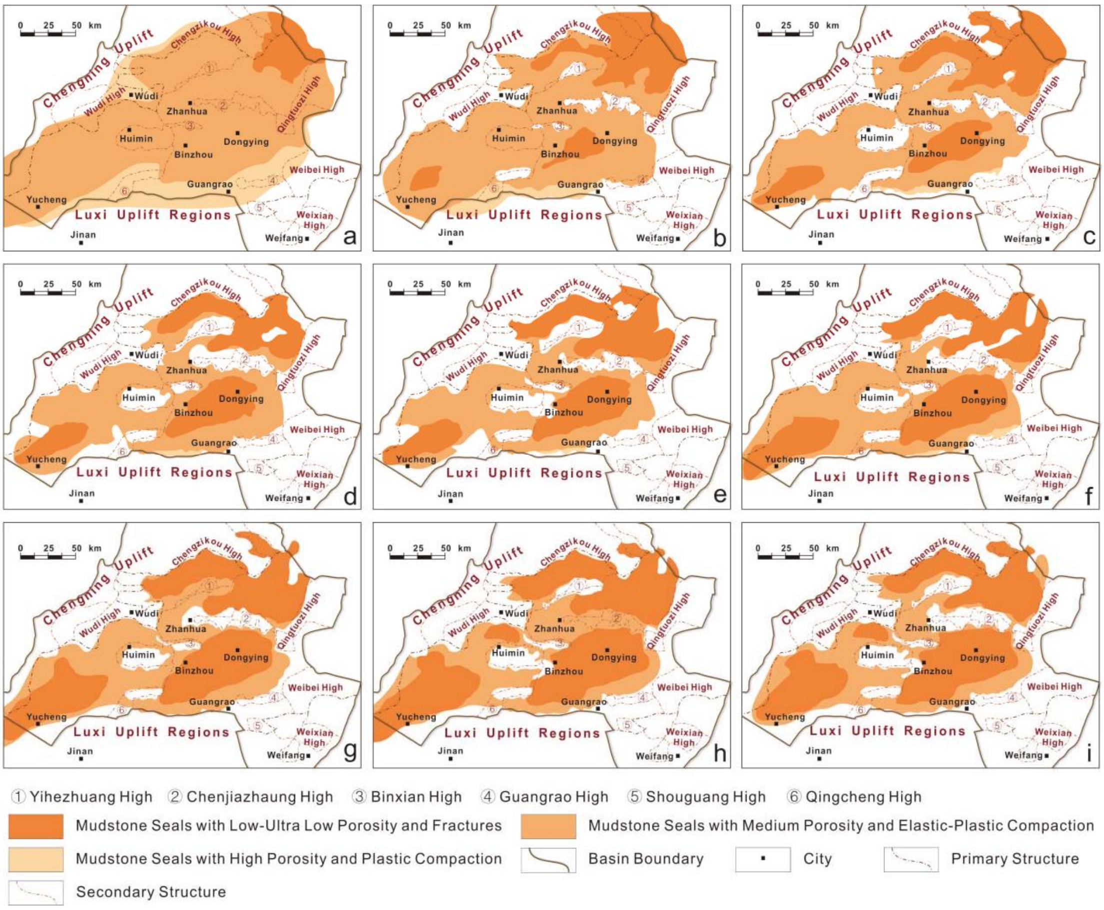

Figure 4. Distribution and classification of mudstone seals in the Jiyang Depression (modified from Wang YJ(2002) [23]; a. Ng formations; b. Ed formations; c. Es1 formations; d. Upper Es2 formations; e. Lower Es2 formations; f. Upper Es3 formations; g. Middle Es3 formations; h. Lower Es3 formations; i. Upper Es4 formations)

3.4 Hydrogeology

According to the classification of salinity of groundwater in China [26], over 50% of the aquifers in the Dongying and Shahejie formations are saline, while the proportion of aquifers with highly brackish water and brine are 10-30% and 5-25% respectively. Water with high salinity cannot be used as drinking or irrigation water, which means there is currently no conflict of interest with water supply in considering these formations for CO_2 storage.

The overall salinity of aquifers in the southern part of the Jiyang Depression (Dongying Sag and Huimin Sag), is usually more than 40 g/L (even reaching up to 350 g/L), which is much higher than the observed salinity of 10-20 g/L in the northern part of the depression (Chezhen Sag and Zhanhua Sag). The Na^+/Cl^- ratio of aquifers in the southern part of the depression is usually lower than in the northern part (Na^+/Cl^- ratio is the ratio of the concentrations of sodium and chloride ions, which is an important indicator of formations tightness and groundwater activity; the higher the value is, the greater the impact of infiltration water on groundwater). Analysis shows that the minimum Na^+/Cl^- ratio in the Jiyang Depression is 0.6, which appears in the middle of the Doingying Sag, while the maximum ratio of 1.3 is found in the Chezhen Sag [27]. These data indicate that meteoric water infiltrate the groundwater from the northern part of Jiyang Depression. According to V. A. SuLing's theory [28, 29], the type of groundwater in the southern part of the depression is completely different from that found in the northern part of the depression (Fig. 5), which also suggests that in the southern Jiyang Depression, the formations are more isolated with weaker groundwater activity compared with the northern part. In addition, hydrodynamic studies show that although each sag in the Jiyang Depression has its own hydrodynamic system, the phreatic water head of the Quaternary strata has overall control, which is the cause of the stagnant state of groundwater in the Jiyang Depression as a whole [30-38]. Good sealing conditions and low groundwater activity will reduce the risk of CO_2 leakage caused by groundwater flow and so these indicators are also seen a positive factor for CO_2 storage in this region.

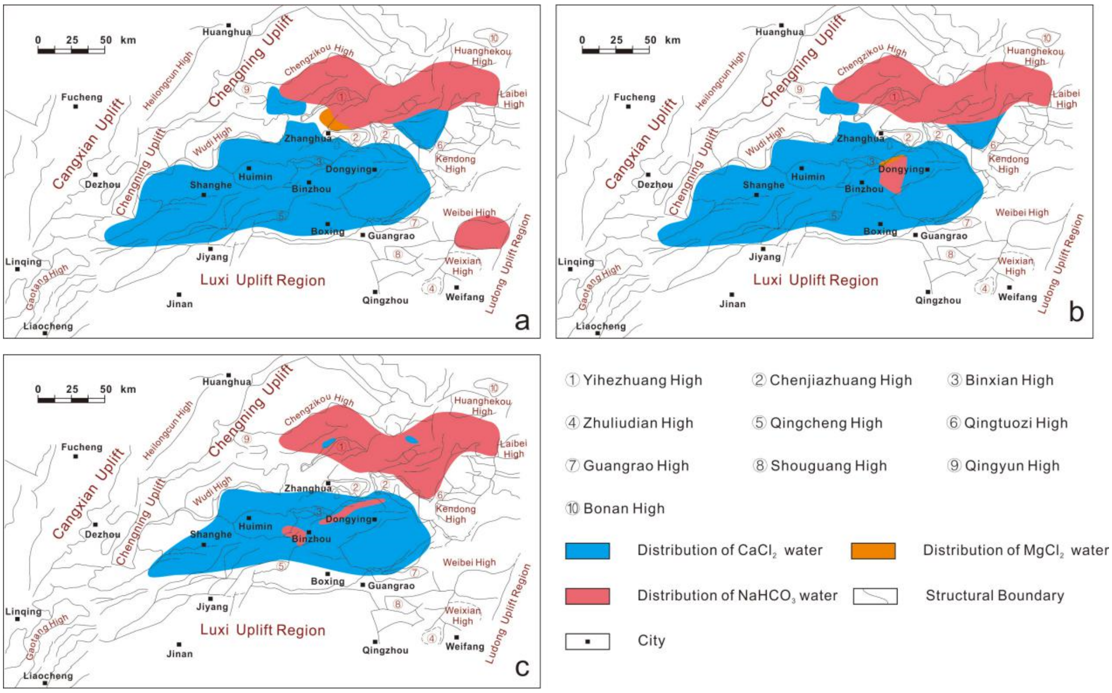

Figure 5. Classification of water type in the Jiyang Depression (a. Ek-Es4 formations; b. Es3 formations; c. Es2-Es1 formations)

3.5 Underground pressure and temperature

Most of formations in the Jiyang Depression have a pressure gradient of 0.9~1.1 MPa per 100 m. Due to the thermal anomaly caused by lithospheric thinning and asthenospheric upwelling during the evolution of the Bohai Bay Basin, the Jiyang Depression has a high geothermal gradient [39]. The thermal field of the Jiyang Depression is asymmetrical: The heat flow in the southern part of the depression is lower, with an average value of 50-80 mW/m^2 in the Dongying Sag and 50-70 mW/m^2 in the Huimin Sag. In the Chezhen Sag, the heat flow increases to 60-

70 mW/m^2, and the highest heat flow value of 60-80 mW/m^2 is observed in the Zhanhua Sag (Fig. 6).

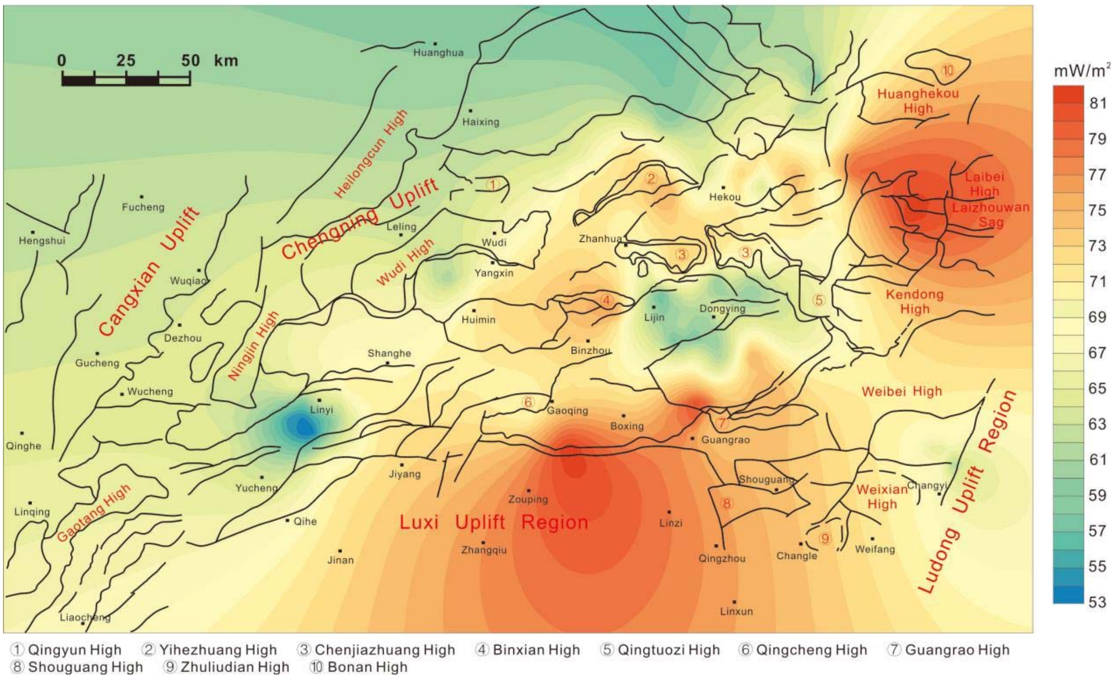

Figure 6. Heat flow distribution in the Jiyang Depression (Heat flow data is from Gong Y L et al (2003) [40])

Under such thermal conditions, the temperature gradient is higher than average for China. In most formations, the temperature gradients are between 3 and 3.5℃ per 100 m, while others are between 3.5 and 4℃ per 100 m. Irrespective of the higher temperature geothermal regime, the injected CO_2 would remain in a favorable highly dense state in almost all the formations under current temperature and pressure conditions (Fig. 7).

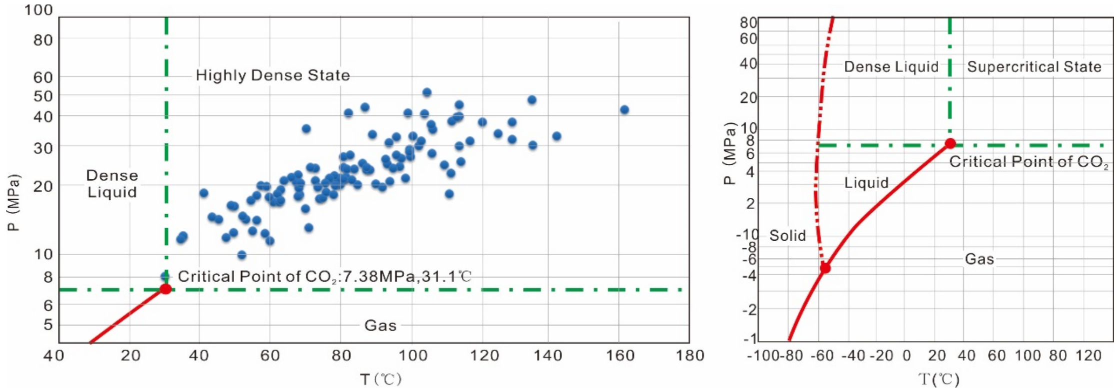

Figure 7. The formation temperature-pressure conditions in the Jiyang Depression

3.6 Stability

Neotectonism could potentially increase the risk of CO_2 leakage. The Jiyang Depression is located on the Tancheng-Lujiang fault zone, with scattered faults. Based on research into fault activity in this area, only a few faults on the boundary of tectonic units are still active and influence the occurrence of earthquakes, including the Wudi-yidu Fault, Guangrao-qihe Fault and Chengzikou Fault. Other faults, which are categorised as basement faults and superficial faults, appear to have been inactive since the Quaternary Period and current geological conditions suggest a low probability of future moderate or strong earthquakes influenced by these faults due to their current geological conditions [41]. No strong earthquakes have occurred in the depression during recorded history. The strongest recorded event is 5.0 on the Richter Scale (M5), which occurred in Kenli Country, AD 1588 [42]. According to studies characterising seismicity in this area, earthquake activity in this region is in a stage of releasing the remaining energy following a seismically active period. Multiple M4 - 5 earthquakes may occur in this stage, but the possibility that an earthquake over M6 could occur is very small [43]. Further study on crustal stability of this region and the adjacent coastal area also indicated that most of the onshore and offshore areas are in a relatively stable state; only submarine areas far from land are unstable. In the last 100 years, only two earthquakes over M5 (both in 1969) happened in the nearby coastal area, with no obvious damage to the depression and the Shenli Oilfield. Research also shows that the possibility of suffering a destructive tsunami in the nearby coastal area is relatively small in the future [44]. In summary, the Jiyang Depression seems quite stable for deep geological storage of CO_2.

4 Assessment of CO_2 storage suitability

4.1 Selected regions

The areas with the most advantageous characteristics for CO_2 storage in the Jiyang Depression were delimited based on the geological conditions described in the previous sections.

The reservoirs in the 2nd member of the Shahejie Formation (ES2) combined with overlying regional mudstone seals in the 1st member of the Shaheije Formation (ES1) and mudstone layers in 2nd member of Shahejie Formation (Es2) constitute the most favorable reservoir-seal assemblages.

The assemblage of reservoirs in the 3rd member of the Shahejie Formation (ES3), mudstones seals of the 3rd member of the Shahejie Formation (ES3), and both mudstones and gypsum layers in the 4th member of the Shahejie Formation (ES4) also have potential to trap CO_2. The reservoirs combined with overlying and underlying mudstones and gypsum in the 4th member of the Shahejie Formation (Es4), and the reservoirs in the Dongying Formation (Ed) combined with seals of the uppermost Dongying Formation and the Guantao Formation (Ng) could together be considered depending on the site specific geological conditions.

In terms of geographical distribution, the recommended assemblage of reservoirs and seals occur more frequently in the Dongying Sag and Huimin Sag. In addition, in these areas the subsurface temperatures are relatively low and the hydrodynamic characteristics are more stable compared with the rest of the depression. Therefore, the authors believe that the southern part of the depression (Dongying Sag and Huimin Sag) is more suitable for CO_2 storage, compared with the northern part of the depression (Chezhen Sag and Zhanhua Sag). Therefore, the authors identified the southern part as the most promising region for further investigation.

4.2 Detailed Assessment of Potential Storage Areas in saline aquifers and oilfields

A successful CO_2 storage project needs to satisfy three key requirements: adequate capacity, good injectivity and safe storage. Thus, detailed assessments are required to further evaluate potential storage sites in promising areas.

Bachu (2003) [45] defined basin-scale criteria for CO_2 storage. The criteria were used for the ranking and selection of sedimentary basins for CO_2 injection. Chadwick et al. (2008) [46] proposed a number of quantitative criteria for reservoir suitability for storage. In this paper, a new scoring system was developed for the ranking of localized areas in terms of their suitability for CO_2 storage. The system considers units in more detail than the system used by Bachu (2003) and builds on the criteria recommended by Chadwick et al., (2008). The criteria developed for this study consider the complex geological nature of onshore geological basins in China where deposition occurred in continental environments, resulting in heterogeneous storage formations, with multiple sandstone and mudstone layers within each geological unit.

The system is divided into four categories: safety, feasibility, economics and acceptability. Each category contained several criteria. The safety category considered the conditions of CO_2 injection and storage security. Criteria were selected based on the possibility of creating CO_2 leakage pathways, including seal quality, faults, legacy well bores and crustal stability. The feasibility category considered the suitability and capacity of a CO_2 storage site and criteria included scale, properties and conditions of potential reservoirs. The economic category focused on the CO_2 storage costs, criteria included capital costs for establishing a storage site and costs for operation and maintenance. The acceptability category considered the potential effects of CO_2 storage on local populations including potential effects on human societies and effects on the environment. In total, 43 criteria with weightings determined by the analytic hierarchy process (AHP) [47-50], were selected for the evaluation (Table 2). In order to make the system user-friendly, criteria have a detailed description and are quantified wherever possible. For each criterion, a score (1, 3 or 5) was given according to detailed data analysis of each candidate CO_2 storage site in the selected region. The final score of the site was the weighted mean value of all the scores used to rank and screen the recommended CO_2 storage sites. By using the scoring system, it is relatively easy to make an initial judgement on suitability of CO_2 storage at a local scale. The design of the system fully considered the characteristics of oilfields in

China. The criteria and corresponding weight would need to be redesigned for other situations.

The scoring system was applied in the candidate storage units in Jiyang Depression (a storage unit is defined as the combination of reservoirs integrated with seals above and below). 147 candidate storage units (including oil reservoirs and saline aquifers) were finally identified in the depression. The final scores of candidate storage units are all between 6.8 and 8.6. Amongst these units, the authors identified 55 storage units with scores over 8.0 as the primary recommended units, and 62 with scores between 7.5 and 8.0 as the secondary recommended units, representing about 37.41% and 42.18% of all studied units respectively. The recommended storage units are mainly concentrated in the 2nd and 3rd member of the Shahejie Formation mainly within the Dongying Sag and the Linyi-Shanghe areas of the central Huimin Sag (Fig. 8).

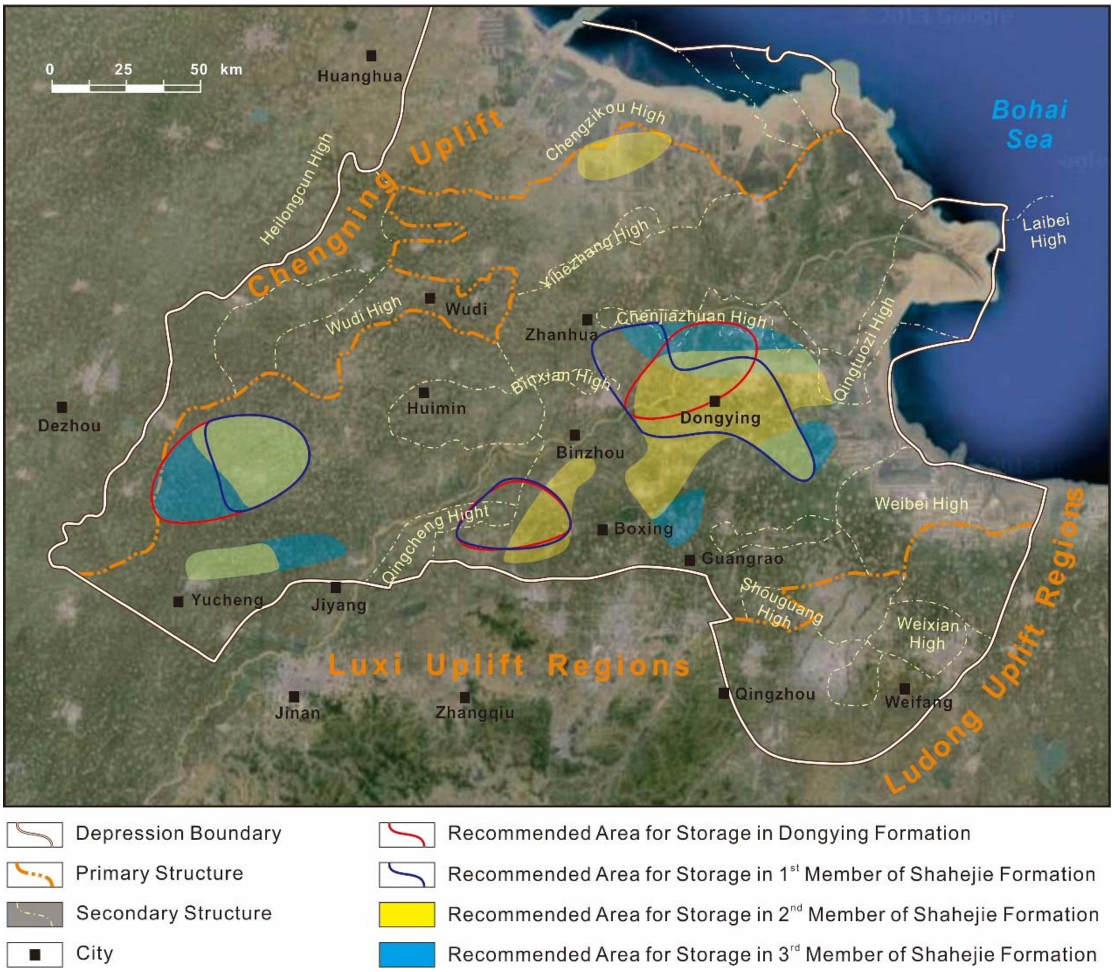

Figure 8. Distribution of recommended CO_2 storage units in the Jiyang Depression

5 Additional screening of candidate oil reservoirs

Amongst all the primary and secondary recommended storage units, 77 candidate oil reservoirs were identified for further evaluation. These units were then further screened with an additional two sets of criteria to determine if they were suitable for CO_2 EOR (Enhanced Oil Recovery) (Table 3). After this screening, 34 depleted oil reservoirs were considered only suitable for storage, and an additional 11 oil reservoirs were potentially suitable for both CO_2 EOR and storage.

6 Potential for CO_2 storage in oil reservoirs and saline aquifers

The theoretical storage capacity of saline aquifers in the primary and secondary recommended storage units was calculated using the method of Wang et al (2014) [53], which was modified based on the methods presented by USDOE [54] and CSLF [55].

$$M_{CO_2} = A \times H \times \emptyset \times \rho_{CO_2a} \times \left[1 - S_{wirr} \times \left(1 - s_{CO_2}\right)\right] \tag{1}$$

$$M_{CO_2e} = M_{CO_2} \times E \tag{2}$$

where, M_{CO_2} is theoretical CO_2 storage capacity (t); A is area of aquifer, (m^3); H is thickness of aquifer (m); $\emptyset$ is porosity of aquifer; S_{wirr} is irreducible water saturation; ρ_{CO_2a} is density of CO_2 in the aquifer(t/m^3); s_{CO_2} is solubility of CO_2 in the aquifer fluid (t/m^3); M_{CO_2e} is effective CO2 storage capacity (t); E is efficiency factor. The efficiency factor used in the calculation was based on IEA GHG, 2009) [56], which, for clastic reservoirs, gave P10 as 1.86%, P50 as 2.70% and P90 as 6.00%. This report assumes that for 10% of cases, *E* would be 1.86% or lower, for 50% of cases, *E* would be 2.70% or lower and for 90% of cases, *E* would be 6.00% or lower.

Mineral trapping was excluded from the capacity calculation because the chemical reaction between CO_2 and rocks is a relatively slow process and the amount of chemically trapped CO_2 is not expected to be significant over the injection lifetime. The capacity would be larger if CO_2 storage capacity by mineral trapping was taken into account, but the complexity of the calculation and the demand for data would increase several-fold and it is unlikely much of this potential could be realised during injection.

Based on the calculations carried out for this study, the total capacity of saline aquifers in primary recommended storage units is 2.49×10^8 t CO_2 respectively using the P50 storage coefficient given above. For secondary recommended storage units, the calculated CO_2 storage potential is 2.07×10^8 t CO_2 using the P50 storage coefficient given above.

The method put forward by Ecofys [57] was used to calculate the CO_2 storage capacity and CO_2 EOR potential of oil reservoirs in the recommended storage units of the Jiyang Depression.

$$M_{CO_2e} = E_R \times OOIP \times C \times \rho_{CO_2r} \times R_{CO_2} \quad \text{for } CO_2 \text{ EOR reservoirs} \tag{3}$$

$$M_{CO_2e} = N_P \times \rho_{CO_2r} \times R_{CO_2} \times \frac{B_o}{\rho_o} \quad \text{for depleted oil reservoirs} \tag{4}$$

where, E_R is enhanced oil recovery after CO_2 EOR, obtained by empirical statistics; $OOIP$ is original oil in place, (m^3); C is contact coefficient of CO_2 with oil, usually 0.75; ρ_{CO_2r} is density of CO_2 in the oil reservoir (t/m^3); R_{CO_2} is ratio for net CO_2 injection to oil production (t/m^3), usually between 0.9 and 5, average value 2.8 is used in this paper; N_p is accumulative oil production (m^3); B_o is oil volume factor; ρ_o is oil density (t/m^3).

The total storage capacity of the selected 34 depleted oil reservoirs is 41.83×10^6t. For the additional 11 oil reservoirs with CO_2 EOR potential, the total storage capacity is 5.06×10^6 tCO_2, and the calculated additional oil production through CO_2 EOR is 15.02×10^6 t.

The current annual emissions of the 11 large-scale CO_2 sources (emission $>20\times10^4$t/a) in the Jiyang Depression are about 14.5×10^6t [58]. Therefore, the total CO_2 storage capacity of saline aquifers and oil reservoirs in the primary and secondary recommended storage units (5.03×10^8t at P50 for saline aquifers) is equal to about 30 years of emissions from the large-scale sources in the area of the Jiyang Depression (if emissions were to remain at present levels).

7 Conclusions

Criteria designed to evaluate geological and societal aspects of CO_2 storage in the Jiyang Depression were used to assess the most promising storage options in terms of geological suitability (capacity and safety), economic viability and potential conflicts of interest, in order to identify the most promising storage options. The storage capacities of these recommended storage units were then calculated. In the Jiyang Depression, the 2nd and 3rd members of the Shahejie Formation appear favourable for CO_2 storage. The recommended storage units are mainly concentrated in these two members over most of the area of the Dongying Sag and the Linyi-Shanghe area of the central Huimin Sag.

The calculated storage capacity of the saline aquifers in these recommended storage units is 4.56×10^8 tCO_2 using a storage efficiency factor of 2.7%; whilst for oil reservoirs in the recommended storage units, the calculated capacity is 46.89×10^6t CO_2. Theoretically, these recommended storage units offer a combined volume that could store the CO_2 emitted from large–scale sources in the Jiyang Depression for more than 30 years at current emission rates. In addition, an estimated 15.02×10^6 t extra oil could be produced through CO_2 EOR from the identified 11 suitable reservoirs in the recommended storage units.

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Table 1. Properties of seals in Jiyang Depression [19-25]

	Average thickness (m)	Porosity (%)	Displacement pressure (MPa)	Maximum gas column height (m)
Ng	250	10-26	0.35-1.75	32-157
Es1	150	10-20	1.17-11.4	104-1017
Es3	300	1-14	1.0-6.4	86-667

Table 2. Scoring system for suitability of CO_2 storage in localized areas

category	Criterion	Good (10)	Intermediate (5)	Poor (1)	Weight
safety	Continuity of top seal	Cover most of the whole basin or depression	Cover secondary tectonic structure or several reservoirs	Cover some part of secondary tectonic structure or single reservoir	0.15182
	Shale volume fraction of seal	>70%	50-70%	<50%	0.07213
	Seal thickness	>100m	50-100m	<50m	0.07213
	Number of overlying seals*	several	single	None	0.03402
	Sealing gas thickness by pressure	>100m	50-100m	<50m	0.01271
	Number of faults	<2/km^2	2-5/km^2	>5/km^2	0.11365
	Sealing capability	closed	Semi-open	open	0.03790
	Earthquake intensity	<6Ms	6-8Ms	>8Ms	0.00550
	Earthquake frequency(>6Ms, within 50 km of the candidate site)	<1/100a	1-3/100a	>3/100a	0.00550
	Volcanicity (within 50 km of the candidate site)	dormant	extinct	active	0.00205
	Hydrodynamic	Stagnant flow	Slow flow	Rapid flow	0.01487
	Well spacing density	<20/km^2	20-30/km^2	>30/km^2	0.04743
	Well completion	Cased and cemented	Cased but not cemented	Open hole	0.01581
feasibility	Reservoir thickness	>80m	50-80m	<50m	0.01423
	Reservoir area	>30km^2	10-30km^2	<10km^2	0.01423
	Reservoir permeability	>500mD	100-500mD	<100mD	0.01423
	Reservoir porosity	>0.2	0.1-0.2	<0.1	0.01423
	Reservoir lithology	Gritstone and more porous rocks	Medium-fine sandstone	Siltstone-shaley sandstone	0.00445
	Depositional environment	Fluvial	Deltaic	Lacustrine	0.01014
	Net/gross ratio	>0.5	0.2-0.5	<0.2	0.00186
	Salinity	>6g/L	3~6g/L	<3g/L	0.00083
	Reservoir depth	800 ~ 3000m	3000 ~ 4000m	<800m , >4000 m	0.10805

	Pressure gradient	0.9 ~ 1.1MPa/100m	<0.9MPa/100m	>1.1MPa/100m	0.04777
	Geothermal gradient	<3℃/100m	3-4℃/100m	>4℃/100m	0.01995
	Heat flow	<50mW/m^2	50-70 mW/m^2	>70 mW/m^2	0.00880
economic	Source scale (larger sources are more economic)	>25×10^4t/Y	10-25×10^4t/Y	<10×10^4t/Y	0.05691
	Cost of transport	Pipeline	Road transport	Ship	0.01050
	Infrastructures	Can use directly	Need reconstruction	None	0.00464
	Site location	Onshore		Offshore	0.02515
	Cost of mitigating geological hazard	None	Low	High	0.00243
	Surface temperature	<10℃	10-20℃	>20℃	0.00027
	Typhoon	None	Affected, but no severe damage	Affected and devastated	0.00027
	Topography	Easy (e.g. plane)	Normal (e.g. hills, wash)	Difficult (e.g. Plateau, mountain area)	0.00027
	Area prone to storm surge	No		Yes	0.00243
	Area prone to ice flooding	No		Yes	0.00243
	Area prone to flooding	No		Yes	0.00243
	Annual precipitation	<500mm	500-700mm	>700mm	0.00027
acceptability	Usable groundwater	Without usable groundwater	Usable groundwater with good seals	Usable groundwater with poor seals	0.00215
	Usable surface water	No rivers or reservoirs	Rivers or reservoirs with distance>150km	Rivers or reservoirs with distance <150km	0.00215
	Distance from nature reserve	>15km	5-15km	<5km	0.00024
	Vegetation coverage	<30%	30-60%	<60%	0.00024
	Population density	<25 persons/km^2	25-200 persons/km^2	>200 persons/km^2	0.03864
	Public acceptance	>70%	30-70%	<30%	0.00429

*overlying seals: all the impermeable seals located above reservoir, regardless local or regional seal.

Table 3. Criteria for screening depleted oil reservoirs and CO_2 EOR reservoirs

Items	**Units**	**Criteria**
Depleted oil reservoirs(Modified from Zeng SP et al, 2005) [51]		
Recovery percent of recoverable reserves	-	>85%
Recovery percent of geological reserves	-	>30%
Effective porosity	-	>15%
Effective permeability	μm^2	$>50\times10^{-3}$
Geological reserves	t	$>400\times10^{4}$
CO_2 EOR reservoirs [52]		
API gravity	°API	>22
Viscosity	mPa.s	<10
Oil saturation	%	>0.20