Site Selection Method and Criteria of CO_2 Geological Storage

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1. Research Goal

Continental facies sediment is in most of basins in China. So it is not suitable to use site selection methods and criteria in China which are develop in other countries. It is necessary and useful to set a series of site selection methods and criteria according to Chinese geological conditions.

2. Main Tasks

Research on site selection method and criteria of CO_2 geological storage

Summarize conditions of site selection of CO_2 geological storage when we consider different storage options, such as depleted oil and gas reservoirs, unminable coal seams, deep saline aquifers and so on. Identify and characterize general conditions (including CO_2 sources, potential CO_2 sources, basin distribution, natural resources), basical geological conditions (including reservoir, caprock, geochemistry, geomechanics, hydrogeology) and social and economic conditions (including population distribution, political, economy, man activities) and their criteria. Overview the different methods to obtain parameters of site selection and define the most suitable method for getting parameters.

3. Expected Outcome

The Report on site Selection Method and Criteria of CO_2 Geological Storage

The Guideline on Site Selection of CO_2 Geological Storage in China

4. Partners

Lead Organization：Center for Hydrogeology and Environmental Geology, CGS

Participant Organization：Department of Thermal Engineering, Tsinghua University

Institute of rock and soil Mechanics, Chinese Academy of Sciences

Item	Actual costs / Budget	01/06/10 - 5/8/2010	8/08/2010 - 31/10/2010	1/11/2010 - 31/12/2010	1/1/2011 - 11/2/2011	14/2/2011 - 30/4/2011	1/5/2011 - 10/6/2011	13/6/2011 - 31/8/2011
Travel Expenses	61350.00	/	$1,130.77	$ 1,246.15	$5,837.17	$10,538.46	$15,807.69	$10,538.46
Materials and Laboratory Equipment	136200.00	$461.54	$2,230.77	$1,984.62	$ 53,225.81	$ 65,153.85	$ 3,257.69	$6,515.38
Project team	94850.00	/	$692.31	$923.08	$7,680.49	$12,000.00	$13,200.00	$28,800.00
Conference	23000.00	/	$7,384.62	/	/	/	/	/
Business	23000.00	$307.69	$1,230.77	$ 1,153.85	$5,483.87	$7,938.46	$3,969.23	$1,587.69
Publication	4600.00	/	$69.23	$153.85	$384.02	$461.54	$646.15	$1,015.38
Commission Business Fee	25000.00	/	/		/	$7,692.31	$8,461.54	$6,153.85
Managemant Fee	32000.00	/	/		$16,000.00	$4,000.00	$4,000.00	$4,000.00
Totals	**$400,000**	**$769**	**$12,738**	**$5,462**	**$88,611**	**$107,785**	**$ 49,342**	**$58,611**

5. The main content of subject

Site Selection Method and Criteria of CO_2 Geological Storage

5.1. Introduction

Excessive greenhouse gas emission by consumption of fossil fuels (e.g. coals, oils and natural gases) has been considered as the leading factors for global climate warming. CO_2 capture and geological storage is regarded as the only way that fossil fuels can be used safety. According to estimation the potential is large to storage CO_2 in oil fields, coal bed and saline aquifers. Site selection is the first step and the key technology on CO_2 geological storage. And it is important to launch demo project of CO_2 geological storage.

The first step implementation works of CO_2 geological storage are site selection and related evaluation in China. A series of key issues which the project storage service life and safety and so on can be depended on the site location of the success or not. Failure site of CO_2 geological storage will bring many adverse effects, even cause irreparable damage. So site selection of CO_2 geological storage is a cautious and complex system engineering.

In 2005, geological storage potential CO_2 was estimated by Ministry of Land and Resources in China. The results showed that the total amount of CO_2 storage in China geological 14548×10^8t. Among them, the 24 major sedimentary basins, which the distribution area of about 34×10^4km^2 of deep saline aquifer can store CO_2 about 14350×10^8t, accounting for 98.64% of the total storage; 46 petroleum basins can store CO_2 about 78×10^8t, accounting for 0.54% of the total storage; 68 major coal area can store CO_2 about 120×10^8t, accounting for 0.82% of the total storage [1] (see figure 1a).

With the expansion of area and rich evaluation materials, the evaluation results showed that the CO_2 theory geological reserves of land in China was 54589 $\times10^8$t in 2011,Among them, deep saline aquifer of CO_2 theory geological reserves was 53531 $\times10^8$t, accounting for 98.1% of the total amount; petroleum of CO_2 theory geological reserves was 221 $\times10^8$t, accounting for 0.4% of the total amount; Gas of CO_2 theory geological reserves was 662 $\times10^8$t, accounting for 1.2% of the total amount; CBM of CO_2 theory geological reserves was 175 $\times10^8$t, accounting for 0.3% of the total (see figure 1 b)According to 60 $\times10^8$t CO_2 emissions of each year, CO_2 geological storage can be available for 900 years in China(Center for Hydrogeology and Environmental Geology , CGS,2010).

The above two evaluation results indicate that CO_2 geological storage potential of deep saline aquifer is more than 98%, far bigger than other storage mediums, is main CO_2 geological storage medium. But the research of site selection of CO_2 geological storage in deep saline aquifer is still in the blank at home and abroad, and it is very essential to establish CO_2 geological storage index system for complex sedimentary basin types and poorer crustal stability in China.

5.2. Products

5.2.1 Establishment index system of site selection of CO_2 geological storage

IPCC report identifies that CO_2 geological storage leak risk smaller than natural gas storage; Comparing with geological disposal of nuclear waste, the harm of CO_2 geological storage is gentle. Therefore, site selection of CO_2 geological storage can reference for the relevant standards with nuclear waste and natural gas geological buried.

Site selection is the first step of CO_2 geological storage engineering, and the most critical step. Site selection of CO_2 geological storage is responsive to natural geographical condition, weather condition, geological condition, social economic, traffic and engineering technology and many other factors. Therefore, Site selection index system can be analysed and established form four aspects: site selection technology, safety, economic suitability, field geological conditions. (see table 1).

Tab.1 Index system of factors ranking method for CO_2 geological storage in deep salt groundwater

Technical Index	Sub-index		Criterion	Classes				Notes method
				good		general	bad	
Technical Index	Reservoir	Macro feature	1. Depth（m）	800～3500		＞3500	＜800	C,D, G
			2. Stratigraphic combination and sand percent（%）	sandstone（carbonatite）clip sandstone，stratiform；sand＞60%		sandstone and mud sandstone nterbedding/sand 20% ~ 60%	mudstone clip sandstone; sand < 20%	B,C, D, E, G
		Hydrogeology	3. Hydrodynamism	hydraulic closed role		hydraulic sealing function	hydraulic migration and diffusion	
			4. Head state（m）	low than ground		same with ground	high than ground	
			5. Mineralization（g/L）	10.0～50.0		3.0～10.0	＜3.0,＞50.0	
		Geothermal	6. Surface temperature（℃）	＜－2		－2～10	＞10	
			7. Geothermal gradient（℃/h）	＜2		2～4	＞4	
			8. Terrestrial heat flow（HFU）	＜54.5		54.5～75	＞75	
		Physical properties	9. Porosity（%）	sandstone	＞15	15～10	＜10	
				carbonatite	＞12	12～4	＜4	
			10. Permeability($\times 10^{-3} \mu m^2$)	sandstone	＞50	50～10	＜10	
				carbonatite	＞10	10～5	＜5	

			11. Anisotropy（The variation coefficient of permeability）	＜0.5	0.5～0.6	＞0.6	
		Store prospect	12. Effective storage（Mt）	＞9	9～3	＜3	D,E,F
	Experimental perfusion engineering evaluation	Perfusion evaluation	13. Injection index（m^3）	＞10^{-14}	10^{-14}～10^{-15}	＜10^{-15}	
			14. Effectively sealed coefficient（%）	＞8	2～8	＜2	
		Perfusion controll technics	15. Injection well completion work pressure（Pa）	less than the cover pressure and wells material pressure	same with the cover pressure and wells material pressure	larger than the cover pressure and wells material pressure	E,F,G,I
			16. Quantity of Injection well（m^3/h）	less than storage capacity	same with storage capacity	larger than storage capacity	
Safety evaluation	Cover	Macro feature	17. Rock	rocks of evaporation	shale rock types	carbonate	B,C,D,E, G
			18. Single thick（m）	＞20	10～20	＜10	
			19. Total thick（m）	＞300	150～300	＜150	
			20. Continuity	continual，regional	local	discontinuous	
		Micro feature	21. Sealing gas index Hg（m）	＞200	100～200	＜100	
		Buffer conditions	22. Sub-cover	many，good quality	one，general quality	no	
	Potential leak	Nature faults	23. Faults	no	limited	large fault ,break	C,D,F,G
		Artificial faults	24. Wells within $100km^2$	no	have ,sealed	many，no sealed	
	Stability	Crustal	25. Motion peak acceleration	＜0.10g	0.10～0.15g	＞0.30g	A,B,C,D,

		stability	of earthquake（g）				E,G
			26. Earthquake	safe	middle	danger	
			27. Active faults within 25m	no	—	yes	
Economical evaluation			28. Carbon source（Mtpa）	＞0.25	0.25～0.10	＜0.10	B,G
			29. Carbon source distance（km）	＜100	100～200	＞200	
			30. Mode of transportation	pipeline	road, rail	ship	
			31. Social environment	accept	middle	repel	
			32. Infrastructure	perfection	middle	imperfection	
			33. Mineral deposits	no		have	
			34. Cost	low	middle	high	
Groud-sur face evaluation	Geology of ground surface	Reservoirs around	35. Occasion to happen geological disasters	no	low—middle	high	A,B,G
			36. Mining subsidence area, karst subsidence area	no		yes	
			37. Subsidence zone	no		yes	
			38. Desert activity	no		yes	
			39. Volcanic activity	no		yes	
			40. Lower than the highest water level of Rivers, lakes and reservoirs / flood storage	no		yes	
		Affect to worker	41. Topography of perfusion site	high convex open terrain	wide-relatively shallow depression	low-lying, complex terrain	

			42. Predominant wind direction	has	many wind directions	no	
	Environmental protection	Character of site	43. City and regional development planning	yes		no	B,D,G
			44. Agricultural reserve, nature reserves, Scenic spot, cultural relics (archaeological) reserves, Life drinking water reserves, Water supply planning vision, mineral resources reserve districts and other zones that need special protection （Whether in special protection area）	no		yes	
			45. Vegetation status (for protection/plant vegetation coverage)	no/low	few/general	many/high	
		Safe distance to drink source	46. Whether there is groundwater aquifers for industrial or agricultural use in the upper of CO_2 reservoir	no	yes，but has water-resisting layer	yes，and no water-resisting layer	
			47. Whether in the main supply drinking	no		yes	

			groundwater area				
			48. Distance to surface water source for drinking（m）	＞150	150±	＜150	
		Safe distance to fragile area	49. Distance to fixed residential areas（m）	＞800	800±	＜800	
			50. The relationship with the predominant wind direction of fixed residential areas	downwind	side wind	upwind	
			51. Distance to special protection area（m）	＞3000	3000±	＜3000	

Annotation：A—Remote sensing survey；B—Comprehensive geological survey；C—Geophysical exploration；D—Drilling；E—Sample testing, analysis； F—Perfusion test； G—Data collection； H—Public survey； I—Other geological means

5.2.2 Site selection evaluation methods with factors ranking

Analytic Hierachy Process(AHP) is studied by T. L.Saaty in the mid-1970s. AHP as a kind of qualitative issues will be translated into effective system of the calculation method of analysis and policy-making. Especially is suitable for those hard to use quantitative analysis of complex problems with simple, flexible and practical features.

1. Site selection evaluation index system

Site selection is the first and most important step of CO_2 geological storage project in deep saline aquifer. The site selection of CO_2 geological storage are restricted by many factors, such as physical geography, meteorology and hydrology, topography, geological structure, reservoir and seal combination and its property, social economy, source and sink matching, transportation and engineering conditions etc. Even so, There can be summarized as the location technology, safety, economic suitability and ground geological-social environment condition in these four aspects to establish the site selection evaluation index system of hierarchical analysis structures(See table 2).

table 2 Site selection index system with factors ranking in deep saline aquifer CO_2 geological storage

Index Layer	Index Sub-Layer	Index
Technology Index Layer	Reservoir Stratum Macro Characteristics	depth, thickness, formation pressure coefficient, sedimentary environment, stratigraphic combination and sand percent, hydrodynamism, mineralization, head state
	Reservoir Physical Parameter	porosity, permeability, anisotropy
	Reservoir Store Prospect	effective storage, service life
	Reservoir Geothermal Geology Characteristics	surface temperature, geothermal gradient, terrestrial heat flow
	Perfusion Test Evaluation	injection index, effectively sealed coefficient
	Perfusion Control Technique	injection well completion work pressure, quantity of injection well, perfusion speed of injection well
Safety Evaluation Index Layer	Macro Feature	rock, single thick, total thick, continuity
	Micro Feature	sealing gas index, sub-cover
	Buffer Conditions	sub-cover
	Nature Faults	faults
	Unfound Faults in the Existing Technology Conditions	(the size of the possibility)
	Artificial Faults	wells within $100km^2$
	Crustal Stability	motion peak acceleration of earthquake, earthquake ,active faults within 25m
Economic Evaluation Index Layer		carbon source scale, carbon source distance, transportation, social environment, infrastructure, mineral resources, cost
Field Location Index Layer	Reservoirs Around	occasion to happen geological disasters, mining subsidence area, karst subsidence area, desert activity, volcanic activity, lower than the highest water level of rivers, lakes and reservoirs / flood storage
	Affect to Worker	topography of perfusion site, predominant wind direction
	Character of Site	agricultural reserve, nature reserves, scenic spot, cultural relics (archaeological) reserves, life drinking water reserves, water supply planning vision, mineral resources reserve districts and other zones that need special protection（whether in special protection area）
	Safe Distance to Drink Source	whether there is groundwater aquifers for industrial or agricultural use in the upper of co_2 reservoir, whether in the main supply drinking groundwater area, distance to surface water source for drinking
	Safe Distance to Fragile Area	distance to fixed residential areas, the relationship with the predominant wind direction of fixed residential areas,

		distance to special protection area

2. Evaluation method of multi-factor ranking siting based on analytical hierarchy process (AHP)

The main thread of the evaluation method of multi-factor ordering location is that objective weighting calculated by the analytical hierarchy process (AHP) is considered into the distance synthetic evaluation conducted by described the many targets of the object being evaluated. If the targets are regarded as the coordinate variables, a higher dimensional space is formed in geometry(Liu Aifang etc.2009).

From the geometric point of view, each object evaluated is a point decided by the many indicators reflecting the object. Then, the scheme selection decision is changed to sort and to evaluate on these points. For purposes of comparison analysis, a natural idea is that firstly determining the reference points in the space, such as the advantages and the worst point, then calculating the distance between the several evaluated objects and the reference point, it is better that the distance is nearer with the optimum point and farther with the worst point(Yang Jianping etc.2007).

On the foundations of the comprehensively considering the more than sixty kind of factors effect the siting of the CO_2 geological sequestration in the deep salt reservoir, the hierarchical structure evaluation indicator system is founded and the evaluation indicator weighting is calculated. The concrete steps of the evaluation are as follows:

(1)Determine the evaluation matrix. The intial indicator matrix X＝（Xij）m×n is conducted in this step which the m is for the number of the evaluated individuals and the n is for the number of the evaluated factors. The indicator matrix which has n factors is expressed as X＝（X1，…，Xn）.

(2)Calculate the objective weighting using the analytical hierarchy process(Liu June et al.2005;Jiao na,2008).The decision makers compare the relative importance of each factor and all the comparative values a ij（i，j＝1，…，n）composes a geminate comparative matrix A:

$$A = (a_{ij})_{m\times n}, ai_j > 0, a_{ji} = \frac{1}{a_{ij}} \quad (1)$$

Calculate the geometry mean value of reciprocal matrix A line by line:

$$\overline{\omega_i} = \sqrt[n]{\sum_{j=1}^{n} a_{ij}} \quad (2)$$

Normalize the $\overline{\omega_i}$:

$$\omega_i = \frac{\overline{\omega_i}}{\sum_{i=1}^{n} \overline{\omega_i}} \quad (3)$$

Calculate the approximate value λ of the maximum eigenvalue of the matrix A:

$$\lambda = \frac{1}{n}\sum_{i=1}^{n}\frac{(A\omega)_i}{\omega_i} \quad (4)$$

Calculate the Consistency indicator and Consistency ratio of reciprocal matrix A and check the consistency. When CR＜0.1,A is considered passing the consistency test.

Calculate the weighting vector: ω＝（ω1， …， ω4）.

(3)Change the indicators to the same direction. If there are inverse indicators (those indicators the smaller the better)and moderate indicators in the n factors of the indicator matrix, then first we should make the indicators to the same direction to the direct indicators. The most easy way is ,for the inverse indicators ,to value:

$$x_{ij}^{'} = \frac{100}{x_{ij}} \quad (5)$$

and the matrix is:

$$X^{'} = (x_{ij}^{'})_{m \times n} \quad (6)$$

(4)The evaluated matrix $X^{'}$ is changed into standard matrix $Y^{'} = (Y_1^{'}, \cdots, Y_n^{'})$ after the non-dimensional-normalized process. After the non-dimensional-normalized process, the new indicators matrix $Y^{'} = (y_{ij}^{'})_{m \times n}$ comes into being, where:

$$y_{ij}^{'} = \frac{x_{ij}^{'}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{'2}}} \quad (7)$$

(5) determine the weighted data matrix. The weighting ω is determined by the analytic hierarchy process (AHP),which is used to get the weighted average of each line of matrix $Y^{'}$.The values are y_{1j}， …， y_{mj}.Then the weighted matrix Y is determined to:

$$Y = \begin{Bmatrix} y_{1j} \\ y_{2j} \\ \cdot \\ \cdot \\ \cdot \\ y_{mj} \end{Bmatrix} = (y_{ij})_{m \times n} \qquad (8)$$

(6) Determine the ideal and negative ideal samples. Because the factors are already changed into the same direction, the maximum values of the various factors of the all samples constitute ideal samples and the minimum values of the various factors of the all samples constitute negative ideal samples, which are respectively expressed by y_j^+ and y_j^-.

(7)Calculate the distances between each evaluated object and the ideal and negative ideal samples.

The distances between the samples and the optimum points are:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_j^+)^2} \quad i = 1, 2, \cdots, m \qquad (9)$$

The distances between the samples and the optimum points are:

$$D_i^- = \sqrt{\sum_{j=1}^{n} (y_{ij} - y_j^-)^2} \quad i = 1, 2, \cdots, m \qquad (10)$$

(8) Calculate the comparative closeness between the evaluated object and the optimum sample. The greater the comparative closeness is, the smaller the relative distance between the evaluated object and the ideal sample is, and the better the evaluated result is. The calculating formula is:

$$C^i = \frac{D_i^-}{D_i^- + D_i^+} \quad (11)$$

The greater the value of C^i is, the better the evaluation value is. （0≤C^i≤1）

(9) Rank. According to the size of the comparative closeness C^i, we can rank the various evaluated objects. That is if C^i has a greater value, the corresponding evaluation result of the evaluated object is better.

5.3. Concluding remarks

CO_2 geological storage potential of deep saline aquifers in sedimentary basins in China is the main media to achieve large-scale CO_2 geological storage, which far greater than oil and gas reservoirs, coal and coalbed methane reservoirs and other geological storage media.

Suitable for large-scale CO_2 geological storage in deep saline aquifer is the cap rock buried below 800m deep, with a certain distribution area, large thickness, high porosity, high permeability, besides, the top plate and bottom board are high water-resisting property , large thickness, stability of the clay, gypsum rock layers, and have not disconnected crack and active fault. Salinity in deep saline aquifer is between 10~50g/L, is neither suitable for agricultural and industrial, nor suitable for human consumption, even not reach mineralization of the underground brine requirements, the deep saline aquifer are not available in today's technology, economic conditions.

The principle of site selection of CO_2 geological storage should have the following four points: the objective reservoir can store CO_2 more than 30 years and have huge effective storage hole; safety principle, economy principle and consistent with environmental protection site selection conditions of the general construction project, and is also not affected by the external adverse geological factors. The three stages of site selection of CO_2 geological storage engineering are: comparison site selection, optimization site selection and determined site selection.

Site selection of comprehensive evaluation index system consists of four index layers: technical, safety, economic suitability and surface geology-social environmental，and more than 50 indicators; could use multiple factors ranking based on analytic hierarchy process (AHP) site evaluation method for the comprehensive evaluation and sorting.

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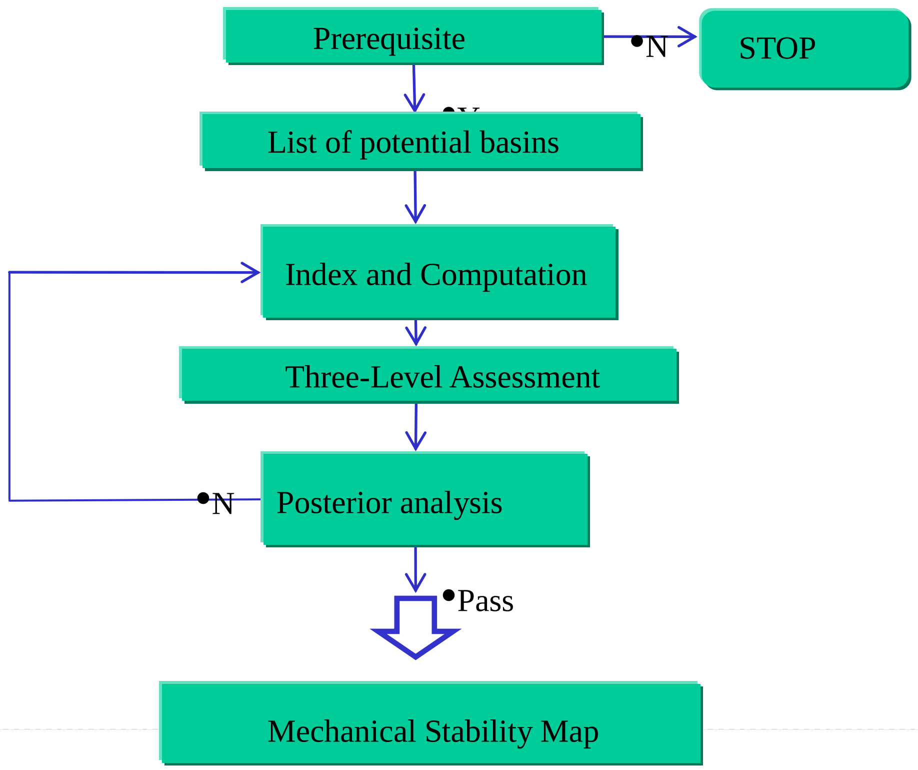
Site Selection Method based on Assessment of Mechanical Stability of Deep Saline Aquifer

Abstract: By review of published site selection guidelines, regulations and standard, a set of key indices associated with mechanical characteristics is determined, and then a multilevel mechanical evaluation method is proposed to assess sedimentary basins with consideration of tectonic structures and macro events by building some prerequisite criteria. Finally, major basins are assessed for potential sequestration of CO_2 and mapped according to traffic-light.

1. Methodology

With consideration of special tectonic structures, the constructed safety evaluation system for CCS geological storage in deep saline aquifers is different from Europe and America. The establishment of the standard evaluation system based on the mechanics related indices is different from the Bachu and Oldenburg's method. On the other hand, the evaluation indices themselves for selected basin-level assessment are divided into three different levels, namely, evaluation index, first-level and secondary-level verification indicators according to a posteriori rule.

1） Assessment flow:



2） Prerequisite Issues

Prerequisite

1） Potential capacity of basin（less than 25 Mt）
2）Depth of potential storage aquifer（less than 1500 m and more than 500 m）
3） Active fault to the injection site（less than 100 km）
4） Temperature of basin（less than 373 K）
5） Developing zones of coal, oil and gas, and geothermal field.

3） Three-level Assessment Indices:

Indice for mechanical stability assessement

- Fault density
- Active faults and earthquake

Level 1 Index

- Tectonics

Level 2 Index

- Geostress
- Geomorphology

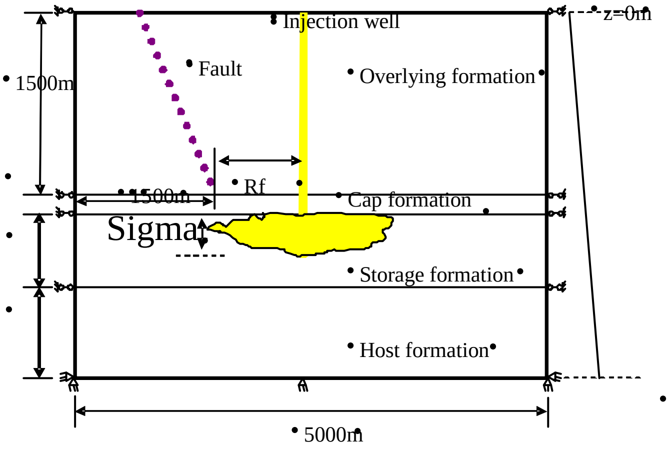
Level 3 Index

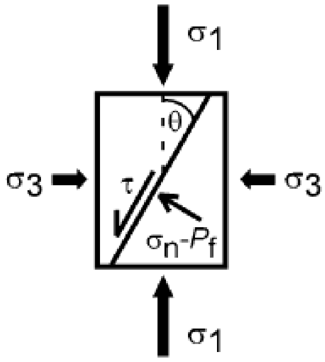
4） Determination of assessment indices

With reasonable assumptions of different injection scenarios, the stress history and critical slip field can be predicted. The fault stability is evaluated by Coulomb criteria and associated with the different modes.

$$\sigma_e = \sigma_n - p_f = f(injection, reservoir)$$

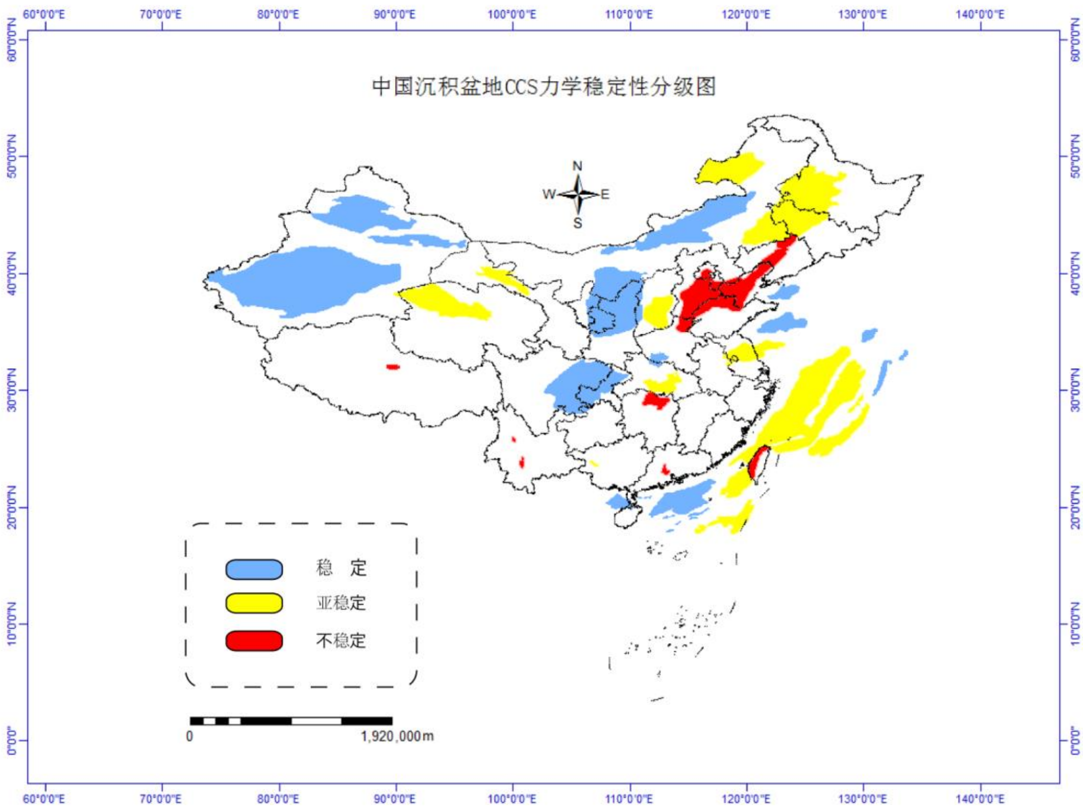
$$R_f = f(\sigma_e, \sigma_{\max})$$





2. Products

1） Suitability of sedimentary basins according to mechanical stability assessment



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i) Qi Li，2011. Writing for Chapter 2 and Chapter 7 of ”Site Selection Guideline for CCS in China”.

ii) Li, Q., Li, X., Wei, N., Liu, X. and Shi, L., 2011. Coupled Geomechanical and Fluid-Flow Analysis of Geological Disposal Site with Chemical Reaction, GeoProc2011, Perth, Australia.

3. Concluding remarks

It is very important to adopt reasonable scenarios to determine the critical value for mechanical performance assessment of potential deep saline basins. The key physical parameters should be examined for the typical basins. In addition, it should be determined the projection relation between the stress changed and the three typical failure modes of the tectonic fault, i.e., normal fault, reverse fault and strike-slip fault.

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