Combining Brine Extraction and Energy Production from Geopressured-geothermal Aquifers Using CO_2

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PRESENTATION OUTLINE 概 要

1 Background 研究背景

CO_2 Sequestration

Background

- Capturing and storing CO_2 in aquifers is a costly process.

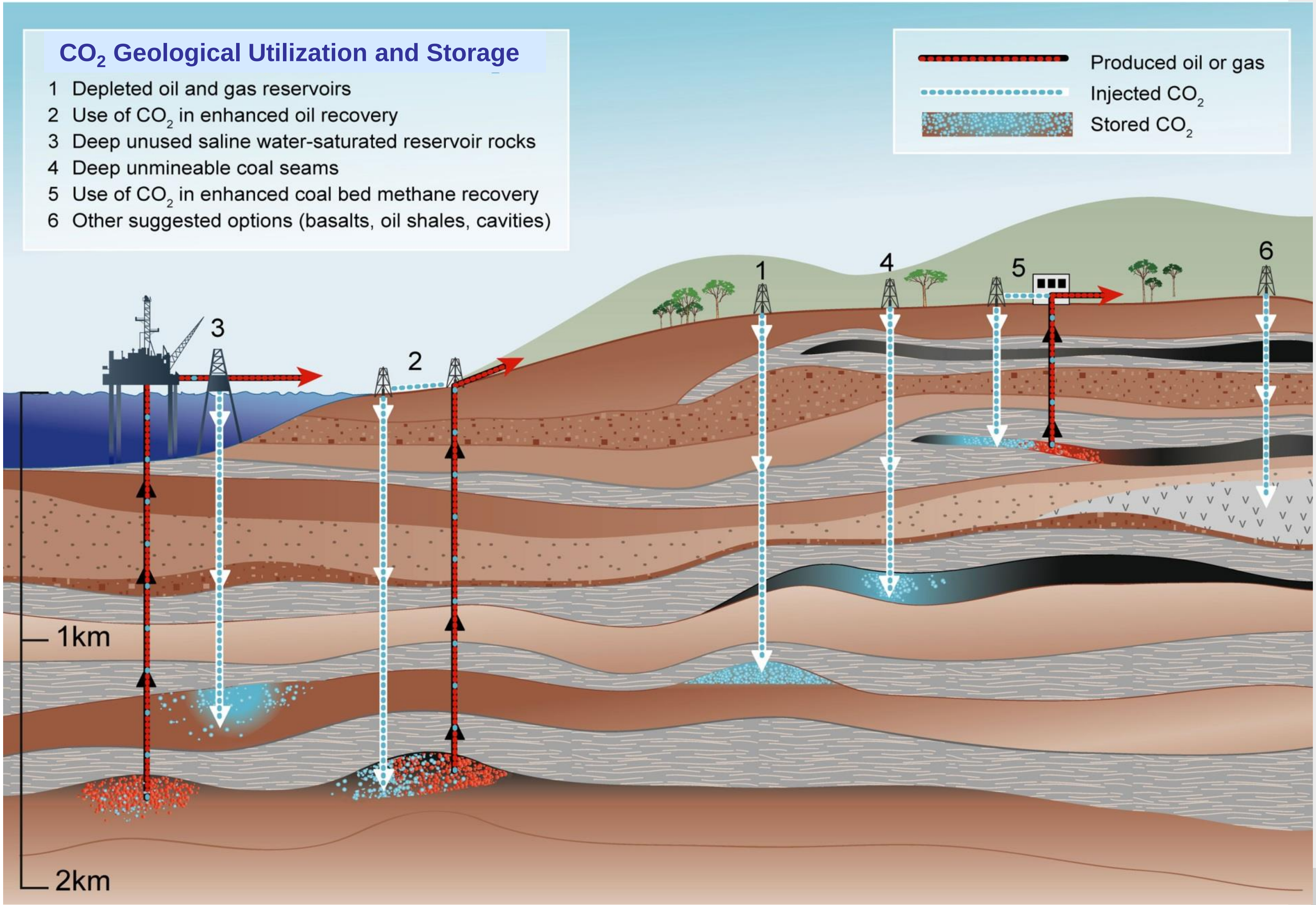
- The storage technology has several constraints：

  Pressure build-up 压力积累

  Injection capacity 注入容量

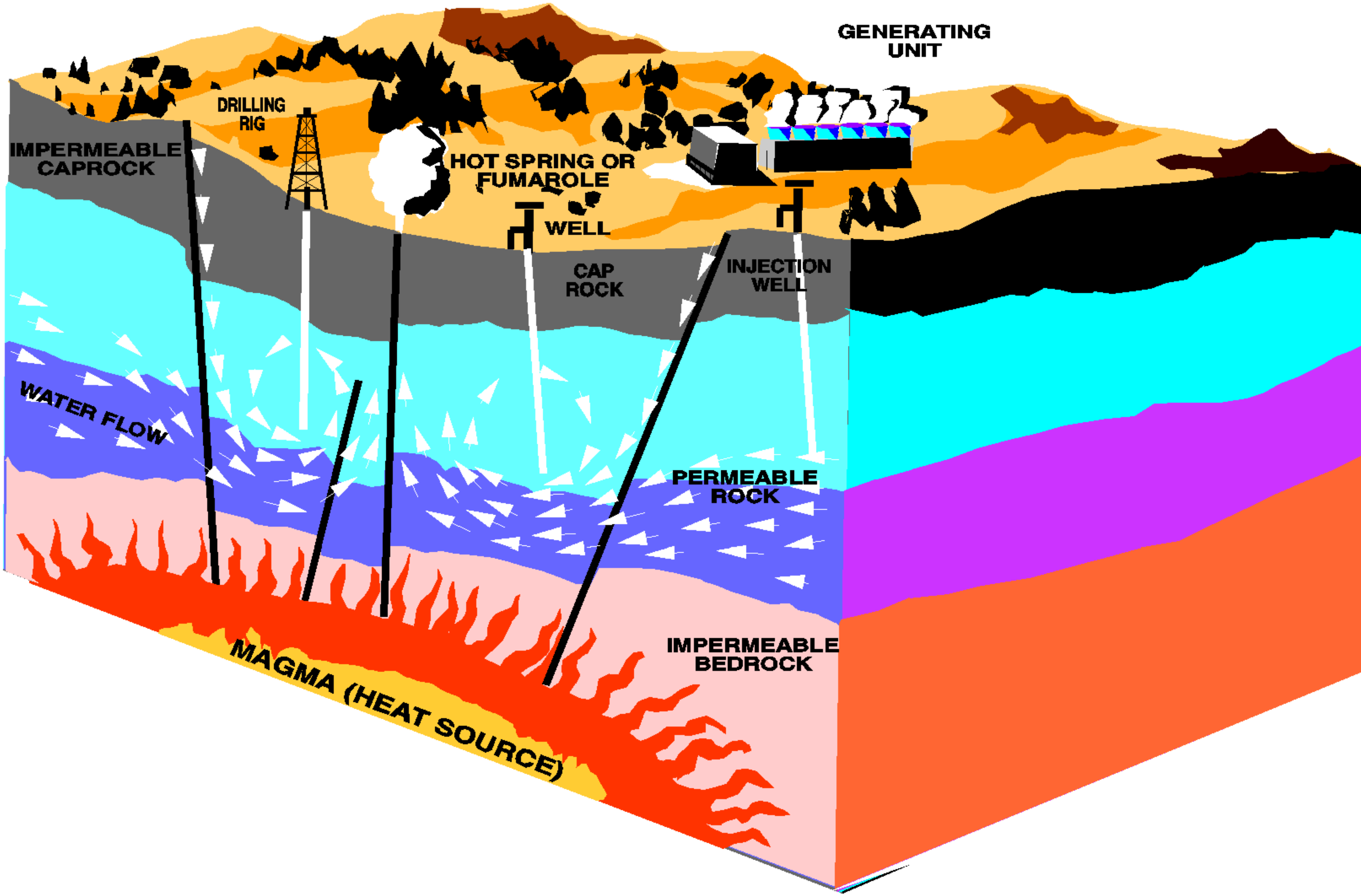
  Environmental effects 环境影响

CO_2 Geological Utilization and Storage



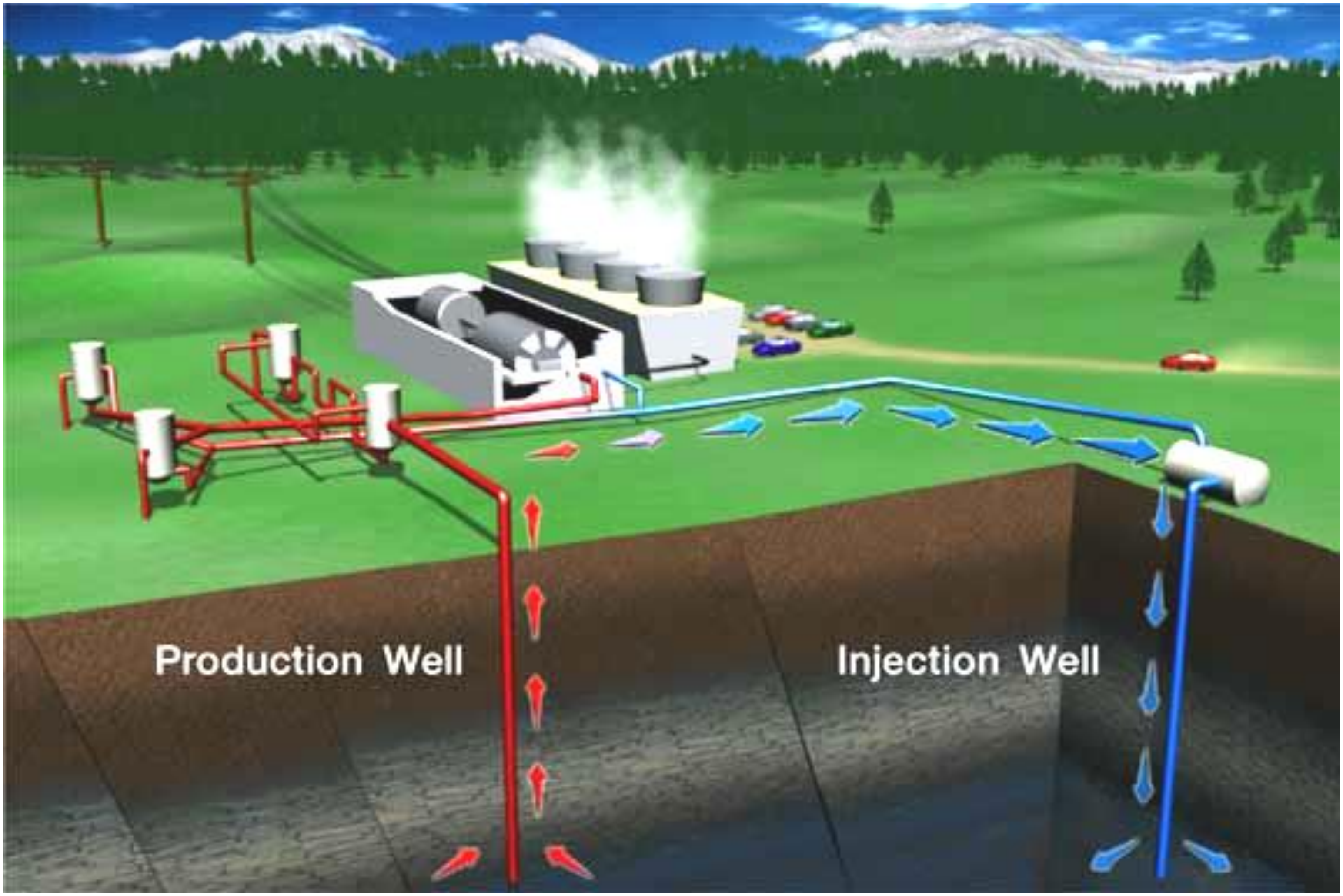
Source: IPCC

Geothermal



Source: Energy Information Administration, Geothermal Energy in the Western United States and Hawaii: Resources and Projected Electricity Generation Supplies, DOE/EIA-0544 (Washington, DC, September 1991

Enhanced Geothermal Systems (EGS)



2 Integrated CO_2 Geological Utilization System CO_2地质利用集成系统

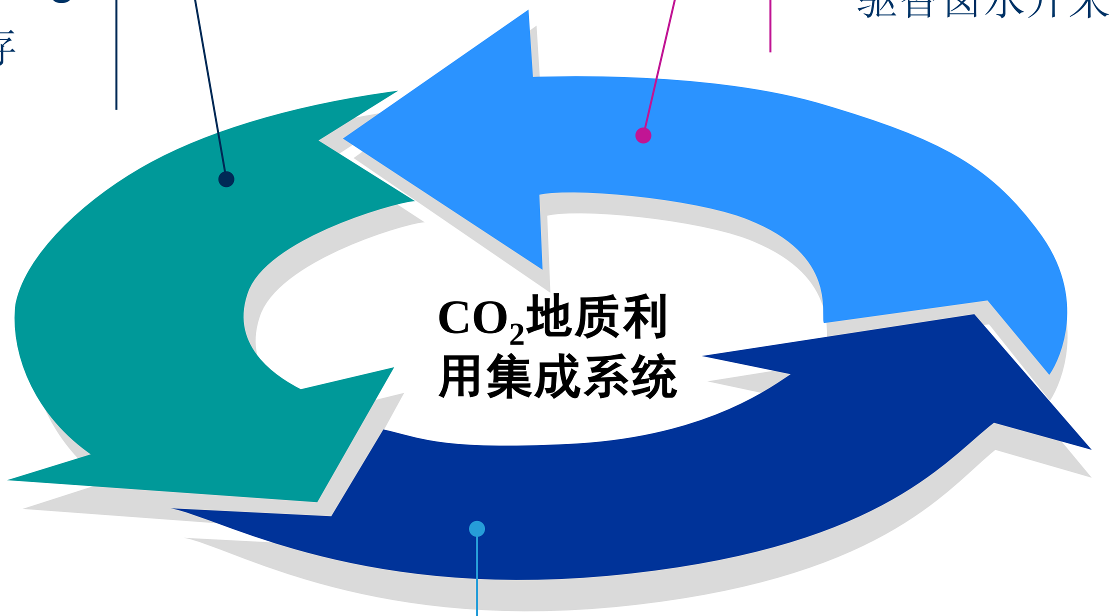
Integrated CO_2 Geological Utilization System

1. CO_2 Storage

CO_2封存

2. Enhanced Brine Extraction

驱替卤水开采



3. Geothermal Energy Utilization

地热能利用

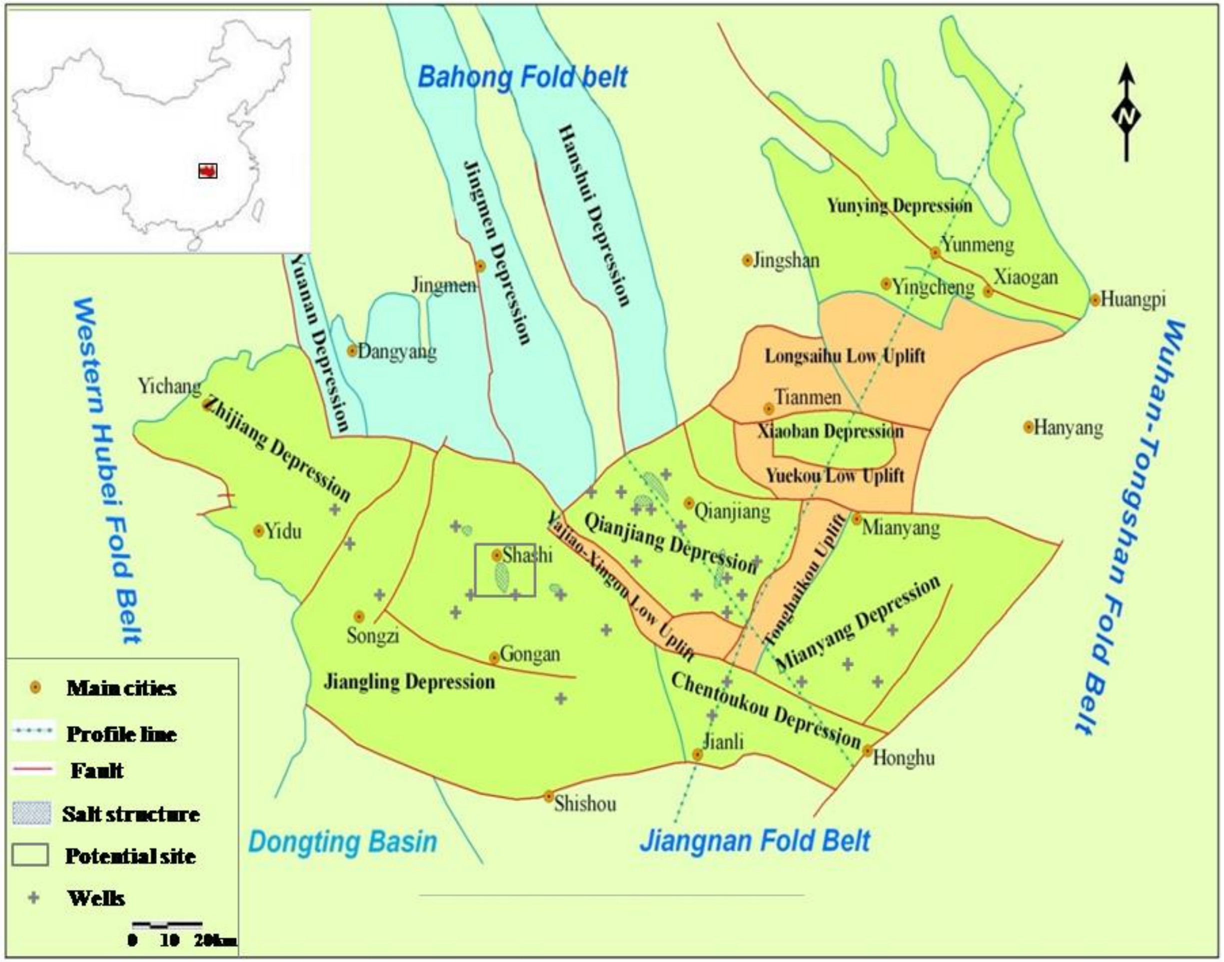
Integrated CO_2 Geological Utilization System

The advantages of this concept are as follows：

Integrated CO_2 Geological Utilization System

- Potential to store CO_2 in an underground aquifer system with high porosity and permeability.
- Simultaneously providing pressure support for brine production activities.
- Produced brines may be used for both geothermal energy content and ions present at economic concentrations.

Why Jianghan Basin?



Location of the research area in Jianghan Basin

The Jianghan Basin is a representative salt-lake rift basin covering an area of 36350 km^2 with the salinity on the order of 150-340g/L . Jiangling Drepression is the brine-richest area.

The temperature of geothermal aquifers is about 100 ° C. The K$^+$ content of this brine is up to 1.6%, which is more than 1.0% of industrial mining grade can be used to produce KCl.

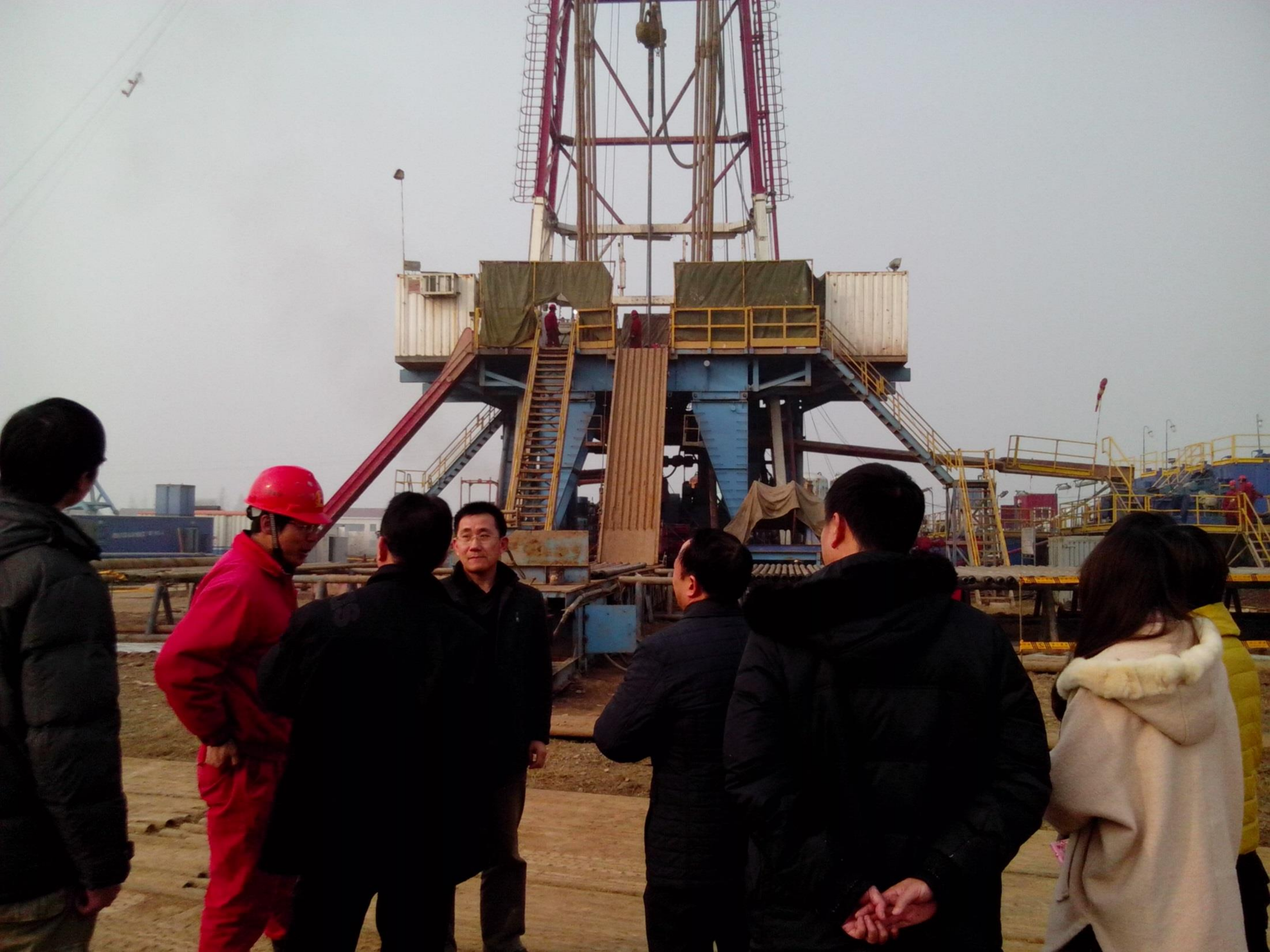
江汉盆地属于我国典型的盐湖裂谷型盆地，面积36350km^2。其地热温度约为100 ° C，卤水中钾含量已超过工业开采水平。

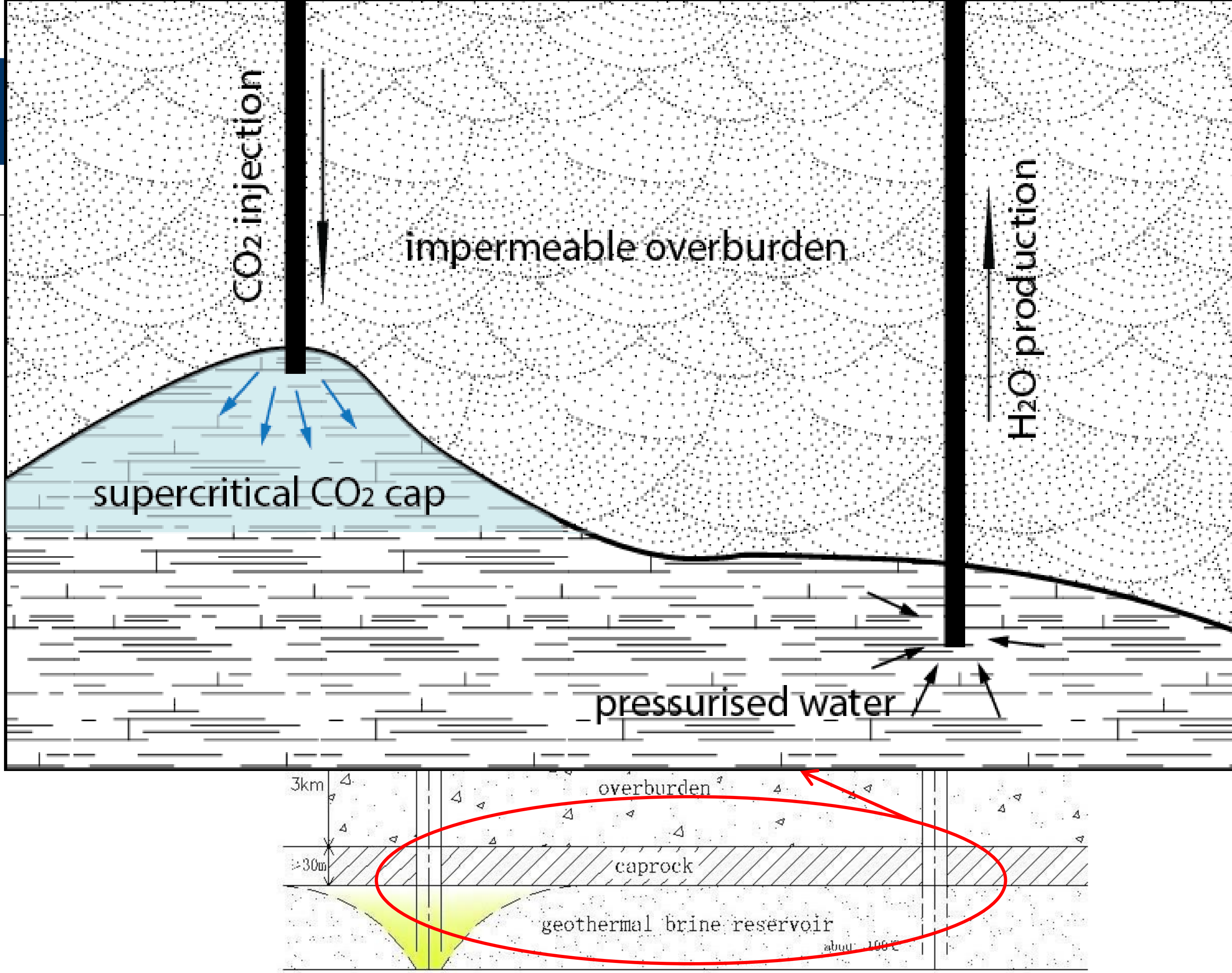
Why Jianghan Basin?

Reservoir and seal pairs of Qianjiang Formation in Jiangling Depression, Jianghan Basin 储盖组合

Formation		Thickness (m)	Sandstone&Interlayer	Reservoir	Caprock
Qian 1	Mud-gypsum rock	110~450	Regional Interlayer		
	Zhouji Sandstone		Sandstone Segment 1		
	Soft-mud rock				
Qian 2	Upper Qian 2	110~700			
	11~15 rhythm		Regional Interlayer		
	Lower Qian 2		Sandstone Segment 2		
Upper Qian 3	Qian 3-1	150~640			
	Three-high resistant Fm				
	Qian 3-2				
Lower Qian 3	Qian 3-3				
	4~8 rhythm		Regional Interlayer		
	Qian 3-4		Sandstone Segment 3		
Upper Qian 4	Qian 4-1	100~700			
	2rhythm				
	Qian 4-0				
	1~6 rhythm		Regional Interlayer		
	7~6 rhythm		Sandstone Segment 4		
	Qian 4-2				
	4 rhythm				
	Qian 4-3				
Lower Qian 4	Lower Qian 4	173~2218			

Formations of abnormally high pressure and temperature lie in the Jianghan basin of China at depth from 2500 to 3500 metres.





A system designed to extract brine and geothermal energy from geothermal reservoirs without pumping equipment

A system without pumping equipment

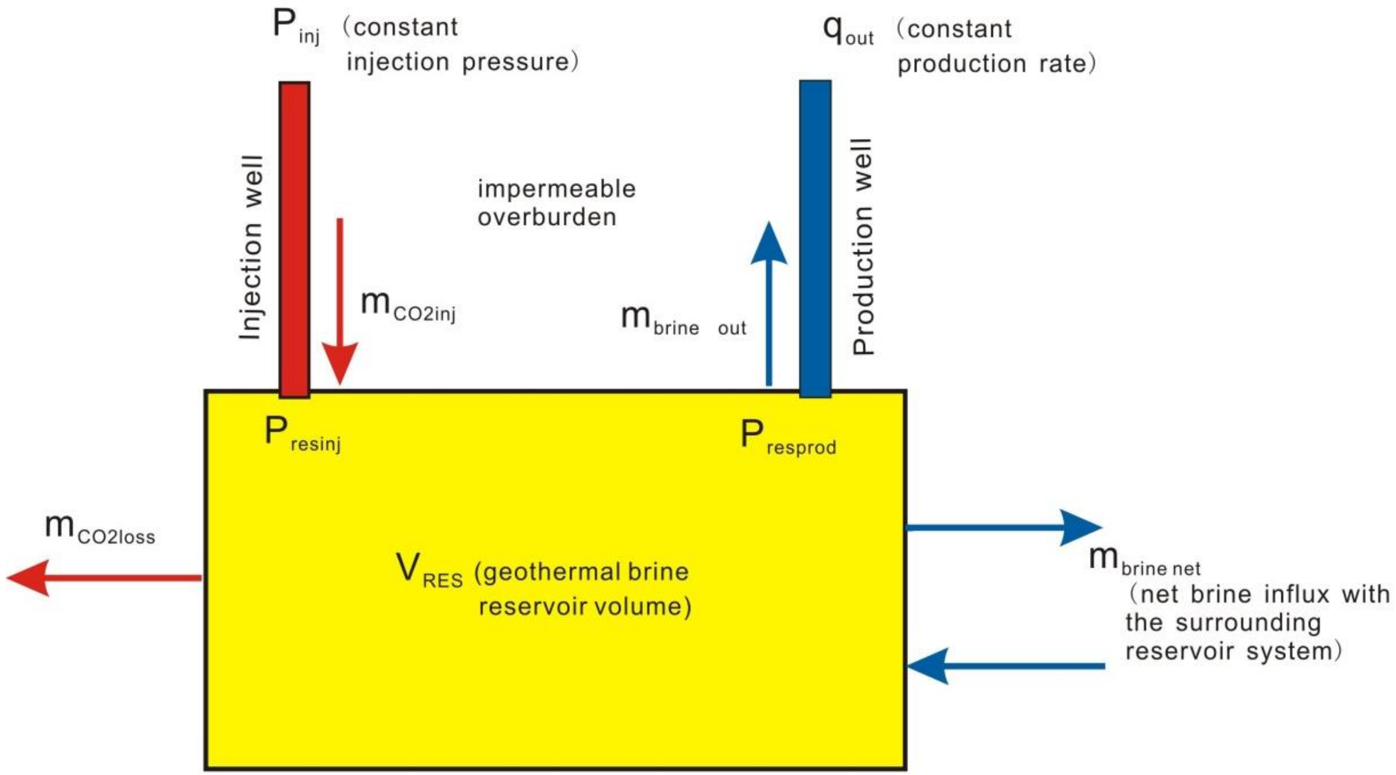
As this strategy offers a number of significant advantages, particularly

- Inherent physical sequestration of some CO_2 as part of the operation (amount needed to fill the reservoir volume), and depending on the geology present, possibility of chemically sequestering CO_2.
- A strong buoyancy effect, whereby the static pressure change (i.e. the change in pressure due to fluid density) in the injection well is much larger than in the production well (due to higher temperatures and lower densities). This leads to high self-driven flow rates, making large pumping equipment unnecessary (although as previously noted, recompression may be economical).
- Manage pressure build-up, the strategy of producing brine can immediately reduce or even completely avoid the pressure build-up associated with CO_2 injection.

3 Conceptual Model Simulation 概念模型模拟

Model design

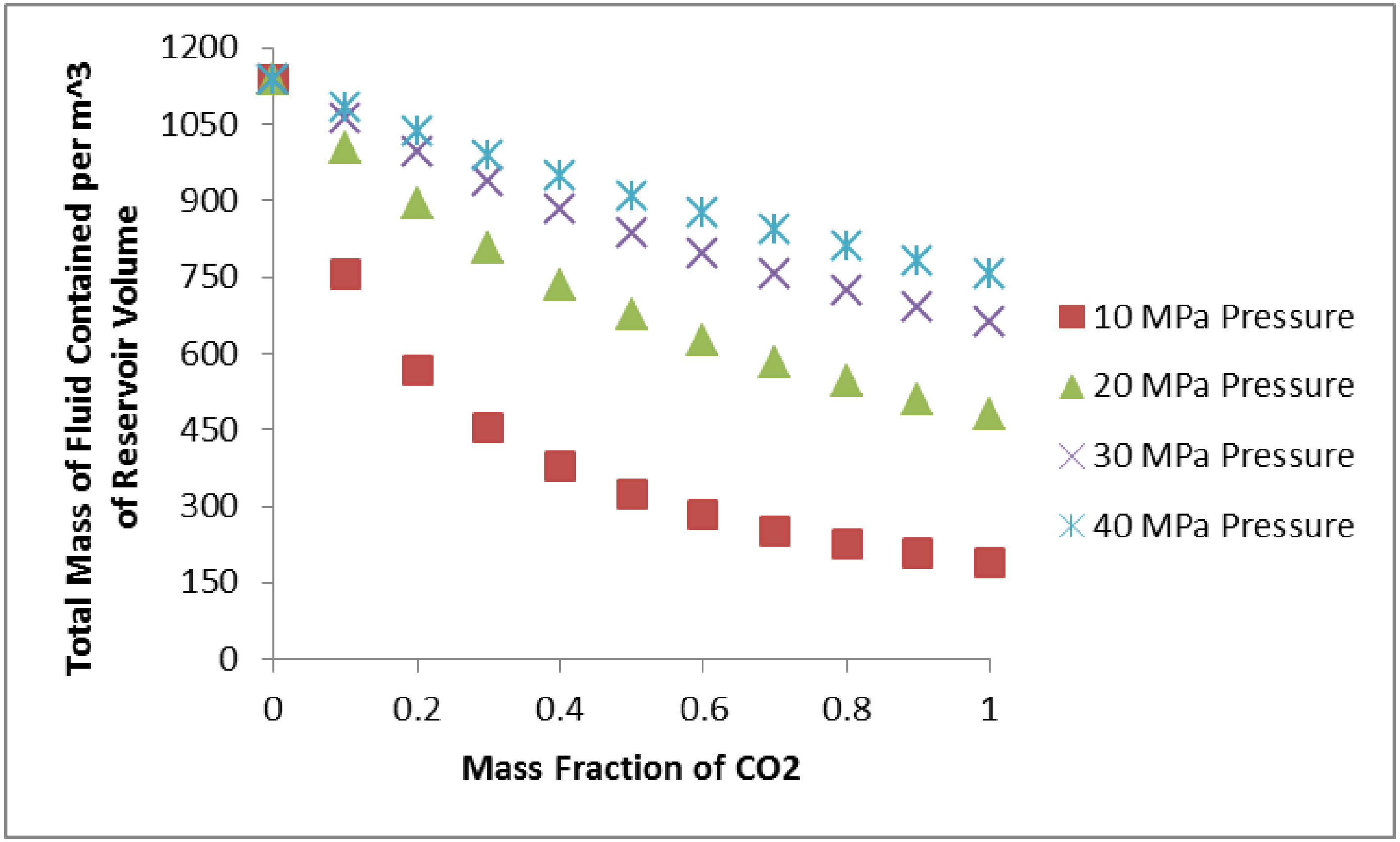
A conceptual model is developed to provide order of magnitude estimates of the total quantity of CO_2 that can be stored in the Basin, total quantities of brine extracted as well as thermal energy content contained in the extracted brine. MATLAB is used to calculate the outputs of the simulated mass balance for defined input parameters.



Assumptions

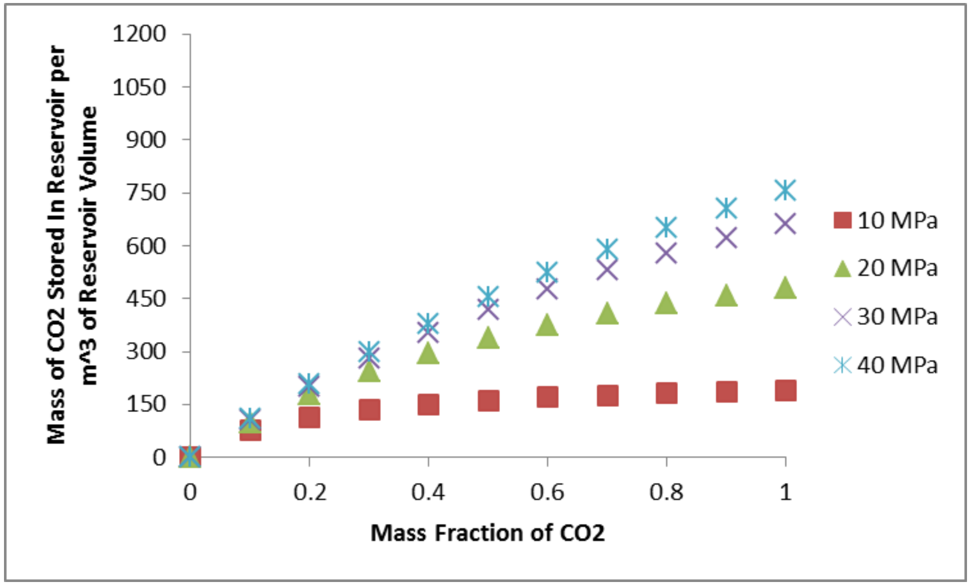
- The system is at mechanical equilibrium – i.e. no internal pressure gradients;
- There is no existing gas cap providing pressure support;
- The brine has a density equivalent to pure water;
- The region of mixing of CO_2 & brine is small, achieved preferably by injecting CO_2 up-dip in shallower regions of relevant aquifer layers;
- The reservoir has been assumed to be homogeneous, which is unlikely to be the case in reality; and
- The effects of localised changes in permeability on CO_2 and brine flows, and their interaction in terms of relative permeability effects, have not been examined in this work.

Total mass of fluid contained per m^3 of reservoir volume versus CO_2 mass fraction



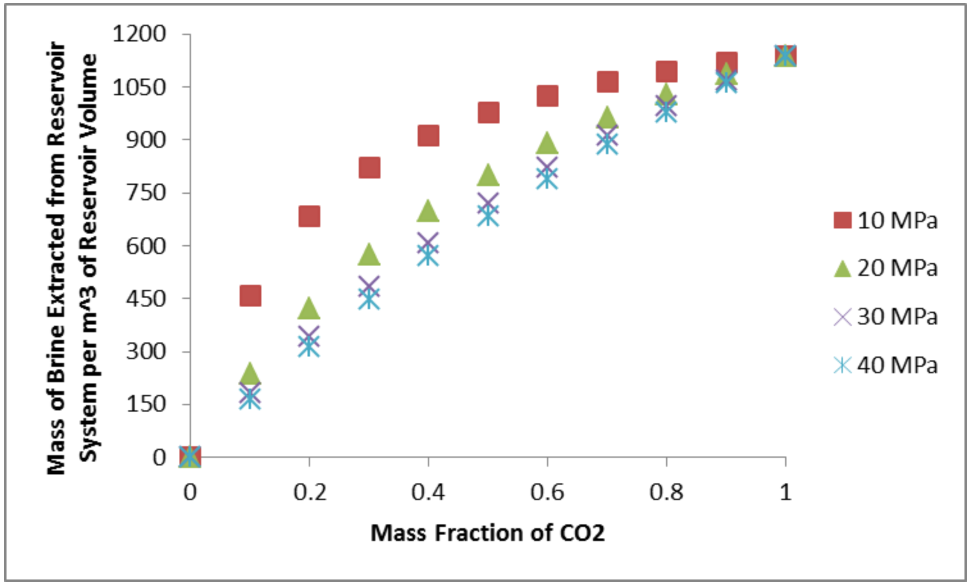
At low pressure (10MPa), there is asymptotic behaviour in response to CO_2 mass fraction. At higher pressure (40MPa), it shows that total mass of fluid contained in reservoir is nearly direct proportional to CO_2 mass fraction. Final reservoir pressure alters the total quantity of fluid that can be stored in the reservoir system.

Mass of CO_2 stored and brine extracted per m^3 of reservoir volume versus mass fraction of CO_2



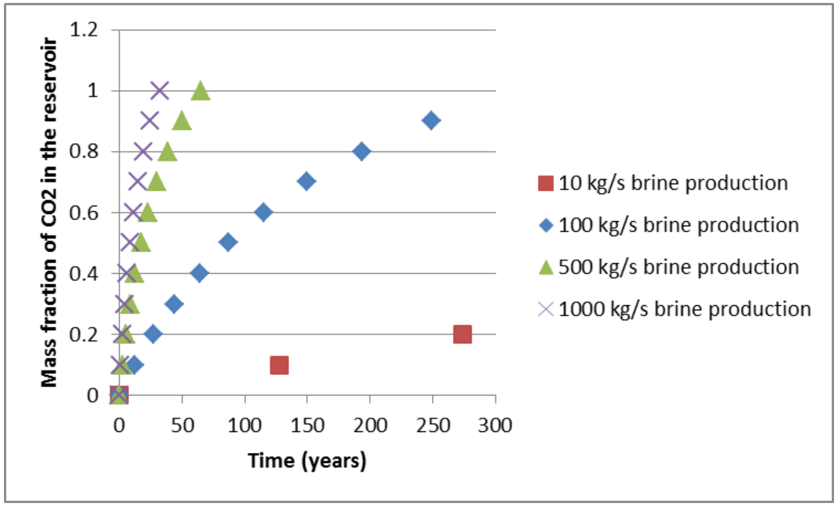
When there is no underground flux at the edges of the reservoir, the maximum amount of brine that can be extracted is 5.15 kg per m^3 of reservoir volume for a reduction in average pressure from 30 MPa down to 20 MPa.

For the same reservoir volume, an injection of just 9.95 million tons of CO_2 would enable extraction of 17.12 million tons of brine (interpolated from results, for a mass fraction X_{CO2} of 0.01 and reservoir pressure 30 MPa) without any reduction in reservoir pressure.

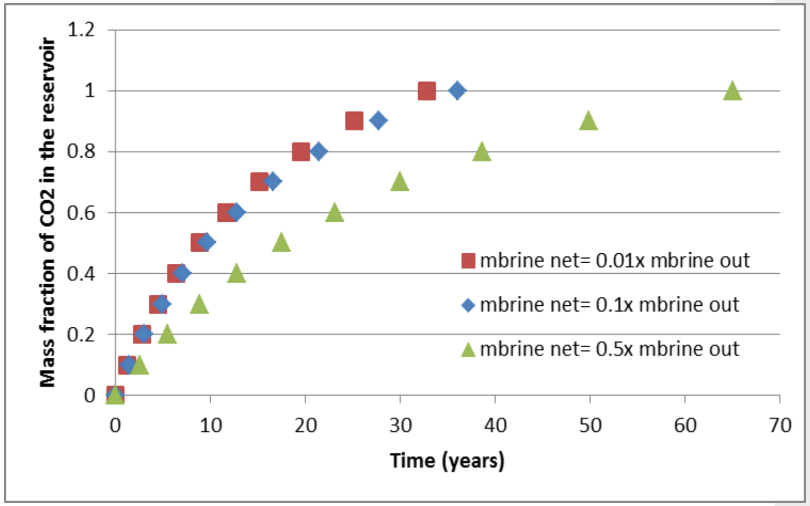


Change in flow at the reservoir boundaries

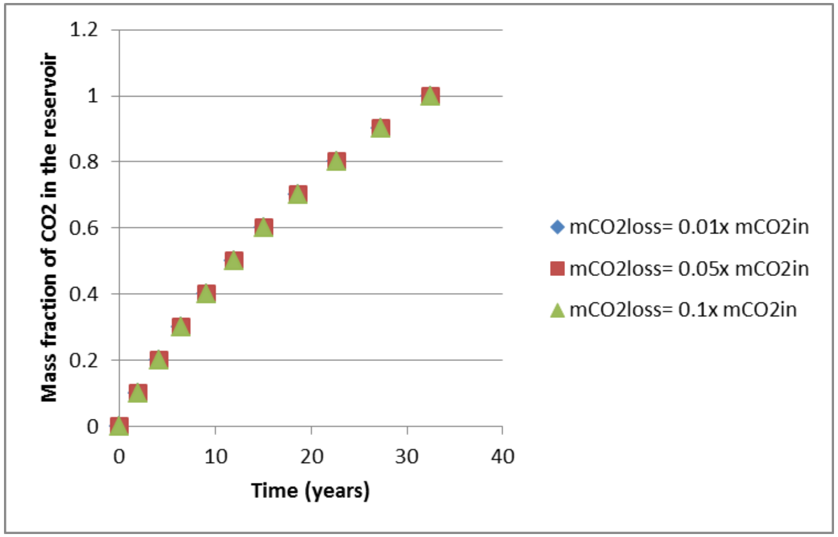
Case 1: No influx or outflow of fluid at the reservoir boundaries



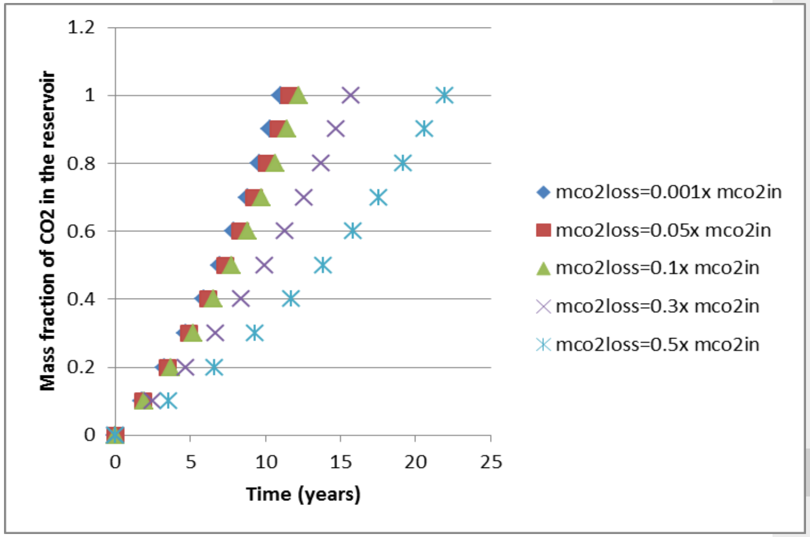
Case 2: No CO_2 loss, with net brine influx at the reservoir boundaries



Case 3: No net brine influx or outflow, with CO_2 loss at the reservoir boundaries



Case 4: With CO_2 loss and net brine influx or outflow at the reservoir boundaries



Geothermal energy content

Due to the low temperature of the brine, **it is not highly-suited to electricity generation**, but there is precedent, such as the Birdville Geothermal Plant in central Australia, and there may be direct local needs for generated electricity in brine processing industries.

The total energy content of the brine, for a surface temperature of 25 °C is **approximately 314 kJ per kg of brine** (estimated from pure water enthalpy). Thus, for production rates of 50-1000 $kg \cdot s^{-1}$ (approximates of one well and a field development), this represents **a substantial thermal energy flow of 15.7 MWth to 313 MWth**.

The Carnot efficiency for a source temperature of 100 °C and a sink temperature of 25 °C is ~20.1%. Assuming a second-law thermodynamic efficiency of 25%, which is conservative for geothermal power developments, the potential electrical output is 5% of thermal heat flow, **the previously mentioned flows of brine could generate 0.8 MWe to 15.8 MWe of electricity**.

4

Multi-well design of CO_2 injection and brine production 抽注井群设计

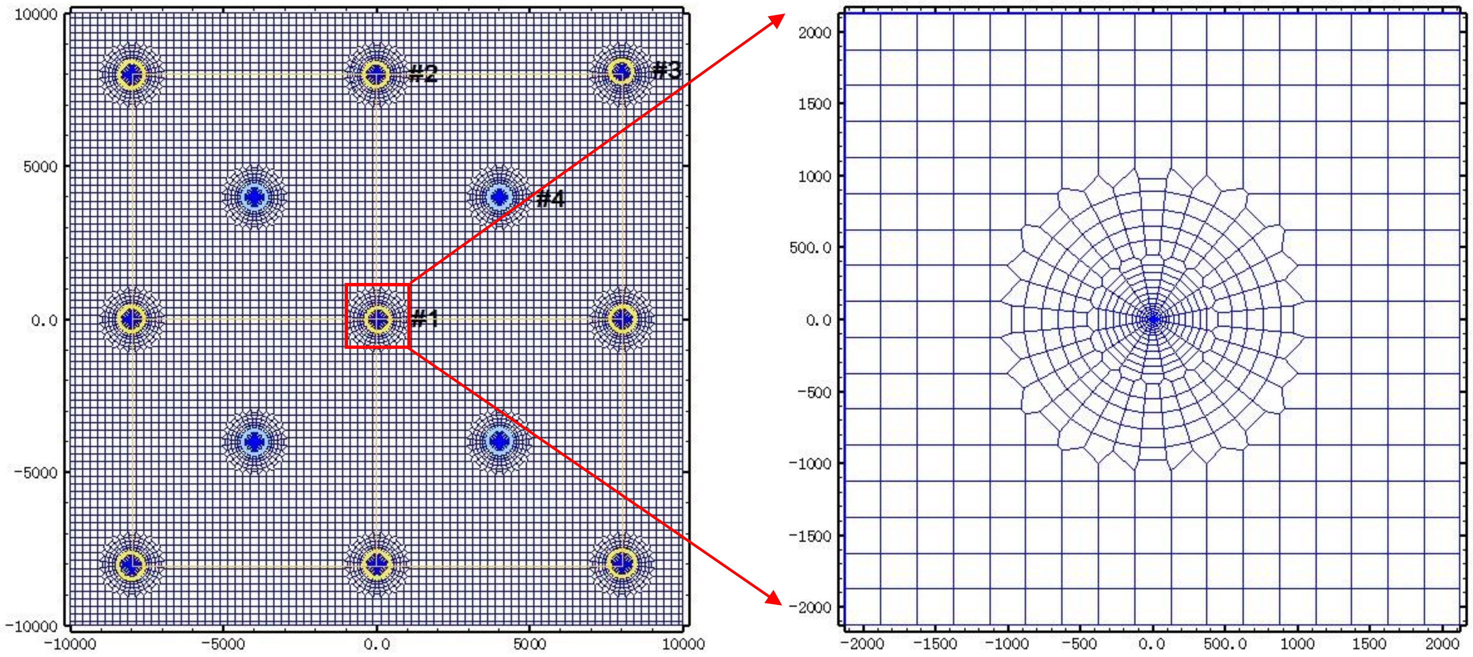
Reservoir Model

Properties	Formation	Seal
Thickness(m)	100	50
Permeability (m^2)	10^{-14}	10^{-20}
Pore compressibility (Pa^{-1})	4.5×10^{-10}	4.5×10^{-10}
Porosity	0.10	0.05
van Genuchten m	0.46	0.46
Van Gemuchten α (Pa^{-1})	5.1e-5	1.6e-7
Residual CO_2 saturation	0.05	0.05
Residual water saturation	0.30	0.30

We developed a 3-D homogeneous model of a 100-m-thick saline formation abundant in potassium-bearing brine with the top of the storage formation located at 3000m below the ground surface and bounded by a 50-m-thick caprock. The outer lateral boundary has a no-flow condition to represent a semi-closed system.

Well placement

As for the strategy of brine extraction and CO_2 injection, we arranged 13 vertical wells in a rectangular pattern with the same well spacing of 8 km in the study area.

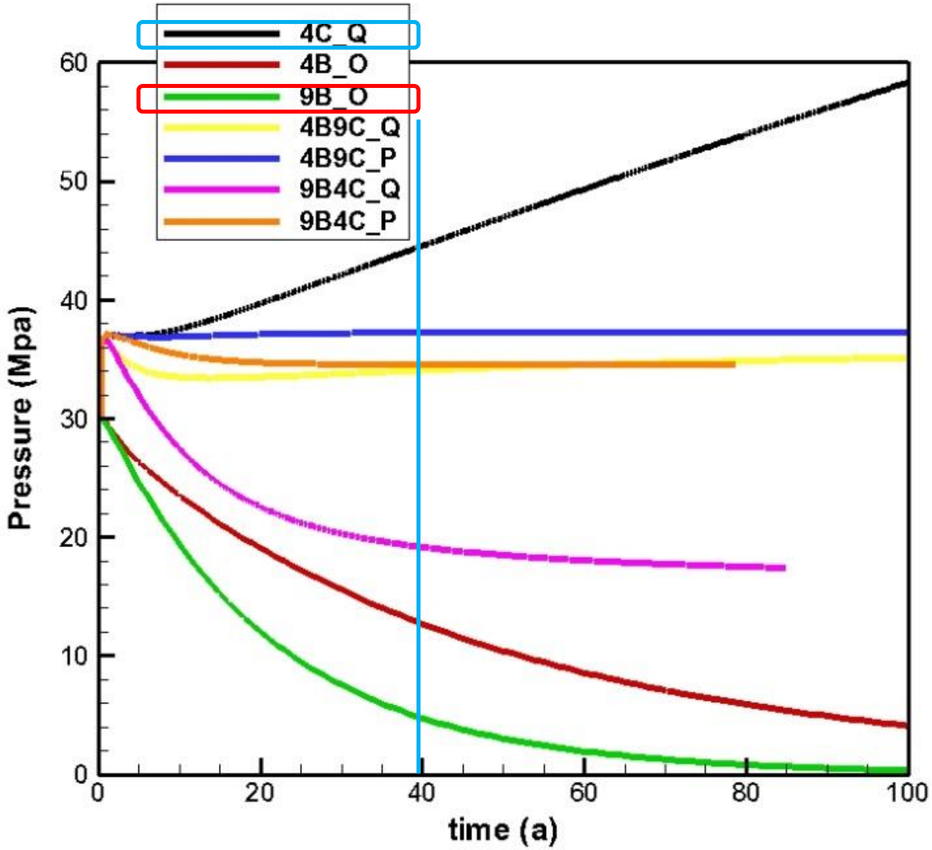


The 13 vertical wells are divided into two groups, and the yellow-circled wells are in one group while others are in another. Due to symmetry, we chose four wells marked as #1, #2, #3 and #4 to observe pressure response and flow change varying with time.

Scheme of rectangular well pattern

Scheme 注采方案	9B4C_Q	4B9C_Q	9B4C_P	4B9C_P
Number of CO_2 wells CO_2注入井个数	4	9	4	9
Number of brine wells 卤水开采井个数	9	4	9	4
CO_2 Injection scheme CO_2注入方案	Constant injection rate 0.25Mt/yr per well		Constant inejction pressure of 40Mpa	
Brine Extraction scheme 卤水开采方案	constant extraction pressure of 1Bar 固定抽水压力为一个大气压			
Simulation Run Time 模拟时间(yr)	Simultaneous CO_2 injection and brine extraction for 100 years and monitoring for 100years			
Simulation Tool 模拟软件	TOUGH_ECO2N_MP			

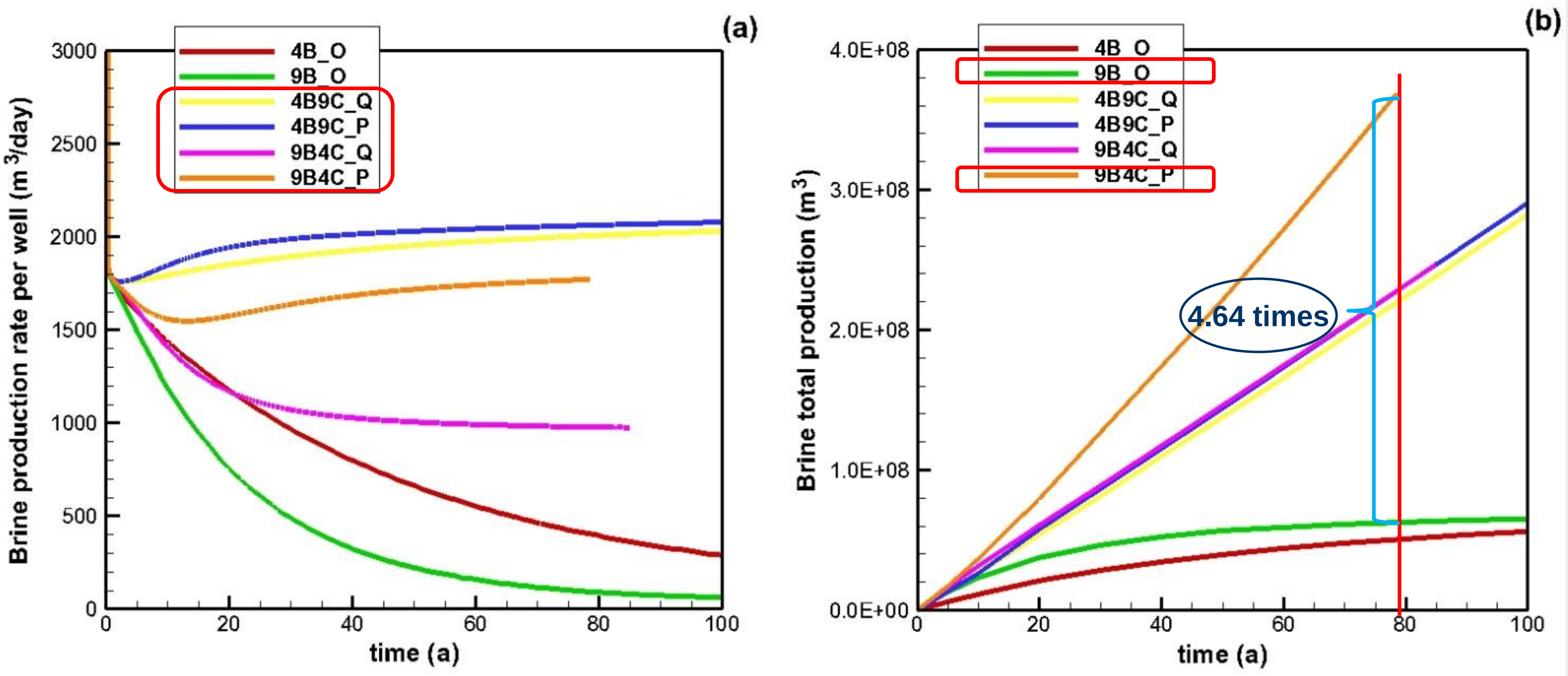
Pressure response at the top storage formation varying with time for different cases



单纯地卤水开采造成储层压力持续的下降；单纯地CO_2灌注则造成储层压力的持续积累；卤水开采与CO_2灌注联合模式可以有效地调控含水层的压力，使其保持在稳定范围内。

For the only brine production cases (9B_O), the pressure significantly declines with time. For the only CO_2 injection case (4C_Q), pressure continuously increases with time.

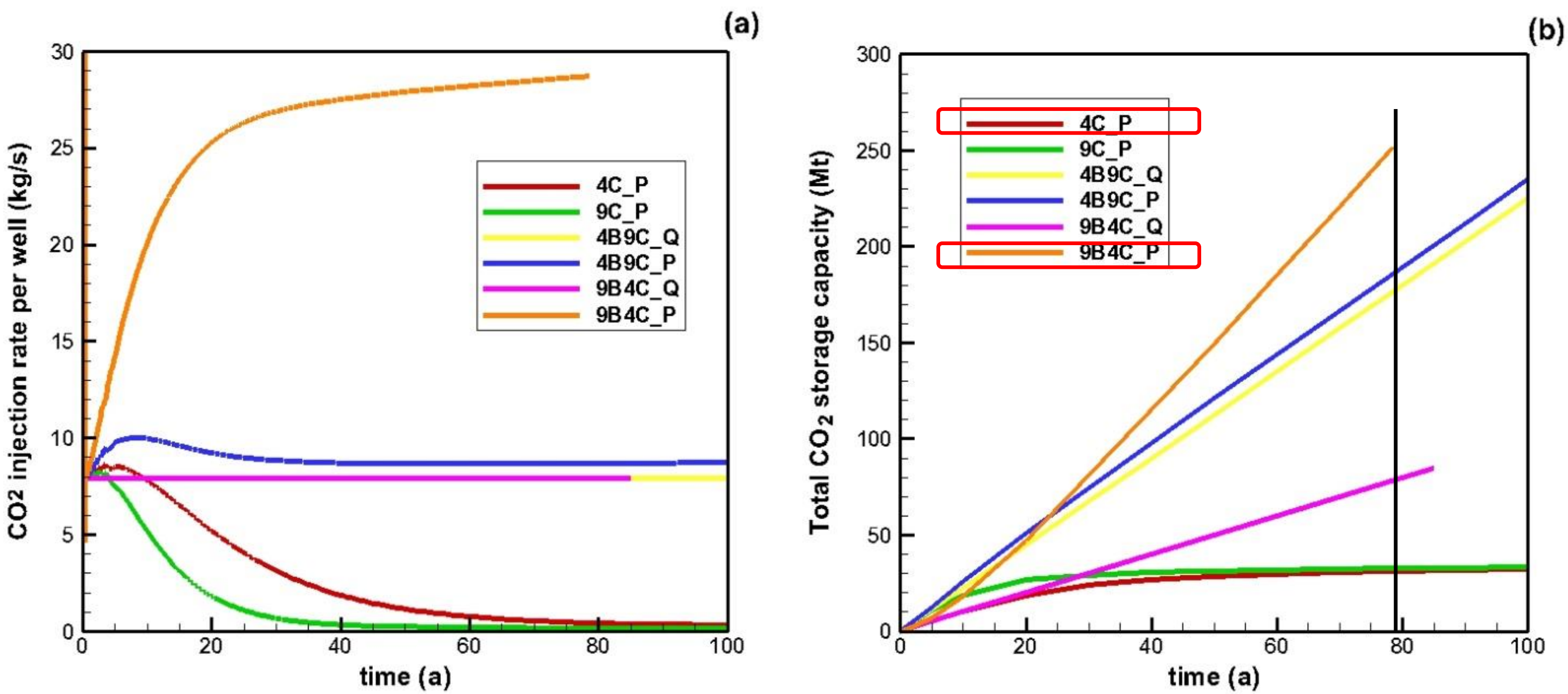
Brine production rate of single well and total production of all extraction wells varying with time



Injecting CO_2 can significantly enhance the brine production capacity of single well and total production. For case 9B4C_P, the average daily production of brine is higher than 1500 m^3/day, and the total brine production reaches up to 3.68×10^8 m^3 after 79 years, accounting for 8.75% of the total brine volume.

卤水开采与CO_2灌注联合模式可显著提高单井卤水日采量及开采总量。

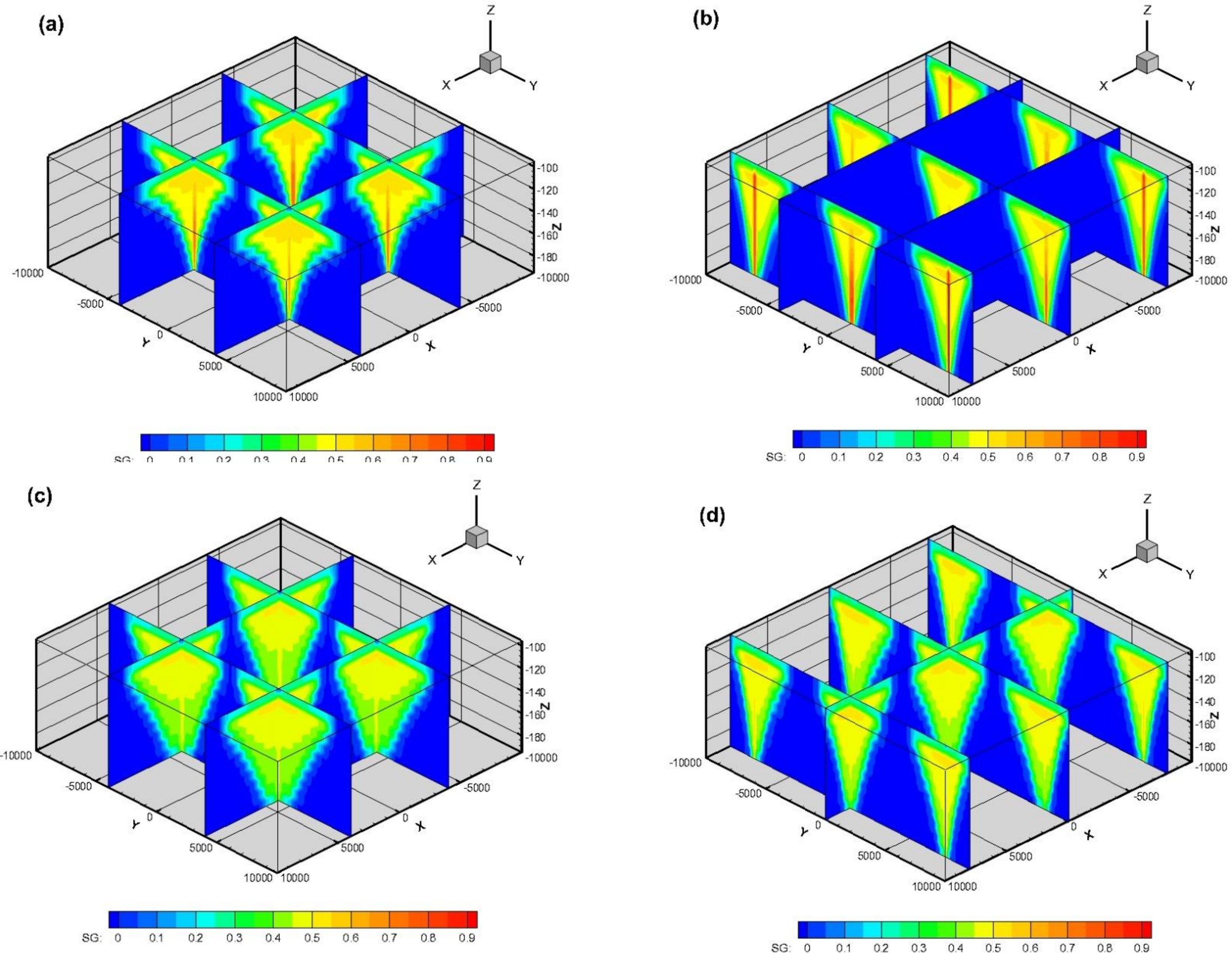
CO_2 injection rate of single well and total injection capacity of all CO_2 injection wells varying with time



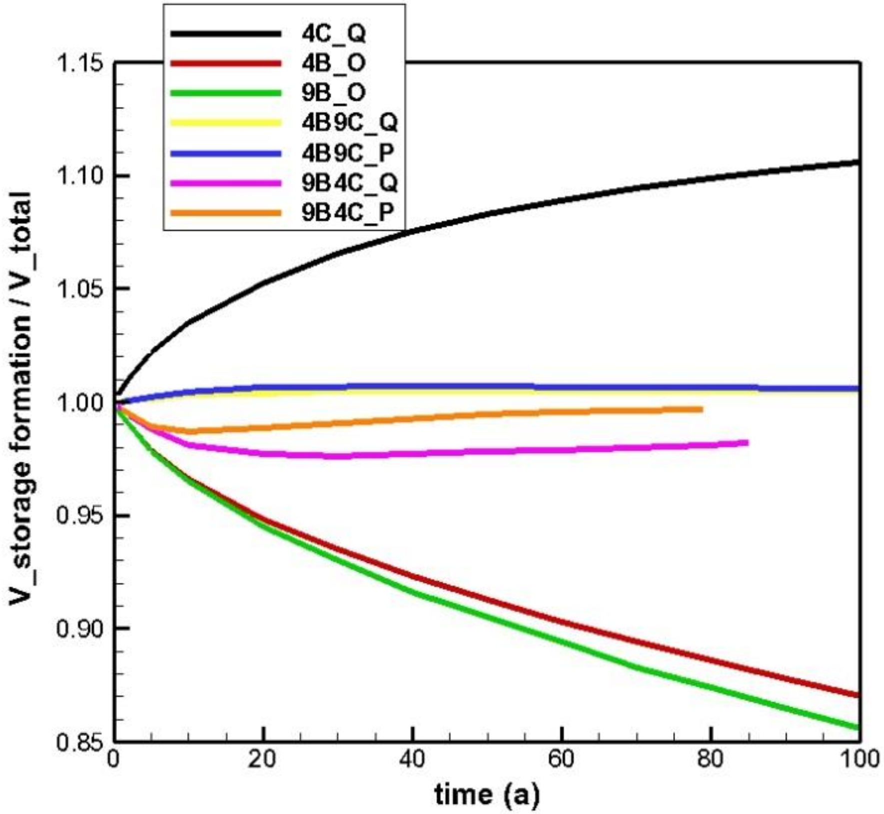
Combined with brine production, CO_2 injectivity and storage capacity is remarkably improved. Particularly for case 9B4C_P, CO_2 injection rate is up to 28kg/s (corresponding to 0.88Mt/yr) and the total storage capacity exceeds 252 Mt CO_2 after 79 years' simultaneous brine extraction and CO_2 injection, increased 6.8 times in comparison to the only CO_2 injection case.

卤水开采与CO_2灌注联合模式下CO_2注入性得到显著提高

Spatial distribution of CO_2 plume （CO_2羽分布）



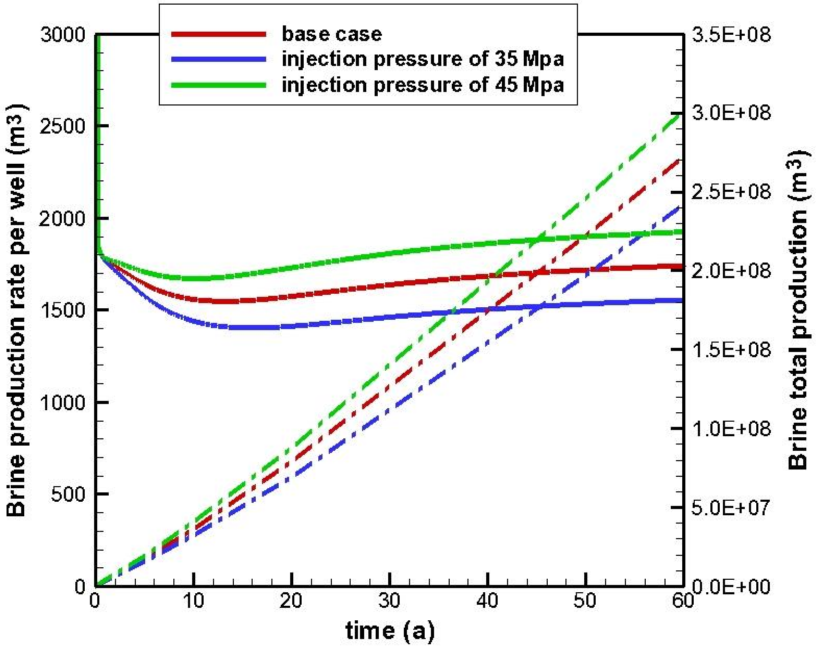
Comparison of volume ratios of water change in the storage formation to total brine production

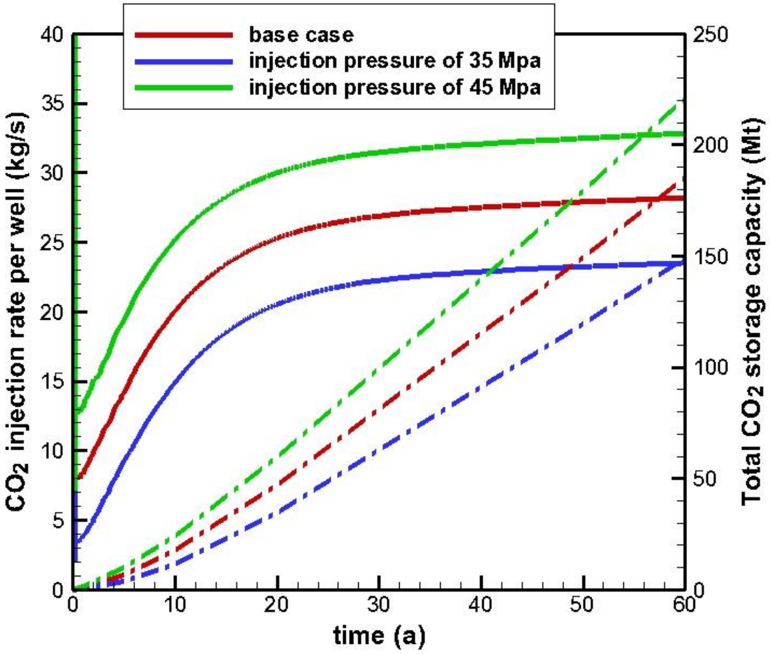


过高的压力梯度导致主作业层与上覆地质体发生越流补给。CO_2与卤水耦合注采模式可有效缓解垂向越流的发生，减少泄露风险及环境影响。

The excessive pressure gradient leads to leakage between the storage formation and the overlying geological units including caprock and top formation. The combination of brine production and CO_2 injection can effectively mitigate the vertical leakage between the geological units.

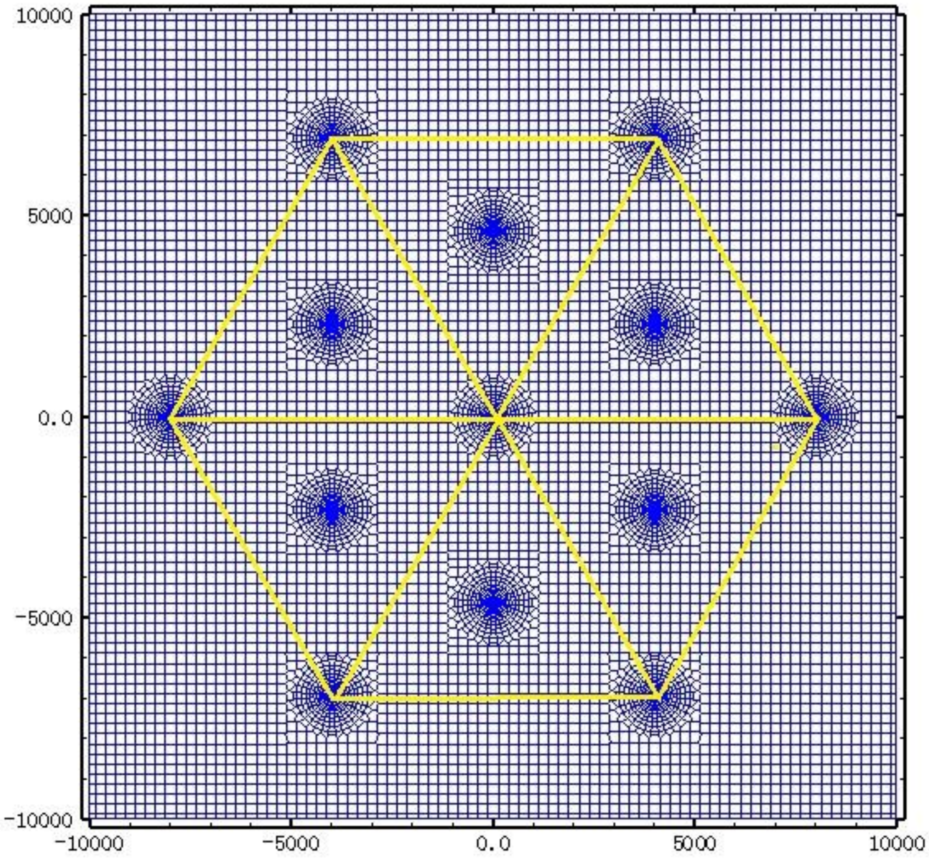
Effect of CO_2 injection pressure on the combined efficiency of brine production and CO_2 injection





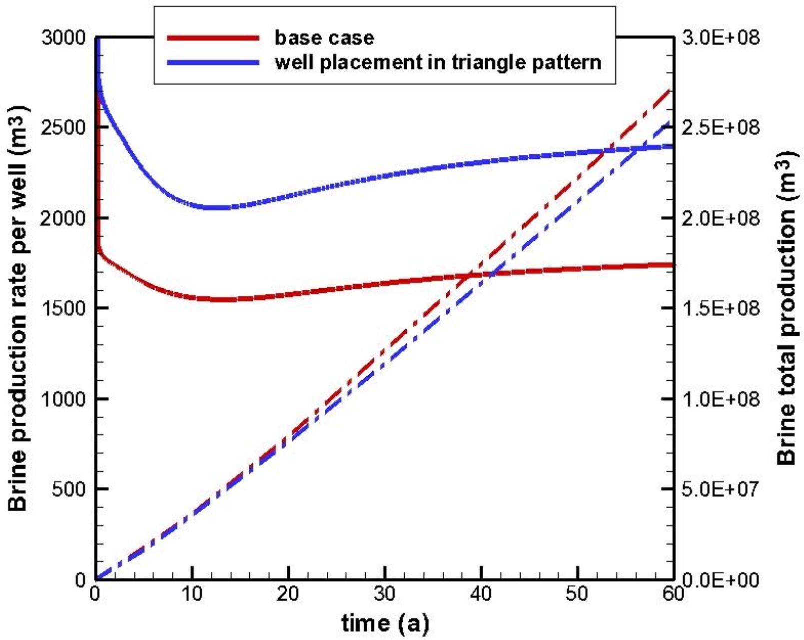
Brine production efficiency and CO_2 injection capacity increases with the injection pressure. Of course, the injection pressure is limited to fracture pressure of the reservoir and capillary entry pressure of caprock.

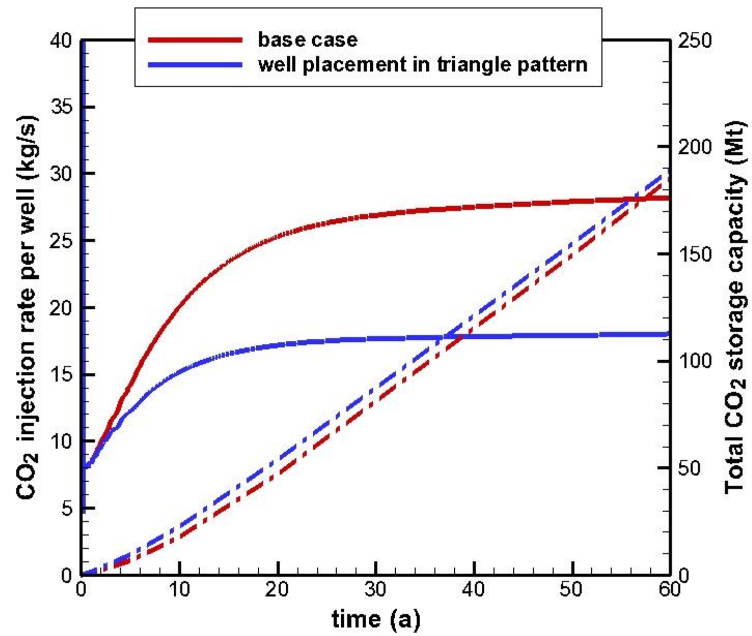
Diagram of well placement in triangle pattern



Note that the yellow line linked wells are brine production wells and the scattered ones are CO_2 injection wells.

Effect of well placement on the combined efficiency of brine production and CO_2 injection





Here we investigate another well placement in triangle pattern with arrangement of 7 brine production wells and 6 CO_2 injection wells. There is no distinct advantage of the both well placement. Therefore in the practical projects, the choice of well placement should be made by taking in account the site topography and project objective.

5 Conclusions 结论

Conclusions

Simultaneous brine extraction and CO_2 storage in deep saline formations can not only effectively regulate the region pressure balance of the storage formation, but also significantly enhance the brine production capacity and CO_2 injectivity as well as the storage capacity, thereby achieving the maximum utilization of underground space.

The total brine production reaches up to 3.68×10^8 m^3 accounting for 8.75% of the total brine volume and the total storage capacity of CO_2 exceeds 252 Mt CO_2 in mass corresponding to 3.65×10^8 m^3 in reservoir pore volume after 79 years' simultaneous brine production and CO_2 injection.

The economic income of K^+ and the other elements can be combined with determination of potential value for electricity conversion of the thermal energy contained in the brine, and together these can be incorporated with the cost of sequestration to approximate overall economic value of this concept.

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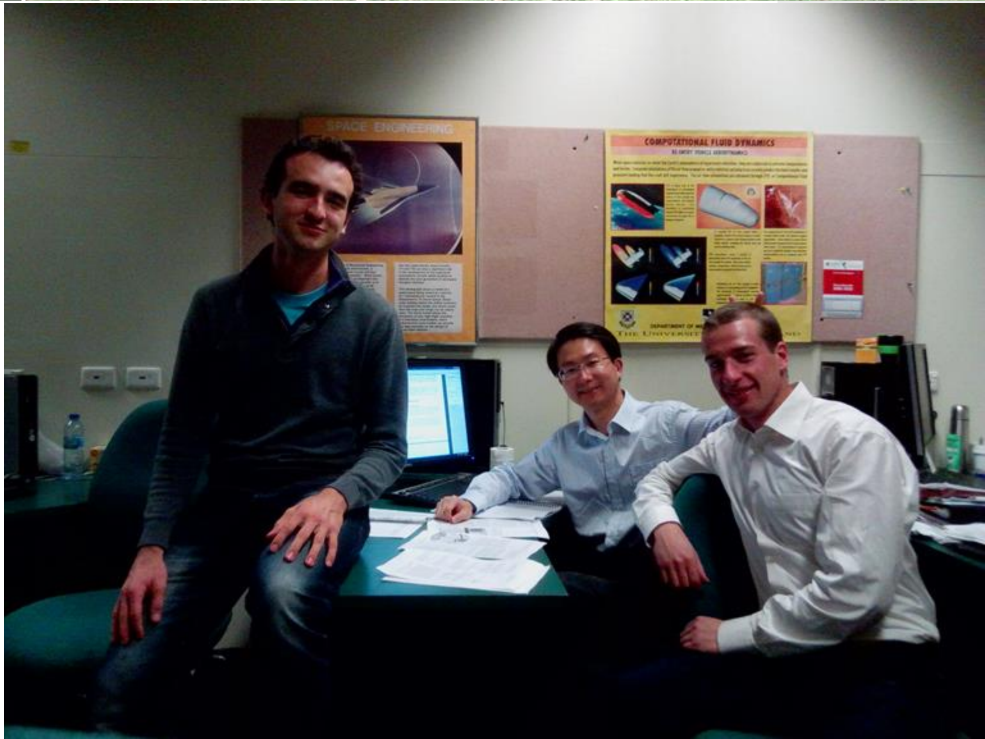

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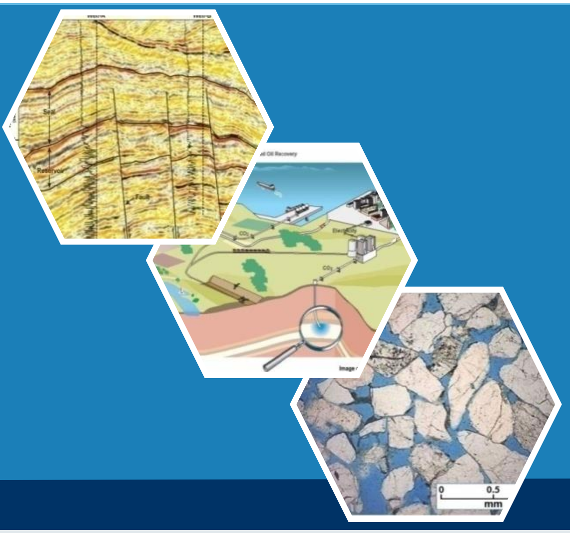

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