Assessment of storage capacity for CO_2 in saline aquifers near hydrocarbon fields, northern Songliao Basin, China

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Abstract

Carbon dioxide Capture and Storage (CCS) is the only technology currently available that can significantly reduce carbon dioxide (CO_2) emissions from conventional fossil fuel use. Depleted oil/gas fields, unmineable coal seams and deep saline aquifers are generally considered to be the main storage options. In this paper, the authors consider opportunities presented by aquifers close to hydrocarbon fields in northern Songliao Basin (China) for storage. Data obtained during exploration and production often delineates nearby structures filled with saline water which have not been charged with hydrocarbons but could offer an opportunity for CO_2 storage. Based on published data and production data from hydrocarbon fields in northern Songliao Basin, the potential for geological storage of CO_2 in these hydrocarbon field saline aquifers (HFSA) has been assessed and in northern Songliao Basin, the central and western regions offer great potential for CO_2 storage in HFSA. Out of the 42 identified oil/gas fields, aquifers near 24 of the fields offer

promising storage potential with an estimated potential storage capacity of 9.8×10^9 tonnes (t) CO_2, which is more than 100 times the current annual emissions of large point sources in the Songliao Basin.

1 Introduction

Fossil fuels are expected to remain a key part of the future energy and industrial production mix, therefore CCS, as the only currently available technology capable of large scale reduction of emissions from fossil fuels, is seen as essential to reduce CO_2 emissions to the atmosphere.[1]

Depleted oil/gas fields, unmineable coal seams, and deep saline formations are generally considered the most promising options for geological storage of CO_2. Deep saline aquifers have the largest potential, but usually, few datasets are available and this increases uncertainty about their suitability for storage. Depleted oil/gas fields are generally well understood and data are available, but in China these fields are often compartmentalized into many small reservoirs, and in many reservoirs numerous boreholes have been drilled to access these small compartments increasing the number of potential leakage pathways if used as a CO_2 storage site. Aquifers are often identified above, below or near the hydrocarbon reservoirs during exploration where traps have not been charged and these aquifer formations are rarely considered for their CO_2 storage potential. However, if these hydrocarbon field saline aquifers (HFSA) and hydrocarbon fields are considered together, this could offer an excellent storage opportunity.

Several studies on the potential for CCS in China have been carried out by Chinese scientists. In many cases, basin-scale assessments and approximate capacity calculations have been published.[2-4] The Songliao Basin is one of the most important sedimentary basins in China, having a wealth of mineral resources supporting a large industrial economy. Some CCS research has already been carried out in the southern part of Songliao Basin where the first CCUS (carbon capture, utilisation and storage) project in China is located.[5] The northern part of the basin has not been studied in detail and so in this paper, the authors focus on the northern Songliao Basin.

In order to select the potential area for CO_2 storage in HFSA, a set of 12 basin-scale weighted criteria and a set of 39 regional-scale weighted criteria were considered. The assessment of CO_2 storage suitability and capacity in HFSA in northern Songliao Basin is presented here.

2 CO_2 storage in oil/gas field saline aquifers

The hydrocarbon field saline aquifers (HFSA) are defined as the aquifers which are located in close proximity to the hydrocarbon fields but are hydrodynamically unconnected to the hydrocarbon fields. Unlike the deep saline aquifers usually considered for storage, hydrocarbon field saline aquifers may be relatively shallow (though still deeper than 800 m) and smaller. HFSA could be considered as potential CO_2 storage sites as they have the following advantages:

a). As HFSA are located near exploited hydrocarbon reservoirs, it can reasonably be assumed the geological conditions, such as structure, lithology, trapping and seal condition, are similar to those of the reservoirs;

b). During the exploration and development of the reservoirs, HFSA may also be revealed which makes it possible to obtain more detailed data (without new data acquisition) than for the deep saline aquifers in unexplored basins;

c). If the wells have been drilled through the HSFA, some of the existing production facilities of the oil/ gas field could be shared by the CO_2 storage facility which would reduce the costs of storage and the areal footprint of anthropogenic activities.

The security of CO_2 storage in HFSA is extremely important because if CO_2 were to leak into nearby formations it could contaminate existing energy reserves.[6] If the nearby hydrocarbon fields are producing, leaking CO_2 might influence production and if CO2 reaches the production wells it would need to be separated from the produced hydrocarbons. After injection, potential CO_2 leakage mechanisms are classified as follows: diffusive loss of dissolved gas through the caprocks, leakage through the pore spaces if capillary entry pressure is exceeded, leakage through faults or fractures and well leakage.[7] If the impermeable seal is suitably thick and unbroken, then leakage through the caprock and faults or fractures will not occur. Extensive oil and gas exploration in hydrocarbon fields near HSFA has resulted in a high density of wells, which may present potential migration pathways and permit large scale leakage.[8] Leakage through wells can also be avoided by good well cementing practices and leakage through pore spaces can be avoided by managing the injection strategy in order to control intraformational pressure. Therefore, the security of CO_2 storage in HFSA is strongly dependent on detailed site selection and operation.

3 Calculation method of physical and chemical trapping in hydrocarbon field saline aquifers

Carbon dioxide will be trapped in HFSA through the same mechanisms as CO_2 storage in deep saline aquifers: structural and stratigraphic trapping, residual CO_2 trapping, hydrodynamic trapping, solubility trapping and mineral trapping.[9] Most existing calculation methods are based on these mechanisms.

The US Department of Energy (USDOE) assumed all pore space in the saline aquifer can be used for CO_2 storage, i.e. all the saline brine can be forced out of the aquifer.[10] The theoretical formula of effective CO_2 storage in saline aquifer from this, which is widely used is as follows:

$$M_{CO_2} = \rho_{CO_2} \times A \times H \times \emptyset \times E \qquad [1]$$

Formulae for the theoretical storage capacity of aquifers are given by the CSLF as the following: [11]

Theoretical storage capacity of structural/stratigraphical trapping in aquifers:

$$M_{CO_{2}s} = A \times H \times \emptyset \times (1 - S_{wirr}) \times \rho_{CO_2} \qquad [2]$$

Theoretical storage capacity of residual trapping in aquifer storage sites:

$$M_{CO_{2}t} = \Delta V_{trap} \times \emptyset \times S_{CO_{2}t} \times \rho_{CO_2} \qquad [3]$$

The theoretical storage capacity of CO_2 dissolved into aquifer pore water:

$$M_{CO_{2}d} = A \times H \times \emptyset \times (\rho_s X_s^{CO_2} - \rho_0 X_0^{CO_2}) \qquad [4]$$

Where, M_{CO_2} is total CO_2 storage capacity (t); $M_{CO_{2}s}$ is structural CO_2 storage capacity (t); $M_{CO_{2}d}$ is soluble CO_2 storage capacity (t); $M_{CO_{2}t}$ is residual CO_2 storage capacity (t); $S_{CO_{2}t}$ is trapped CO_2 saturation (%); 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_2} is density of CO_2 in the aquifer (kgm^{-3}); s_{CO_2} is solubility of CO_2 in the aquifer fluid (kgm^{-3}); ρ is density of formation water (kgm^{-3}); X^{CO_2} is CO_2 content (mass fraction) in formation water (%), and the subscripts 0 and S stand for initial CO_2 content and CO_2 content at saturation respectively; E is the CO_2

storage efficiency factor which reflects the fraction of the total pore volume that is filled by CO_2 (dimensionless);

Based on these two established methods, the authors decided to calculate the theoretical CO_2 storage capacity in HFSA considering only structural, stratigraphical and solubility trapping. Residual CO_2 trapping, hydrodynamic trapping and mineral trapping have strong and complex interrelationships and occur on very different timescales, which can only really be calculated through complex numerical modelling.[9] Mineralization is a relatively slow process and is not expected to offer a significant amount of storage capacity over the injection lifetime. For solubility trapping in HFSA, the following assumptions were made:

a). Some water cannot be displaced from the aquifer by the injected CO_2 (irreducible water saturation). CO_2 can dissolve into this connate water;

b). Some CO_2 will dissolve into the water which is displaced by the CO_2; this could then migrate out of the aquifer and could then be produced through any pressure relief wells or production wells.

Therefore, the calculation method for theoretical CO_2 storage capacity used for this paper was defined as follows:

$$M_{CO_2s} = A \times H \times \emptyset \times (1 - S_{wirr}) \times \rho_{CO_2} \qquad [5]$$

$$M_{CO_2d} = A \times H \times \emptyset \times S_{wirr} \times s_{CO_2} \qquad [6]$$

$$M_{CO_2} = M_{CO_2s} + M_{CO_2d} \qquad [7]$$

If the aquifer is not a continuous thick layer of potential reservoir formations, the aquifer thickness (denoted by H) was calculated through formation thickness multiplied by net/gross ratio.

4 Geological setting of the Songliao Basin

The Songliao Basin lies at latitude 42°25' to 49°23'N and longitude 119°40' to 128°24'E. It is elongated in the NNE-SSW direction and is around 750 km long and 330 – 370 km wide with a total area of around 260 000 km^2. The northern region considered for this paper covers an area of around 119 500 km^2. The Songliao Basin is one of the most important basins in north-eastern China: The basin has considerable mineral resources and therefore has a well established industrial base as well as the largest oilfield in China, the Daqing Oil field. The petroleum, heavy machinery and automotive industries are highly developed[12] and so the Songliao Basin has contributed significantly to the national economy of China since the 1950s.

4.1 General geology

The basement rocks of Songliao Basin are composed of Palaeozoic metamorphic sandstone, marble, slate and phyllite, with large-scale granitoid intrusions of Indosinian - early Yanshanian, Hercynian and Caledonian age.

The Songliao basin is an extensional-rift basin,[13, 14] most the basin lies in the fold belt of the southern margin of Siberian plate where early Hercynian and late Hercynian-Indosinian events influenced the tectonic setting.[15] Since the Cretaceous period, the basin has experienced three main evolutionary stages: rifting and extension during the Late Jurassic - Early Cretaceous, thermal sag during the Late Cretaceous period and basin inversion after the Late Cretaceous period.[16, 17]

The oldest structural layers which were deposited during rifting are cut by dominantly NNE trending normal faults, which are distributed as a series of isolated NNE trending isolated rift faults or as groups of rift faults. In the structural layers deposited during the thermal sag phase of basin formation, the scale of faulting is much smaller. [18] The thermal sag deposits can be divided into six tectonic units, four of which are present in the northern Songliao Basin (Fig.1).

The Songliao Basin is relatively seismically inactive; only five events with magnitude greater than 6.0 have been recorded since 1918, two of which were in the northern part.[21]

4.2 Sedimentary geology

The Songliao Basin is filled with sediments of Upper Jurassic to Cenozoic age with a maximum cumulative thickness of up to 11,000 m. The Cretaceous sediments are more than 7000 m thick in the deepest parts of the basin. During the Cretaceous, fluvial deposition occurred in the basin centre, while the basin margins show lacustrine deposits. Vertically, the sequence shows alternating fluvial and lacustrine facies (Fig. 2). Two large scale lake transgressions occurred during the Cretaceous period, which connected the basin lake with the Eastern Asian palaeo-sea bringing an influx of marine sediments.[22-24]

4.3 Petroleum Geology

The proven oil reserves of the Songliao Basin are 58.8×10^{8} tonnes (t).[25] The major source rocks of the basin are the deeply buried, dark, lacustrine mudstones of the Cretaceous Qingshankou Formation to the 1st member of Nenjiang Formation. Secondary source rocks are mudstones of the 2nd member of the Nenjiang Formation and 2nd to 3rd members of the Cretaceous Yaojia Formation. There are five proven source-reservoir-seal pairs in the Songliao Basin (Fig. 2). Most hydrocarbons accumulated in structural traps and combined structural - stratigraphic traps. The majority of the oil fields are located in the depocentre of the basin.

5 Delineation of potential storage areas

5.1 Assessment of the geological characteristics at basin scale

Bachu advanced a set of criteria for defining the suitability of a sedimentary basin for geological storage.[26] Using these 15 criteria, a sedimentary basin can be given a score to indicate its suitability.[27, 28] For this paper, as recommended by Bachu and to simplify the assessment, the criteria were modified and the suitability of the Songliao Basin was judged by the distribution of the HFSA individual scores instead of the total score since only one basin was assessed.

The Songliao Basin scored more than 3 out of 5 points for each criterion, with an average score of 4.5 (Table 1). Therefore, from a basin perspective, Songliao Basin is very suitable for geological storage of CO_2.

5.2 Assessment of suitability for geological storage of CO_2 at reservoir scale

The reservoir properties of the hydrocarbon fields and HFSA were assessed in terms of their suitability for CO_2 storage.

5.2.1 Reservoirs

The hydrocarbon reservoirs and HFSA were assessed using the criteria set out in Table 1.

Several sandstone formations were deposited as the Songliao Basin experienced multiple cycles of water table fluctuations, while the palaeo-climate alternated between wet and warm to hot and dry during basin subsidence. The main lithology of the potential storage formations is well-sorted, coarse-siltstone to fine arkose sandstone and feldspathic litharenite sandstone.[22, 29, 30]

The deepest formations assessed for storage potential in this paper are sandstone layers in the lower Quantou and upper Denglouku formations, and conglomerate layers in the lower Denglouku Formation and deeper Yingcheng and Shahezi formations.[31] These formations were discarded as candidate storage targets as generally they lie at depths greater than 3000 m (Fig. 1), which is the advised maximum depth limit for CO_2 storage as at these depths, compaction will most likely have reduced porosity and permeability. A few parts of these formations are shallower than 3000 m, but even these limited fragments lie deeper than 2800 m. Porosity and permeability data from these formations are less than 10% and less than 1 mD respectively,[32] which makes them unfavourable for CO_2 storage.

The most promising reservoirs for CO_2 storage in the northern Songliao Basin are in the Yaojia and Qingshankou formations which are widely distributed throughout the basin (Fig.3). The Yaojia Formation contains reservoirs of mainly deltaic interbedded sands, with a thickness of 40 to 150 m, an average porosity of 20% and permeability of about 200 mD.[33, 34] The period when the

Qingshankou Formation was deposited (88±1 to 96±2 million years ago) was the time when the first large-scale lacustrine transgression occurred in the Songliao Basin and sediments deposited during this time offer potential storage opportunities in sandstone and siltstone reservoirs. The Qingshankou Formation has a total reservoir sandstone thickness of 50 to 200 m, an average porosity of 18.8% and an average permeability of 203 mD.[33, 35]

Potential reservoirs are also found in the Nenjiang and upper Quantou formations, the physical characteristics (e.g. depth) are not ideal, but these formations may still have some potential for storage. In the Nenjiang Formation, there are lacustrine sandstone and interbedded deltaic sandstone - shale reservoirs, with a thickness of 40 — 200 m, average porosity of 20.4% and permeability of 193.4 mD.[33, 36] The Quantou Formation comprises mudstone, sandy mudstone and sandstone and has a thickness of 20 – 150 m, an average porosity of 12% and an average permeability of 10 — 30 mD.[33]

The Sifangtai and Mingshui formations are the shallowest formations assessed for CO_2 storage in this area. Although these formations are generally quite thick, in some areas they lie at depths less than 800 m, and in some places, the formations are even exposed at outcrop (Fig. 1). Moreover, regional cap rocks are not present on the top of the Sifangtai and Mingshui formations. They are therefore unfavourable for storage; outcrop offers a potential leakage pathway for stored CO_2 as it migrates upward and as these formations are shallow the injected CO_2 would not remain in a highly dense phase for efficient storage.

5.2.2 Seals

Regional seals in the northern Songliao Basin comprise thick mudstone layers in the Qingshangkou and lower Nenjiang formations (Fig.2). The mudstones in the lower Qingshankou Formation, which directly overlie the reservoirs of the Quantou Formation, contain dark lacustrine mudstones with a thickness of over 300 m (Fig. 4)[37] which have a diffusion coefficient less than $10^{-5}cm^2\ s^{-1}$ (the diffusion coefficient can be used alongside the fluid properties to indicate how rapidly the fluid will move through the rock and is a measure of permeability) and a displacement pressure of 3.9 MPa for natural gas[33] (Displacement pressure is a measure of the differential pressure a rock can support and therefore its ability to act as a caprock for buoyant fluids). For CO_2, the displacement pressure was theoretically converted to 2.0 — 3.4 MPa. The black mudstone of the Nenjiang formation has a thickness of 200 – 300 m,[38] a diffusion coefficient of $8.4 \sim 18 \times 10^{-6}cm^2\ s^{-1}$ and a displacement pressure of 5 MPa for natural gas (equivalent to a displacement pressure of 2.5 — 3.7 MPa for CO_2). These seals in the lower Qingshankou and Nenjiang formations cover the entire basin. The seals in the upper Qingshankou Formation are present across most of the basin, but there are a few regions where these impermeable rocks are absent. Undercompaction is very common in these regional seals, which has enhanced the plasticity of the seals, and as a result, fewer fractures and faults penetrate the sealing formations and transmissivity of faults is reduced (when pore fluids cannot escape in response to increased sediment loading, the trapped fluid supports the increased sediment load and pore pressure increases, as a result, the porosity is preserved and the formations are undercompacted and overpressured [39, 40]).

Local seals include highly compacted rock in the uppermost Nenjiang Formation, the middle

Yaojia Formation, the lower Mingshui and lower Quantou formations (Fig. 2). In the northern Songliao Basin, although there are many potential local seals, their sealing quality is expected to be quite poor due to their poor areal distribution (Fig. 4). For example, seals in the lower Mingshui Formation are only found in some areas of the western slope and central depression of the basin.[33] Additionally, in the seals of the uppermost Nenjiang and lower Quantou Formations, mudstone is interbedded with sandstone which reduces the plasticity of the seals. Despite these drawbacks, the local seals are still expected to be effective in some areas.

Natural gas reservoirs associated with CO_2 are present in the lower Qingshankou, upper Quantou and Yingcheng formations[41]. The presence of these naturally-occurring CO_2 reservoirs and hydrocarbon reservoirs demonstrate the ability of the seals to contain buoyant fluids which suggests this region is very favourable for CO_2 storage.

5.2.3 Pressure and Temperature (PT)

High pressure and quite high temperatures are required for CO_2 to exist in its supercritical phase, however, these conditions also make wellhead engineering more challenging and add to the cost of CO_2 storage.

Statistical analysis shows that in the northern Songliao Basin, more than 80% of reservoirs have a pressure gradient lower than 1.1 MPa per 100m. Although a few areas have demonstrated abnormal pressures, there is generally a normal pressure regime in northern Songliao Basin.

Statistical analysis also showed that the geothermal gradient of more than 75% of reservoirs in northern Songliao Basin lies between 3.5 - 5°C per 100 m, while only 11% have temperature gradients lower than 3°C per 100 m. According to an assessment carried out by the authors on 19 boreholes distributed across the whole basin, the average heat flow of the whole Songliao Basin is about 69 mWm^{-2},[42,43] a little higher than the world average of 63 mWm^{-2}.

In order to determine the likely impact of temperature and pressure on the state of the injected CO_2, statistics about the distribution of the reservoir temperature and pressure in the oil fields of northern Songliao Basin were collated (Fig. 5). These plots show that although lower temperatures are observed at some sites, injected CO_2 would remain in its supercritical phase in most reservoirs under the higher than normal geothermal regime. In the remainder of the reservoirs, CO_2 should achieve a liquid state with high density, very close to its supercritical state. Thus the pressure and temperature conditions are very likely to be suitable for CO_2 storage.

5.2.4 Salinity

The classification of salinity of underground water in China is shown in the Table 2. Analysis indicated that the salinity of the aquifers in the oil and gas field of northern Songliao Basin is 3000 – 13 000 mgL^{-1}. Over 75 % of the aquifers are highly brackish, while all the others are saline. Thus the aquifers are suitable for CO_2 storage in terms of salinity and these aquifers are also not a potable water source, reducing the risk of a conflict of usage (although very high salinities would be unfavourable as viscosity of pore fluid would be increased).

In terms of distribution, generally, in the formations above the Quantou Formation, the salinity of aquifers is high in the centre of the basin, and tends to be lower near the margins. In the formations below the Quantou Formation, the pattern is reversed (Fig. 6).

5.2.5 Hydrodynamic system

An active hydrodynamic system increases the risk of CO_2 migrating out of the CO_2 storage reservoirs along with the groundwater. Thus, the favourable hydrodynamic state for CO_2 storage is that of a weak hydrodynamic system with slow flow speed and low hydrostatic head.

The hydrodynamic field in the northern Songliao Basin is asymmetrical. Groundwater migrates towards the basin centre in the northeast uplift area and northern plunge area, where the area is recharged by precipitation. However, in the basin centre (which also includes the Sanzhao, Qijia-Gulong, Changling and Heiyupao depressions) groundwater migrates outwards from the basin centre.[45] These two different zones meet along a line from Well Lai 271 to Well Du 48,[46] so the northern Songliao Basin is divided into three regions: 1) hydrodynamic area recharged by precipitation in the northeast which has a strong hydrodynamic drive and a seepage velocity of 10 – 20 cm a^{-1}; 2) the region with a relatively weak hydrodynamic drive between the Nehe - Baiquan - Mingshui and Heiyupao and Wuyu'er depressions, with a seep velocity of 5 — 10 cm a^{-1}; and finally 3) the region in the south of the Heiyupao and Wuyu'er depressions where the hydrodynamic drive is very weak.[47]

Across the whole basin, the hydrostatic head level is higher than the ground surface, generally only by up to 250 m though there are a few high pressure regions where hydrostatic head is estimated to be 400 m above the ground surface. When a well is drilled into an aquifer with hydrostatic head level higher than the ground surface, if not controlled, the groundwater can move upwards inside the well casing to a level that is higher than the level of the ground surface[48], this may which may increase the risk of CO_2 migration with the groundwater. Thus, the hydrostatic head level was considered seriously during the potential area selection and received a relatively high weighting.

Generally, the hydrodynamic regime is favourable for CO_2 storage, such that large scale leakage of CO_2 caused by the movement of groundwater is not expected.

5.2.6 CO_2 source

After 2003, the CO_2 emissions of the industrial sector in northeast China showed rapid growth. The Songliao Basin is the most important industrial area in northeast China, where the machinery, metallurgy, petroleum, chemical industries are highly developed. Long-term industrial production, high population density, and dependence on traditional fossil fuels means the CO_2 emissions in this region are very high. Although the emission intensity is being reduced by increased efficiency and changing industrial processes, overall the total amount of CO_2 emissions are still increasing as the growth of industry is very rapid.[49] In the northern Songliao Basin, the number of both high concentration sources (CO_2 concentration higher than 80%) and large stationary point emission sources (which emit more than 10×10^3t/y) of CO_2 is extremely large.[50, 51.]

In addition to these anthropogenic sources, the amount of naturally sourced CO_2 produced from this basin is quite large. Gas reservoirs in the northern Songliao Basin are often associated with mantle-derived CO_2 gas. Analysis of the wells and layers containing CO_2 shows that in 21% of cases, CO_2 accounts for more than 80% of the produced gas; and for 5 — 30% of the produced gas, the percentage of CO_2 will be as high as 63%.[52] The CO_2 is removed during gas processing to purify the produced gas and prevent pipeline corrosion. The removed CO_2 could be stored in a geological reservoir, presently it is released into the atmosphere. The gas reservoirs associated with high concentration CO_2 are mainly found in the Yingcheng Formation[52, 53] which lies at depths greater than 3000 m was therefore not considered for CO_2 storage. A few gas reservoirs associated with low CO_2 concentrations can be found in the upper Quantou formation and upper Qingshankou Formation[51] where the seals are good enough to separate HFSA from other formations and prevent the injected CO_2 from migrating into the surrounding reservoirs.

5.3 Selected regions

The areas with the most advantageous characteristics for CO_2 storage in northern Songliao Basin were delimited based on the geological conditions described in the previous sections:

The potential storage reservoirs in the Nenjiang Formation reservoir have a wide areal distribution and great thickness, but are too shallow in some places. North of Daqing, for example, near the Well Gu 2 in the Qijia-Gulong Depression, the depth of reservoir rocks in the Nenjiang Formation is less than 800 m. This was also the case in the west of the Longhupao Terrace and east of the Qijia-Gulong Depression. Meanwhile, the salinity of aquifers in the Nenjiang Formation decreases gradually from east to west to 3000 mgL^{-1} in the area east of Daqing and Da'an. Therefore, the most promising area for CO_2 storage in the Nenjiang Formation is bounded to the west by the West Slope area and by the Daqing anticline to the east and lies to the south of Daqing and to the north of Zhaoyuan (Fig.7).

The depth to the Yaojia and Qingshankou formations is generally more than 800 m. The reservoirs with the greatest thickness are distributed to the north along Qinggang – Anda - Da'an, where salinity is also quite high. However, in the area to the west of Qiqiha'er and Tailai, the thickness of both the Yaojia and Qingshankou formations decreases to less than 50 m and the thickness of seals decreases to less than 60 m. Thus these areas were selected as the east and west bounds for most promising area of CO_2 storage in the Yaojia and Qingshankou formations. The north boundary is marked by the Heiyupao-Wuyu'er depression based on the hydrodynamic regime (Fig. 7).

The reservoirs in the Quantou Formation are concentrated in the Central depression and overlain by thick mudstone caprocks from Taikang - Qinggang to Baicheng - Zhaoyuan, where the salinity and hydrodynamic regime are also favourable (Fig. 7).

5.4 Detailed assessment of potential storage areas

The most promising areas for storage identified by the authors were then studied in more detail. A set of 39 criteria, each with several categories, was developed for the assessment and ranking of localised areas in terms of their suitability for CO_2 storage (at oil/gas field scale). The weightings, which express the relative importance of the different criteria, were determined by the AHP

(Analytic Hierarchy Process) method (Table 3).[54] This set of criteria was applied then used to rank the potential storage sites in HSFA in the primary and secondary areas recommended for storage. After detailed data analysis, for each criterion, a score between 1 and 5 was given to every candidate hydrocarbon field with HFSA. Then the weighted average score was calculated using the scores for each criterion and its weight listed in Table 3.

The authors considered HFSA in 42 hydrocarbon fields which lie within the areas identified as most promising for CO_2 storage. From this dataset, HFSA near nine hydrocarbon fields scored over 8 using the assessment criteria in Table 3 and are therefore defined as the primary recommended area for storage locations in the northern Songliao Basin (Fig. 7), 15 scored 7 — 8, which was used to define the secondary area recommended for geological storage of CO_2 in northern Songliao Basin (Table 4). All of these HFSA are concentrated in the Daqing placanticline, north of the Longhupao, Qijian-Gulong and Sanzhao depressions (Fig. 7).

6. Storage capacity calculation

The storage capacity of the HFSA identified in section 5.4 was calculated using equation [7].

6.1 Determination of irreducible water saturation

Irreducible water saturation is one of the most difficult parameters to quantify when calculating storage capacity. For the HSFA where irreducible water saturation data were not available, the parameter was estimated using the formula [8] and porosity and permeability data.[55] The calculation has been verified by comparison with actual data from core testing.

$$K^{\frac{1}{2}} = c\frac{\emptyset^3}{S_{wi}} \qquad [8]$$

Where, K is permeability (mD); S_{wi} is irreducible water saturation; $\emptyset$ is porosity; c is a constant (for oil with medium density, c=250).

6.2 Determination of CO_2 density and solubility

The solubility of CO_2 in the formation water is related to temperature, pressure, ion type and content of the formation water. A calculation model of CO_2 solubility, which considered the content of Cl^- (Chloride) and HCO^{3-} (Bicarbonate) ions, temperature and pressure was used in this paper.[56, 57] This model was used to calculate the CO_2 solubility in the HFSA (Table 5). The density of the formation water at subsurface conditions, used to calculate the CO_2 solubility, was determined through the Nomograph given by Schowalter[58], using temperature, pressure and salinity data.

The CO_2 density in the different HFSA was determined in relation to a chart of CO_2 density with temperature and pressure, which was presented by Bachu (Table 5).[59]

6.3 Results

The total capacity of the HFSA in the primary recommended storage area was calculated to be 7.7 × 10^9 t CO_2 using equation [7]. The largest HFSA has a potential storage capacity of 4.9 × 10^9 t CO_2. For the 15 HFSA in the secondary recommended storage area, the total calculated storage potential is 2.1 × 10^9 t CO_2, with the largest having a calculated capacity of 732.1 × 10^6 t CO_2. Based on these calculations, the total potential storage capacity of the primary and secondary storage areas identified in Fig. 7 is 9.8 × 10^9 tCO_2, which could theoretically contain more than 100 years of emissions from the large–scale sources in the whole Songliao Basin if they were to remain at present levels, as the current annual CO_2 emissions in Songliao Basin are 95 × 10^6 t.[60] There are 11 HFSA in this region with a total CO_2 storage capacity over 100 × 10^6 t, accounting for about 50% of the total number of hydrocarbon fields, but their total capacity accounted for about 95% of the calculated total for the primary and secondary storage areas (Table 5).

Some of the smaller HFSA scored highly as the weighting of reservoir conditions such as reservoir characteristics and security of storage is higher than the weighting of reservoir area and thickness, which are very important for capacity. Thus, the total score of these smaller HFSA is higher than some HFSA which have a large volume but less favourable other characteristics.

7 Conclusions

(1) Cretaceous strata are favourable for CO_2 storage in Hydrocarbon Field Saline Aquifers (HFSA) in the northern Songliao Basin. The sandstone reservoirs in the Yaojia and Qingshankou formations are the most favourable, while the Nenjiang and Quantou formations are reasonably favourable.

(2) The Daqing placanticline and the region north of the Longhupao and Qijia-Gulong Depression and the Sanzhao Depression are the most promising areas and so are identified as the primary area recommended for storage in the northern Songliao Basin. The central depression and west western slope also have advantageous characteristics for CO_2 storage and so are identified as the secondary area recommended for storage in the northern Songliao Basin.

(3) The calculated storage capacity of the primary area recommended for storage is 7.7×10^9 t CO_2; while the secondary area recommended for storage has a calculated capacity of 2.1×10^9 t CO_2. Theoretically, these areas offer a combined storage capacity that could store the CO_2 emissions from large–scale sources in the Songliao Basin for more than 100 years (at current emission rates).

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Tables

Table1 Suitability assessment criteria of CO_2 storage for basin scale (Modified After Bachu[26])

Criterion	**Classes**				
	1	2	3	4	5
Tectonic setting	Very unstable (e.g. subduction)	Unstable (e.g. syn-rift, intramontane, strike-slip)	Intermediate (e.g. foreland)	Mostly stable (e.g. passive margin)	Stable * (e.g. cratonic)
size	Very small (<1 000 km^2)	small (1000–5000 km^2)	medium (5000–25 000 km^2)	large (25000–50 000 km^2)	Very Large * (>50 000 km^2)
Depth	Very shallow (<300 m)	shallow (300-800 m)	deep (2500-3500m）	Very deep (>3500 m)	Moderate * (800-2500 m)
Reservoir-seal assemblage	Very poor	Poor	Moderate	good	Very good *
Faults & Fractures	Extensive		Moderate *		Limited
Hydrogeology	Shallow, short flow systems, or Compaction flow		Intermediate flow systems *		Regional flow systems; topography or erosional flow
Geothermal	Very warm (>100 °C/km)	Warm (100-40 °C/km)	Moderate * (30–40 °C/km)	Cold (20–30 °C/km)	Very cold (<20 °C/km)
Hydrocarbon potential	None	Small	Medium	Large	Giant *
Maturity	Unexplored	Exploration	Developing	Mature *	Over Mature
Resources	None	Few	Intermediate *	Many	Very many
On/offshore	Deep offshore		Shallow offshore		Onshore *
Climate	Arctic	Subarctic	Desert	Tropical	Temperate *

* indicates the score given to Songliao Basin

Table 2: Classification of salinity of groundwater in China

Salinity	**<1 g/L**	**1.0-3.0 g/L**	**3.0-10.0 g/L**	**10.0-50.0 g/L**	**>50.0 g/L**
Classification	Fresh water	Brackish water	Highly brackish water	Saline water	Brine

Table 3 Suitability criteria for CO_2 storage at local (hydrocarbon field contains HFSA) scale

Criteria	Good(10)	Intermediate(5)	Poor(1)	Weight
Seal continuity	Regional	Local (large scale)	Local (small scale)	0.0628
Seal lithology	Mudstone	Mudstone interbedded with shale	Shale, dense limestone	0.0593
Seal thickness	>200m	50-200m	<50m	0.0559
Number of seals	Several	Single	None	0.0528
Number of faults	None	few	more	0.0498
Sealing gas ability	>200m	100-200m	<100m	0.0470
Pressure coefficient	0.9 -1.1	<0.9	>1.1	0.0444
hydrostatic head	Lower than surface	Slightly higher than surface	Higher than surface	0.0419
Reservoir permeability	>50md	10-50md	<10md	0.0395
Reservoir porosity	>0.2	0.1-0.2	<0.1	0.0373
Reservoir thickness	>50m	20-50m	<20m	0.0342
Reservoir area	>200km^2	20-200km^2	<20km^2	0.0342
Reservoir lithology	Gritstone and more porous and permeable rocks	Medium-fine sandstone	Siltstone-shaly sandstone	0.0296
Depositional environment	Fluvial	Deltaic	Lacustrine	0.0296
Net/gross ratio	>0.6	0.2-0.6	<0.2	0.0296
Geothermal gradient	<3°C/100m	3-4°C/100m	>4°C/100m	0.0249
Heat flow	<50mW/m^2	50-70mW/m^2	>70mW/m^2	0.0249
Depth	800-3000m	>3000m	<800m	0.0249
Salinity	>6g/L	3-6g/L	<3g/L	0.0222
Hydrodynamic	Weak, stagnant	Relatively weak, slow flow	Relatively strong, rapid flow	0.0209
Source scale	>25×10^{4}t/a	10-25×10^{4}t/Y	<10×10^{4}t/a	0.0198
Transport	Pipeline	Road transport	Ship	0.0186
Well spacing density	<10/km^2	10-30/km^2	>30/km^2	0.0176
Cementing of well	Cased and cemented	Cased but not cemented	Open hole	0.0166
Earthquake intensity	<6Ma	6-8	>8	0.0157
Earthquake frequency	No earthquake> 6Ma in 100 years	Occasional earthquakes>6Ma in 100 years	Frequent earthquakes>6Ma in 100 years	0.0148
Volcanicity	None		More	0.0140
Geological hazard	None		More	0.0132
Wind direction	Unique dominant wind direction	Multiple dominant directions	No dominant wind direction	0.0124
Physiognomy	Simple (e.g. plane)	Normal (e.g. hills, wash)	Complex (e.g. Plateau, mountain area)	0.0117
Surface temperature	<10 °C	10-20 °C	>20 °C	0.0111
Facilities	Good	Normal	None	0.0105
Area prone to flooding	No		Yes	0.0099

Population density	Scarce	Normal	Dense	0.0093
Usable groundwater	Without usable groundwater	Usable groundwater with good seals	Usable groundwater without good seals	0.0088
Usable surface water	No rivers or reservoirs	Rivers or reservoirs exist, but at distance >50km	Rivers or reservoirs exist at distance<50km	0.0083
Public acceptance	well	normal		0.0078
Protected area	None	few	more	0.0074
Vegetation	few	normal	more	0.0070

Table 4 HFSA in different oilfields and their storage potential rank

(HF* is an arbitrary character used to identify different hydrocarbon fields)

	Oil/gas field	**Ranking**	**Oil/gas field**	**Ranking**	**Oil/gas field**	**Ranking**
Primary Area Recommended for storage	HFX-3	9.30	HFL-1	8.56	HFX-1	8.67
	HFS-1	8.92	HFP-1	8.33	HFJ-1	8.62
	HFL-3	8.06	HFX-5	8.26	HFS-2	8.09
Secondary Area Recommended for storage	HFA-1	7.92	HFZ-1	7.61	HFY-3	7.54
	HFY-4	7.62	HFY-2	7.55	HFT-8	7.49
	HFW-2	7.48	HFX-2	7.42	HFQ-1	7.35
	HFC-3	7.42	HFW-1	7.35	HFS-4	7.34
	HFG-1	7.23	HFG-2	7.12	HFT-11	7.08
No Potential	HFT-10	6.98	HFB-1	6.62	HFE-1	6.43
	HFX-7	6.90	HFF-1	6.60	HFL-2	6.41
	HFA-2	6.78	HFS-3	6.56	HFS-5	6.26
	HFO-2	6.75	HFO-1	6.45	HFP-1	6.22
	HFX-6	6.22	HFC-1	6.13	HFT-9	5.99
	HFS-6	6.19	HFC-2	6.02	HFW-3	5.92

Table 5 CO_2 storage potential of HFSA in Songliao Basin

		S_{CO2} (kg/m^3)	**Φ (%)**	**Swi (%)**	**ρ_{CO2} (Kg/m^3)**	**M_{CO2s} (10^6t)**	**M_{CO2d} (10^6t)**	**M_{CO2} (10^6t)**
Primary Potential Area	Max(HFS-1)	57.28	25.50	0.13	743.38	4645.26	219.03	4864.29
	Min(HFJ-1)	49.60	16.50	0.09	594.34	1.74	0.08	1.82
	Total	51.91	21.27	0.20	623.93	7272.52	438.15	7710.67
Secondary Potential Area	Max(HFZ-1)	48.27	16.25	0.31	560.74	516.62	215.50	732.12
	Min(HFY-2)	46.92	18.90	0.07	469.95	5.09	0.18	5.27
	Total	47.75	19.30	0.25	679.41	1562.89	510.03	2072.92

Figures

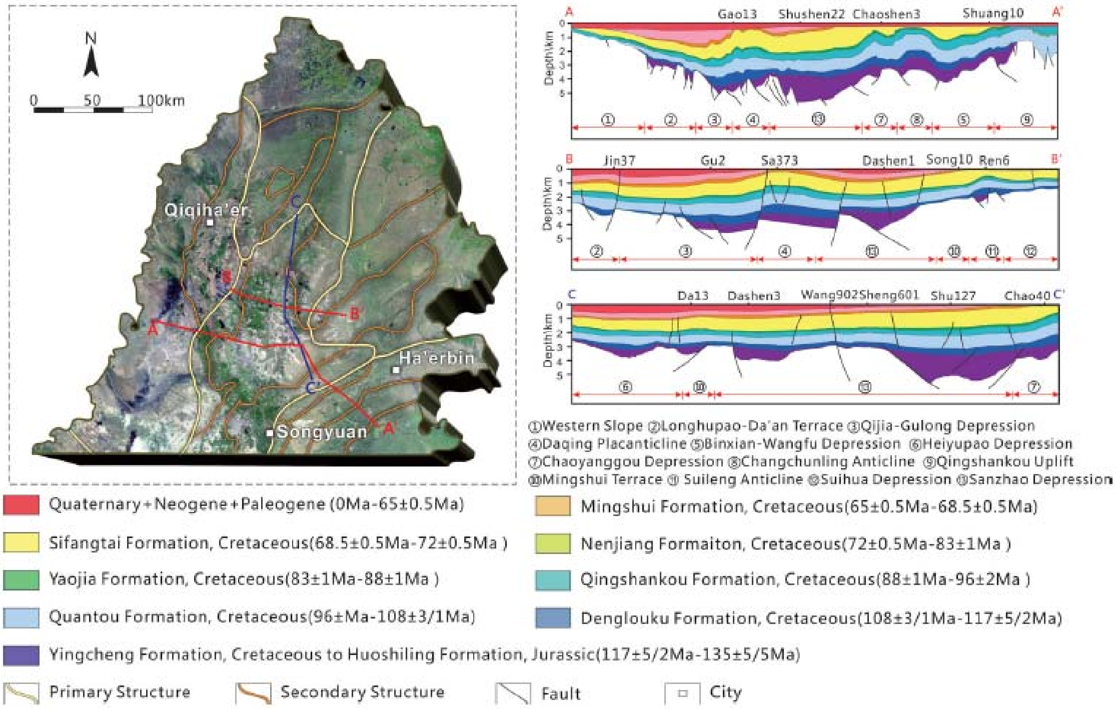

Fig.1 Tectonic units and cross-section of the northern Songliao Basin (Section A-A' was modified from Chen J et al., 2009;[19] Section B-B' and C-C' were modified from Lei P et al., 2010[20])

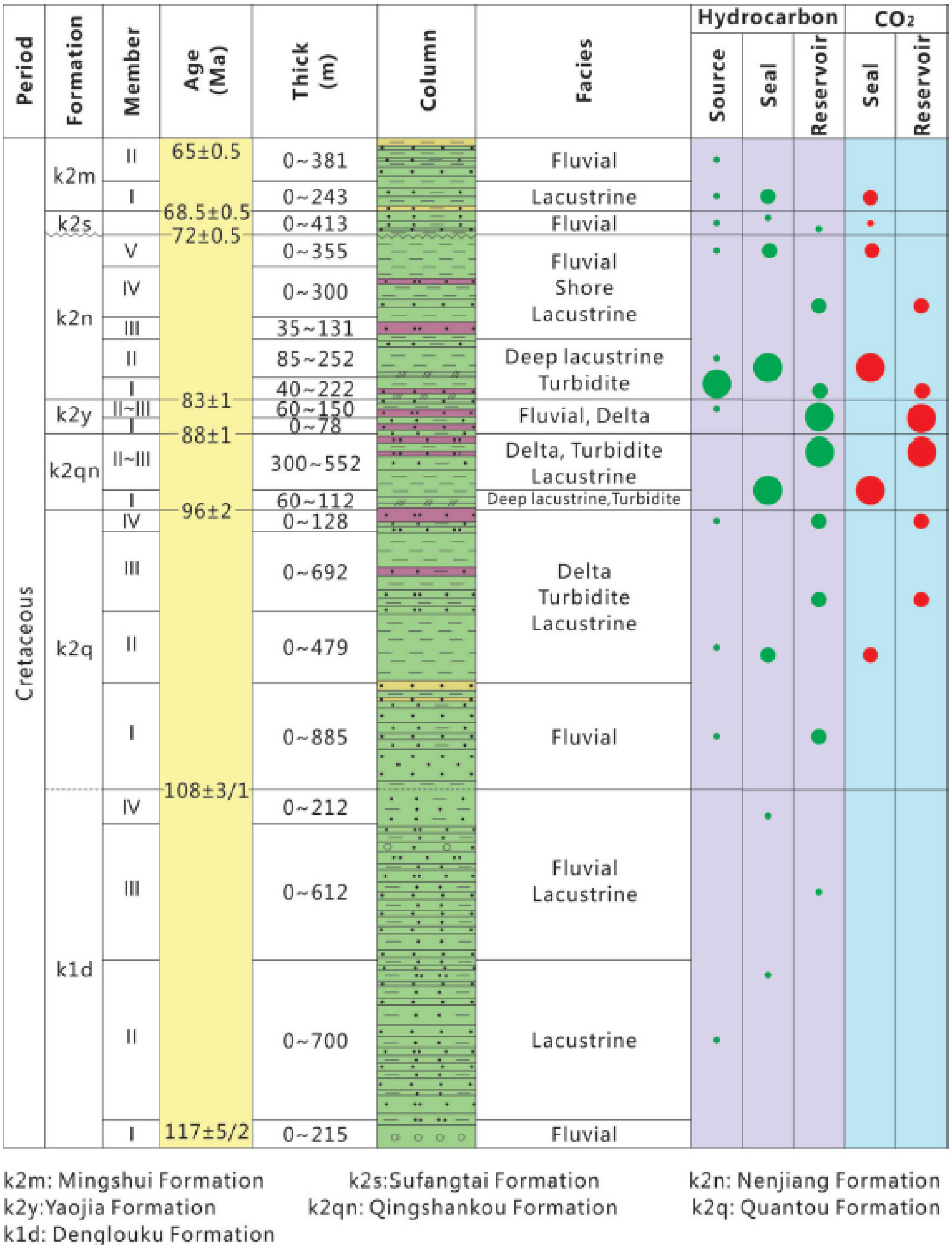

Fig.2 Summary stratigraphy column of Cretaceous sediments in the northern Songliao Basin. (The size of circle under 'source' column indicates the scale of source rock; the size of circle under 'seal' column indicates the ability of seals to trap hydrocarbon/CO_2; the size of circle under 'reservoir' column indicates the suitability and potential for hydrocarbon trapping/CO2 storage.)

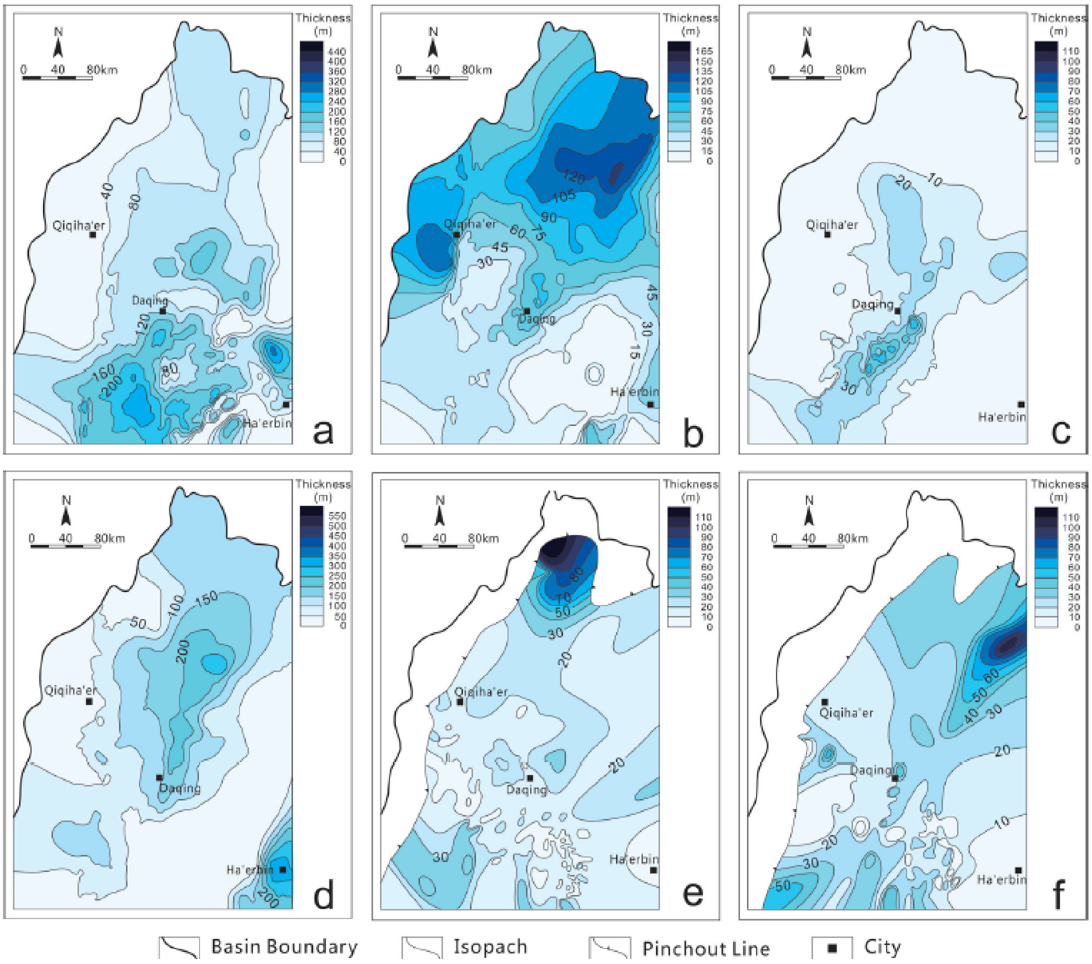

Fig. 3 Isopach maps of sandstone thickness in potential storage formations in the northern Songliao Basin (Modified after Hou Qijun, 2009[33]) (a) 3rd, 4th member of Nenjiang Formation (b) 2nd, 3rd member of Yaojia Formation (c) 1st member of Yaojia formation (d) Qingshankou Formation (e) 4th member of Quantou Formation (f) 3rd member of Quantou Formation

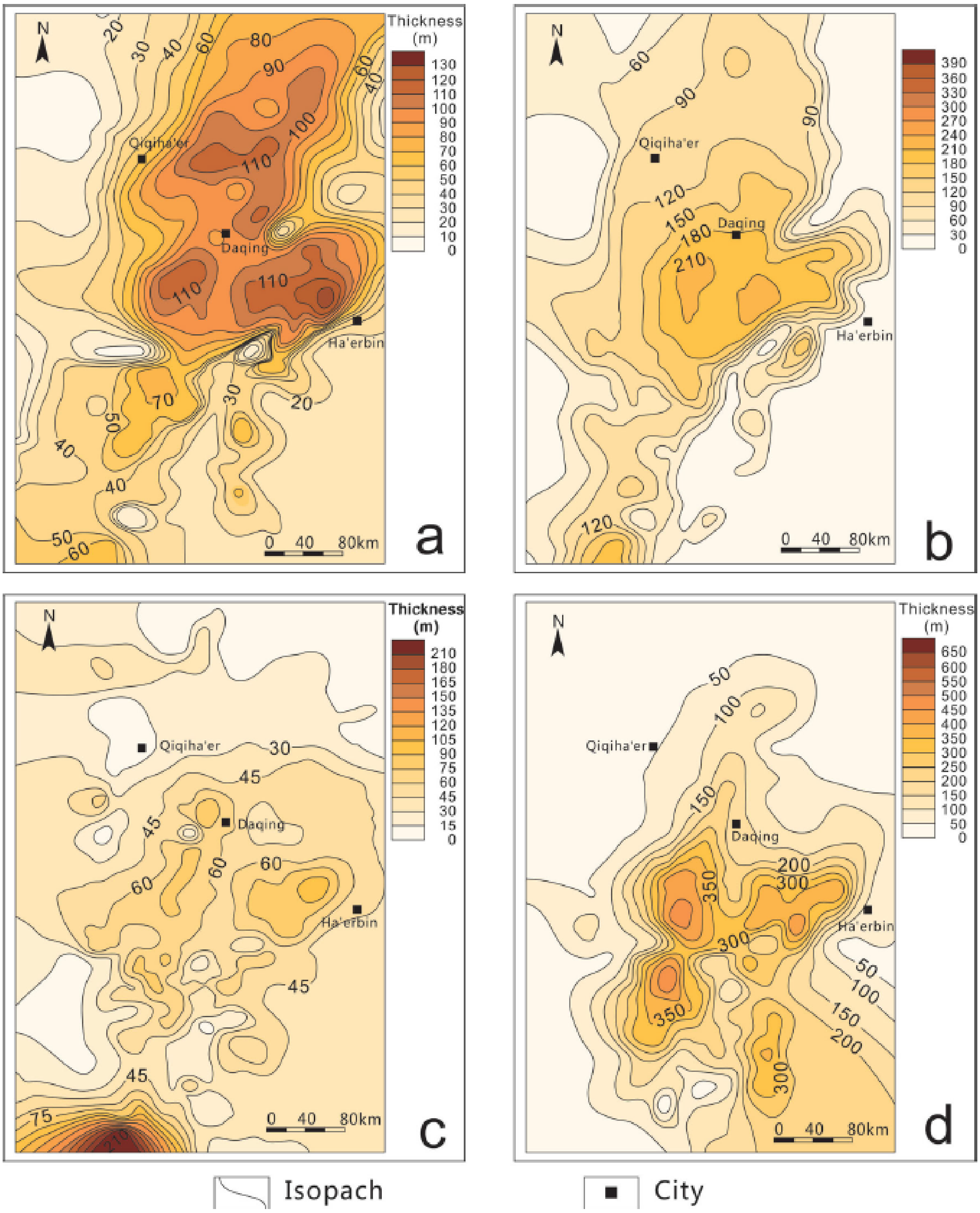

Fig. 4 Isopach map of mudstones in the northern Songliao Basin (Modified after Hou Qijun, 2009[33]) (a) 1st member of Nenjiang Formation (b) 2nd member of Nenjiang Formation (c) 1st member of Qingshankou Formation (d) 2nd, 3rd members of Qingshankou Formation

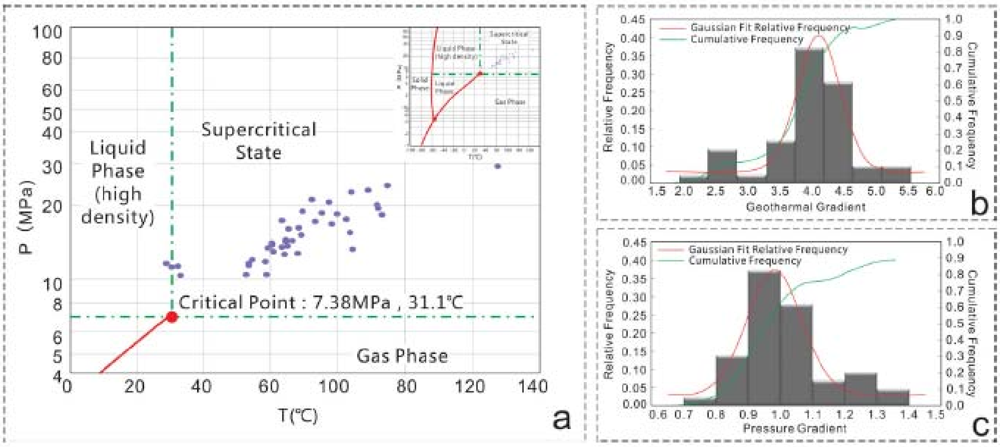

Fig. 5. Statistical analysis of PT conditions in northern Songliao Basin (a) distribution of temperature and pressure in different oilfields (b) statistical analysis of geothermal gradient (c) statistical analysis of pressure gradient

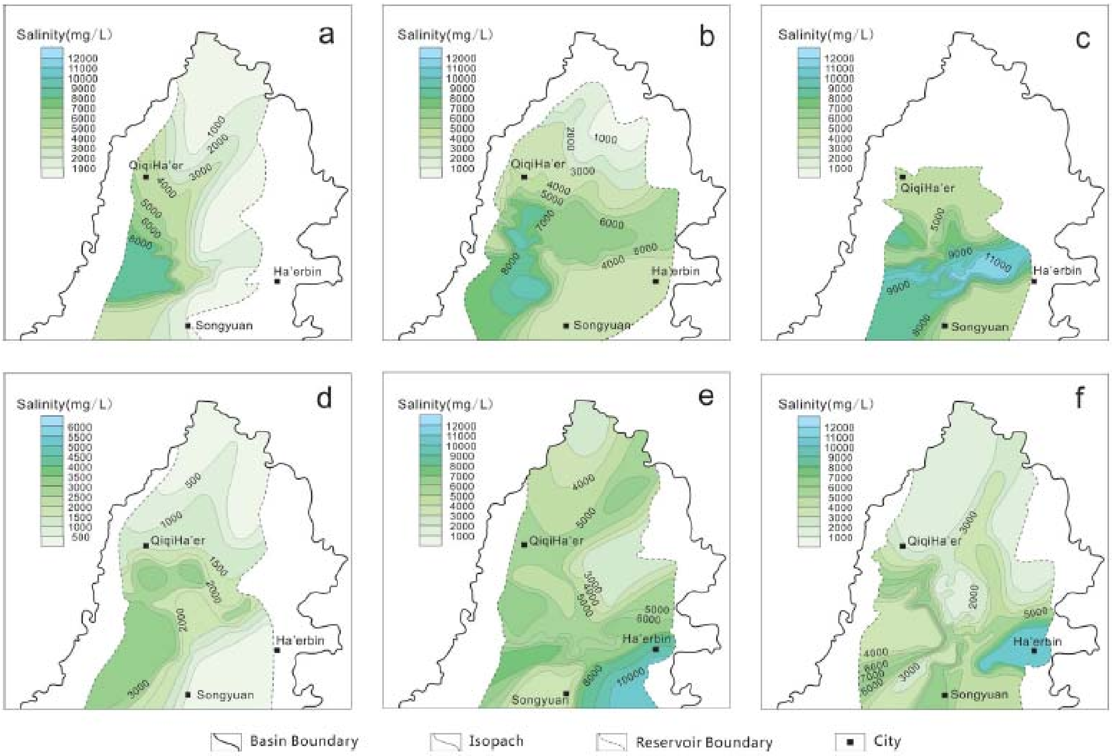

Fig.6 Salinity of HFSA in different formations in northern Songliao Basin [44] (a) 3rd, 4th member of Nenjiang Formation (b) 2nd, 3rd member of Yaojia Formation (c) 1st member of Yaojia formation (d)

Qingshankou Formation (e) 4th member of Quantou Formation (f) 3rd member of Quantou Formation

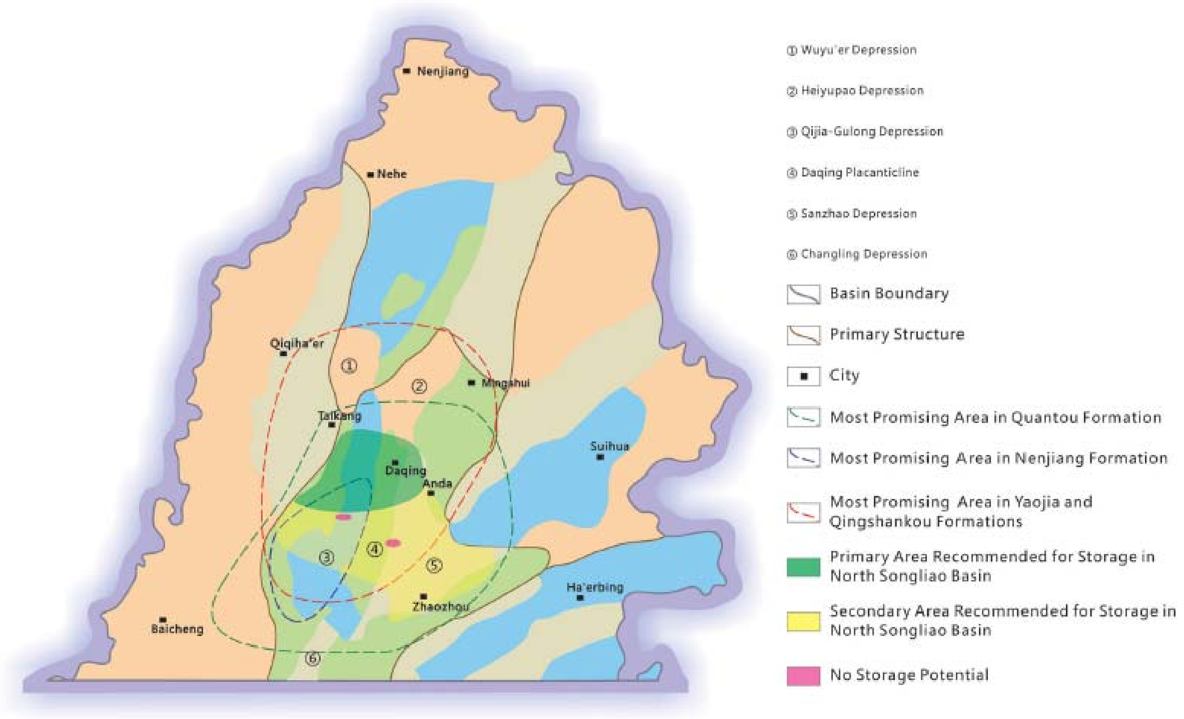

Fig.7 Areas recommended for geological storage of CO_2 in northern Songliao Basin

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