

1 **Assessment of storage capacity for CO₂ in saline aquifers**
2 **near hydrocarbon fields, northern Songliao Basin, China**

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11
12 **Abstract**

13 Carbon dioxide Capture and Storage (CCS) is the only technology currently available that can
14 significantly reduce carbon dioxide (CO₂) emissions from conventional fossil fuel use. Depleted
15 oil/gas fields, unmineable coal seams and deep saline aquifers are generally considered to be the
16 main storage options. In this paper, the authors consider opportunities presented by aquifers close
17 to hydrocarbon fields in northern Songliao Basin (China) for storage. Data obtained during
18 exploration and production often delineates nearby structures filled with saline water which have
19 not been charged with hydrocarbons but could offer an opportunity for CO₂ storage. Based on
20 published data and production data from hydrocarbon fields in northern Songliao Basin, the
21 potential for geological storage of CO₂ in these hydrocarbon field saline aquifers (HFSA) has been
22 assessed and in northern Songliao Basin, the central and western regions offer great potential for
23 CO₂ storage in HFSA. Out of the 42 identified oil/gas fields, aquifers near 24 of the fields offer

1 promising storage potential with an estimated potential storage capacity of 9.8×10^9 tonnes (t) CO₂,
2 which is more than 100 times the current annual emissions of large point sources in the Songliao
3 Basin.

4

5 **1 Introduction**

6 Fossil fuels are expected to remain a key part of the future energy and industrial production mix,
7 therefore CCS, as the only currently available technology capable of large scale reduction of
8 emissions from fossil fuels, is seen as essential to reduce CO₂ emissions to the atmosphere.¹

9

10 Depleted oil/gas fields, unmineable coal seams, and deep saline formations are generally
11 considered the most promising options for geological storage of CO₂. Deep saline aquifers have
12 the largest potential, but usually, few datasets are available and this increases uncertainty about
13 their suitability for storage. Depleted oil/gas fields are generally well understood and data are
14 available, but in China these fields are often compartmentalized into many small reservoirs, and in
15 many reservoirs numerous boreholes have been drilled to access these small compartments
16 increasing the number of potential leakage pathways if used as a CO₂ storage site. Aquifers are
17 often identified above, below or near the hydrocarbon reservoirs during exploration where traps
18 have not been charged and these aquifer formations are rarely considered for their CO₂ storage
19 potential. However, if these hydrocarbon field saline aquifers (HFSA) and hydrocarbon fields are
20 considered together, this could offer an excellent storage opportunity.

21

22 Several studies on the potential for CCS in China have been carried out by Chinese scientists. In

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

7

8 In order to select the potential area for CO₂ storage in HFSA, a set of 12 basin-scale weighted
9 criteria and a set of 39 regional-scale weighted criteria were considered. The assessment of CO₂
10 storage suitability and capacity in HFSA in **northern Songliao** Basin is presented here.

11

12 **2 CO₂ storage in oil/gas field saline aquifers**

13 The hydrocarbon field saline aquifers (HFSA) are defined as the aquifers which are located in
14 close proximity to the hydrocarbon fields but are hydrodynamically unconnected to the
15 hydrocarbon fields. Unlike the deep saline aquifers usually considered for storage, hydrocarbon
16 field saline aquifers may be relatively shallow (though still deeper than 800 m) and smaller. HFSA
17 could be considered as potential CO₂ storage sites as they have the following advantages:

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

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

1 c). If the wells have been drilled through the HSFA, some of the existing production facilities of
2 the oil/ gas field could be shared by the CO₂ storage facility which would reduce the costs of
3 storage and the areal footprint of anthropogenic activities.

4

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

18

19 **3 Calculation method of physical and chemical trapping in hydrocarbon field** 20 **saline aquifers**

21 Carbon dioxide will be trapped in HFSA through the same mechanisms as CO₂ storage in deep
22 saline aquifers: structural and stratigraphic trapping, residual CO₂ trapping, hydrodynamic

1 trapping, solubility trapping and mineral trapping.⁹ Most existing calculation methods are based
2 on these mechanisms.

3

4 The US Department of Energy (USDOE) assumed all pore space in the saline aquifer can be used
5 for CO₂ storage, i.e. all the saline brine can be forced out of the aquifer.¹⁰ The theoretical formula
6 of **effective** CO₂ storage in saline aquifer from this, which is widely used is as follows:

7
$$M_{CO_2} = \rho_{CO_2} \times A \times H \times \phi \times E \quad [1]$$

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

9 **Theoretical storage capacity of structural/stratigraphical trapping in aquifers:**

10
$$M_{CO_{2S}} = A \times H \times \phi \times (1 - S_{wirr}) \times \rho_{CO_2} \quad [2]$$

11 **Theoretical storage capacity of residual trapping in aquifer storage sites:**

12
$$M_{CO_{2t}} = \Delta V_{trap} \times \phi \times S_{CO_{2t}} \times \rho_{CO_2} \quad [3]$$

13 **The theoretical storage capacity of CO₂ dissolved into aquifer pore water:**

14
$$M_{CO_{2d}} = A \times H \times \phi \times (\rho_s X_s^{CO_2} - \rho_0 X_0^{CO_2}) \quad [4]$$

15

16 Where, M_{CO_2} is total CO₂ storage capacity (t); $M_{CO_{2S}}$ is structural CO₂ storage capacity (t);
17 $M_{CO_{2d}}$ is soluble CO₂ storage capacity (t); $M_{CO_{2t}}$ is residual CO₂ storage capacity (t); $S_{CO_{2t}}$ is
18 **trapped CO₂ saturation (%)**; A is area of aquifer, (m²); H is thickness of aquifer (m); ϕ is
19 porosity of aquifer (%); S_{wirr} is irreducible water saturation (%); ρ_{CO_2} is density of CO₂ in the
20 aquifer (kgm⁻³); s_{CO_2} is solubility of CO₂ in the aquifer fluid (kgm⁻³); ρ is density of formation
21 water (kgm⁻³); X^{CO_2} is CO₂ content (mass fraction) in formation water (%), and the subscripts 0
22 and S stand for initial CO₂ content and CO₂ content at saturation respectively; E is the CO₂

1 storage efficiency factor which reflects the fraction of the total pore volume that is filled by CO₂
2 (dimensionless);

3

4 Based on these two established methods, the authors decided to calculate the theoretical CO₂
5 storage capacity in HFSA considering only structural, stratigraphical and solubility trapping.

6 Residual CO₂ trapping, hydrodynamic trapping and mineral trapping have strong and complex
7 interrelationships and occur on very different timescales, which can only really be calculated

8 through complex numerical modelling.⁹ Mineralization is a relatively slow process and is not
9 expected to offer a significant amount of storage capacity over the injection lifetime. For solubility

10 trapping in HFSA, the following assumptions were made:

11 a). Some water cannot be displaced from the aquifer by the injected CO₂ (irreducible water
12 saturation). CO₂ can dissolve into this connate water;

13 b). Some CO₂ will dissolve into the water which is displaced by the CO₂; this could then migrate
14 out of the aquifer and could then be produced through any pressure relief wells or production
15 wells.

16 Therefore, the calculation method for theoretical CO₂ storage capacity used for this paper was
17 defined as follows:

18
$$M_{CO_2s} = A \times H \times \phi \times (1 - S_{wirr}) \times \rho_{CO_2} \quad [5]$$

19
$$M_{CO_2d} = A \times H \times \phi \times S_{wirr} \times s_{CO_2} \quad [6]$$

20
$$M_{CO_2} = M_{CO_2s} + M_{CO_2d} \quad [7]$$

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

1

2 **4 Geological setting of the Songliao Basin**

3 The Songliao Basin lies at latitude 42°25' to 49°23'N and longitude 119°40' to 128°24'E. It is
4 elongated in the NNE-SSW direction and is around 750 km long and 330 – 370 km wide with a
5 total area of around 260 000 km². The northern region considered for this paper covers an area of
6 around 119 500 km². The Songliao Basin is one of the most important basins in north-eastern
7 China: The basin has considerable mineral resources and therefore has a well established industrial
8 base as well as the largest oilfield in China, the Daqing Oil field. The petroleum, heavy machinery
9 and automotive industries are highly developed¹² and so the Songliao Basin has contributed
10 significantly to the national economy of China since the 1950s.

11 **4.1 General geology**

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

15

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

22

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

6

7 The Songliao Basin is relatively seismically inactive; only five events with magnitude greater than
8 6.0 have been recorded since 1918, two of which were in the northern part.²¹

9

10 **4.2 Sedimentary geology**

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

18

19 **4.3 Petroleum Geology**

20 The proven oil reserves of the Songliao Basin are 58.8×10^8 tonnes (t).²⁵ The major source rocks of
21 the basin are the deeply buried, dark, lacustrine mudstones of the Cretaceous Qingshankou
22 Formation to the 1st member of Nenjiang Formation. Secondary source rocks are mudstones of

1 the 2nd member of the Nenjiang Formation and 2nd to 3rd members of the Cretaceous Yaojia
2 Formation. There are five proven source-reservoir-seal pairs in the Songliao Basin (Fig. 2). Most
3 hydrocarbons **accumulated** in structural traps and combined structural - stratigraphic traps. The
4 majority of the oil fields are located in the depocentre of the basin.

5

6

7 **5 Delineation of potential storage areas**

8 **5.1 Assessment of the geological characteristics at basin scale**

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

14

15 The Songliao Basin scored more than 3 out of 5 points for each criterion, with an average score of
16 4.5 (Table 1). Therefore, from a basin perspective, Songliao Basin is very suitable for geological
17 storage of CO₂.

18

19

20 **5.2 Assessment of suitability for geological storage of CO₂ at reservoir scale**

21 **The reservoir properties of the** hydrocarbon fields and **HFSA were** assessed in terms of their
22 suitability for CO₂ storage.

1 5.2.1 Reservoirs

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

3

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

8

9 The deepest formations assessed for storage potential in this paper are sandstone layers in the
10 lower Quantou and upper Denglouku formations, and conglomerate layers in the lower Denglouku
11 Formation and deeper Yingcheng and Shahezi formations.³¹ These formations were discarded as
12 candidate storage targets as generally they lie at depths greater than 3000 m (Fig. 1), which is the
13 advised maximum depth limit for CO₂ storage as at these depths, compaction will most likely have
14 reduced porosity and permeability. A few parts of these formations are shallower than 3000 m, but
15 even these limited fragments lie deeper than 2800 m. Porosity and permeability data from these
16 formations are less than 10% and less than 1 mD respectively,³² which makes them unfavourable
17 for CO₂ storage.

18

19 The most promising reservoirs for CO₂ storage in the northern Songliao Basin are in the Yaojia
20 and Qingshankou formations which are widely distributed throughout the basin (Fig.3). The
21 Yaojia Formation contains reservoirs of mainly deltaic interbedded sands, with a thickness of 40 to
22 150 m, an average porosity of 20% and permeability of about 200 mD.^{33, 34} The period when the

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

6

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

14

15 The Sifangtai and Mingshui formations are the shallowest formations assessed for CO₂ storage in
16 this area. Although these formations are generally quite thick, in some areas they lie at depths less
17 than 800 m, and in some places, the formations are even exposed at outcrop (Fig. 1). Moreover,
18 regional cap rocks are not present on the top of the Sifangtai and Mingshui formations. They are
19 therefore unfavourable for storage; outcrop offers a potential leakage pathway for stored CO₂ as it
20 migrates upward and as these formations are shallow the injected CO₂ would not remain in a
21 highly dense phase for efficient storage.

22

1 5.2.2 Seals

2 Regional seals in the northern Songliao Basin comprise thick mudstone layers in the
3 Qingshankou and lower Nenjiang formations (Fig.2). The mudstones in the lower Qingshankou
4 Formation, which directly overlie the reservoirs of the Quantou Formation, contain dark lacustrine
5 mudstones with a thickness of over 300 m (Fig. 4)³⁷ which have a diffusion coefficient less than
6 $10^{-5} \text{cm}^2 \text{s}^{-1}$ (the diffusion coefficient can be used alongside the fluid properties to indicate how
7 rapidly the fluid will move through the rock and is a measure of permeability) and a displacement
8 pressure of 3.9 MPa for natural gas³³ (Displacement pressure is a measure of the differential
9 pressure a rock can support and therefore its ability to act as a caprock for buoyant fluids). For
10 CO_2 , the displacement pressure was theoretically converted to 2.0 – 3.4 MPa. The black mudstone
11 of the Nenjiang formation has a thickness of 200 – 300 m,³⁸ a diffusion coefficient of $8.4 \sim 18 \times$
12 $10^{-6} \text{cm}^2 \text{s}^{-1}$ and a displacement pressure of 5 MPa for natural gas (equivalent to a displacement
13 pressure of 2.5 – 3.7 MPa for CO_2). These seals in the lower Qingshankou and Nenjiang
14 formations cover the entire basin. The seals in the upper Qingshankou Formation are present
15 across most of the basin, but there are a few regions where these impermeable rocks are absent.
16 Undercompaction is very common in these regional seals, which has enhanced the plasticity of the
17 seals, and as a result, fewer fractures and faults penetrate the sealing formations and transmissivity
18 of faults is reduced (when pore fluids cannot escape in response to increased sediment loading, the
19 trapped fluid supports the increased sediment load and pore pressure increases, as a result, the
20 porosity is preserved and the formations are undercompacted and overpressured^{39,40}).

21

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

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

8

9 Natural gas reservoirs associated with CO₂ are present in the lower Qingshankou, upper Quantou
10 and Yingcheng formations⁴¹. The presence of these naturally-occurring CO₂ reservoirs and
11 hydrocarbon reservoirs demonstrate the ability of the seals to contain buoyant fluids which
12 suggests this region is very favourable for CO₂ storage.

13

14 5.2.3 Pressure and Temperature (PT)

15 High pressure and quite high temperatures are required for CO₂ to exist in its supercritical phase,
16 however, these conditions also make wellhead engineering more challenging and add to the cost of
17 CO₂ storage.

18

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

22

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

6

7 In order to determine the likely impact of temperature and pressure on the state of the injected
8 CO₂, statistics about the distribution of the reservoir temperature and pressure in the oil fields of
9 northern Songliao Basin were collated (Fig. 5). These plots show that although lower temperatures
10 are observed at some sites, injected CO₂ would remain in its supercritical phase in most reservoirs
11 under the higher than normal geothermal regime. In the remainder of the reservoirs, CO₂ should
12 achieve a liquid state with high density, very close to its supercritical state. Thus the pressure and
13 temperature conditions are very likely to be suitable for CO₂ storage.

14

15 5.2.4 Salinity

16 The classification of salinity of underground water in China is shown in the Table 2. Analysis
17 indicated that the salinity of the aquifers in the oil and gas field of northern Songliao Basin is 3000
18 – 13 000 mgL⁻¹. Over 75 % of the aquifers are highly brackish, while all the others are saline.
19 Thus the aquifers are suitable for CO₂ storage in terms of salinity and these aquifers are also not a
20 potable water source, reducing the risk of a conflict of usage (although very high salinities would
21 be unfavourable as viscosity of pore fluid would be increased).

22

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

4

5 5.2.5 Hydrodynamic system

6 An active hydrodynamic system increases the risk of CO₂ migrating out of the CO₂ storage
7 reservoirs along with the groundwater. Thus, the favourable hydrodynamic state for CO₂ storage is
8 that of a weak hydrodynamic system with slow flow speed and low hydrostatic head.

9

10 The hydrodynamic field in the northern Songliao Basin is asymmetrical. Groundwater migrates
11 towards the basin centre in the northeast uplift area and northern plunge area, where the area is
12 recharged by precipitation. However, in the basin centre (which also includes the Sanzhao,
13 Qijia-Gulong, Changling and Heiyupao depressions) groundwater migrates outwards from the
14 basin centre.⁴⁵ These two different zones meet along a line from Well Lai 271 to Well Du 48,⁴⁶ so
15 the northern Songliao Basin is divided into three regions: 1) hydrodynamic area recharged by
16 precipitation in the northeast which has a strong hydrodynamic drive and a seepage velocity of 10
17 -20 cm a^{-1} ; 2) the region with a relatively weak hydrodynamic drive between the Nehe - Baiquan
18 - Mingshui and Heiyupao and Wuyu'er depressions, with a seep velocity of $5 - 10 \text{ cm a}^{-1}$; and
19 finally 3) the region in the south of the Heiyupao and Wuyu'er depressions where the
20 hydrodynamic drive is very weak.⁴⁷

21

22 Across the whole basin, the hydrostatic head level is higher than the ground surface, generally

1 only by up to 250 m though there are a few high pressure regions where hydrostatic head is
2 estimated to be 400 m above the ground surface. When a well is drilled into an aquifer with
3 hydrostatic head level higher than the ground surface, if not controlled, the groundwater can move
4 upwards inside the well casing to a level that is higher than the level of the ground surface⁴⁸, this
5 may which may increase the risk of CO₂ migration with the groundwater. Thus, the hydrostatic
6 head level was considered seriously during the potential area selection and received a relatively
7 high weighting.

8

9 Generally, the hydrodynamic regime is favourable for CO₂ storage, such that large scale leakage
10 of CO₂ caused by the movement of groundwater is not expected.

11

12 5.2.6 CO₂ source

13 After 2003, the CO₂ emissions of the industrial sector in northeast China showed rapid growth.
14 The Songliao Basin is the most important industrial area in northeast China, where the machinery,
15 metallurgy, petroleum, chemical industries are highly developed. Long-term industrial production,
16 high population density, and dependence on traditional fossil fuels means the CO₂ emissions in
17 this region are very high. Although the emission intensity is being reduced by increased efficiency
18 and changing industrial processes, overall the total amount of CO₂ emissions are still increasing as
19 the growth of industry is very rapid.⁴⁹ In the northern Songliao Basin, the number of both high
20 concentration sources (CO₂ concentration higher than 80%) and large stationary point emission
21 sources (which emit more than 10×10^3 t/y) of CO₂ is extremely large.^{50, 51.}

22

1 In addition to these anthropogenic sources, the amount of naturally sourced CO₂ produced from
2 this basin is quite large. Gas reservoirs in the northern Songliao Basin are often associated with
3 mantle-derived CO₂ gas. Analysis of the wells and layers containing CO₂ shows that in 21% of
4 cases, CO₂ accounts for more than 80% of the produced gas; and for 5 – 30% of the produced gas,
5 the percentage of CO₂ will be as high as 63%.⁵² The CO₂ is removed during gas processing to
6 purify the produced gas and prevent pipeline corrosion. The removed CO₂ could be stored in a
7 geological reservoir, presently it is released into the atmosphere. The gas reservoirs associated
8 with high concentration CO₂ are mainly found in the Yingcheng Formation^{52, 53} which lies at
9 depths greater than 3000 m was therefore not considered for CO₂ storage. A few gas reservoirs
10 associated with low CO₂ concentrations can be found in the upper Quantou formation and upper
11 Qingshankou Formation⁵¹ where the seals are good enough to separate HFSA from other
12 formations and prevent the injected CO₂ from migrating into the surrounding reservoirs.

13

14 **5.3 Selected regions**

15 The areas with the most advantageous characteristics for CO₂ storage in northern Songliao Basin
16 were delimited based on the geological conditions described in the previous sections:

17

18 The potential storage reservoirs in the Nenjiang Formation reservoir have a wide areal distribution
19 and great thickness, but are too shallow in some places. North of Daqing, for example, near the
20 Well Gu 2 in the Qijia-Gulong Depression, the depth of reservoir rocks in the Nenjiang Formation
21 is less than 800 m. This was also the case in the west of the Longhupao Terrace and east of the
22 Qijia-Gulong Depression. Meanwhile, the salinity of aquifers in the Nenjiang Formation decreases

1 gradually from east to west to 3000 mgL^{-1} in the area east of Daqing and Da'an. Therefore, the
2 most promising area for CO_2 storage in the Nenjiang Formation is bounded to the west by the
3 West Slope area and by the Daqing anticline to the east and lies to the south of Daqing and to the
4 north of Zhaoyuan (Fig.7).

5

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

13

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

17

18 **5.4 Detailed assessment of potential storage areas**

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

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

6

7 The authors considered HFSA in 42 hydrocarbon fields which lie within the areas identified as
8 most promising for CO₂ storage. From this dataset, HFSA near nine hydrocarbon fields scored
9 over 8 using the assessment criteria in Table 3 and are therefore defined as the primary
10 recommended area for storage locations in the northern Songliao Basin (Fig. 7), 15 scored 7 – 8,
11 which was used to define the secondary area recommended for geological storage of CO₂ in
12 northern Songliao Basin (Table 4). All of these HFSA are concentrated in the Daqing placanticline,
13 north of the Longhupao, Qijian-Gulong and Sanzhao depressions (Fig. 7).

14

15 **6. Storage capacity calculation**

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

17

18 **6.1 Determination of irreducible water saturation**

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

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

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

4

5 **6.2 Determination of CO₂ density and solubility**

6 The solubility of CO₂ in the formation water is related to temperature, pressure, ion type and
7 content of the formation water. A calculation model of CO₂ solubility, which considered the
8 content of Cl⁻ (Chloride) and HCO³⁻ (Bicarbonate) ions, temperature and pressure was used in this
9 paper.^{56,57} This model was used to calculate the CO₂ solubility in the HFSA (Table 5). The density
10 of the formation water at subsurface conditions, used to calculate the CO₂ solubility, was
11 determined through the Nomograph given by Schowalter⁵⁸, using temperature, pressure and
12 salinity data.

13

14 The CO₂ density in the different HFSA was determined in relation to a chart of CO₂ density with
15 temperature and pressure, which was presented by Bachu (Table 5).⁵⁹

16

17 **6.3 Results**

18 The total capacity of the HFSA in the primary recommended storage area was calculated to be 7.7
19 $\times 10^9$ t CO₂ using equation [7]. The largest HFSA has a potential storage capacity of 4.9×10^9 t
20 CO₂. For the 15 HFSA in the secondary recommended storage area, the total calculated storage
21 potential is 2.1×10^9 t CO₂, with the largest having a calculated capacity of 732.1×10^6 t CO₂.

22 Based on these calculations, the total potential storage capacity of the primary and secondary

1 storage areas identified in Fig. 7 is 9.8×10^9 tCO₂, which could theoretically contain more than
2 100 years of emissions from the large-scale sources in the whole Songliao Basin if they were to
3 remain at present levels, as the current annual CO₂ emissions in Songliao Basin are 95×10^6 t.⁶⁰
4 There are 11 HFSA in this region with a total CO₂ storage capacity over 100×10^6 t, accounting
5 for about 50% of the total number of hydrocarbon fields, but their total capacity accounted for
6 about 95% of the calculated total for the primary and secondary storage areas (Table 5).

7
8 Some of the smaller HFSA scored highly as the weighting of reservoir conditions such as reservoir
9 characteristics and security of storage is higher than the weighting of reservoir area and thickness,
10 which are very important for capacity. Thus, the total score of these smaller HFSA is higher than
11 some HFSA which have a large volume but less favourable other characteristics.

12

13 **7 Conclusions**

14 (1) Cretaceous strata are favourable for CO₂ storage in Hydrocarbon Field Saline Aquifers (HFSA)
15 in the northern Songliao Basin. The sandstone reservoirs in the Yaojia and Qingshankou
16 formations are the most favourable, while the Nenjiang and Quantou formations are reasonably
17 favourable.

18 (2) The Daqing placanticline and the region north of the Longhupao and Qijia-Gulong Depression
19 and the Sanzhao Depression are the most promising areas and so are identified as the primary area
20 recommended for storage in the northern Songliao Basin. The central depression and west western
21 slope also have advantageous characteristics for CO₂ storage and so are identified as the secondary
22 area recommended for storage in the northern Songliao Basin.

1 (3) The calculated storage capacity of the primary area recommended for storage is 7.7×10^9 t
2 CO₂; while the secondary area recommended for storage has a calculated capacity of 2.1×10^9 t
3 CO₂. Theoretically, these areas offer a combined storage capacity that could store the CO₂
4 emissions from large-scale sources in the Songliao Basin for more than 100 years (at current
5 emission rates).

6
7

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13
14

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- 14

1 **Tables**

2

3 Table1 Suitability assessment criteria of CO₂ storage for basin scale
 4 (Modified After Bachu²⁶)

Criterion	Classes				
	1	2	3	4	5
Tectonic setting	Very unstable (e.g. subduction)	Unstable (e.g. syn-rift, intramontan e, 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 *

5 * indicates the score given to Songliao Basin

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1 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

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1 Table 3 Suitability criteria for CO₂ 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

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1 Table 4 HFSA in different oilfields and their storage potential rank
 2 (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

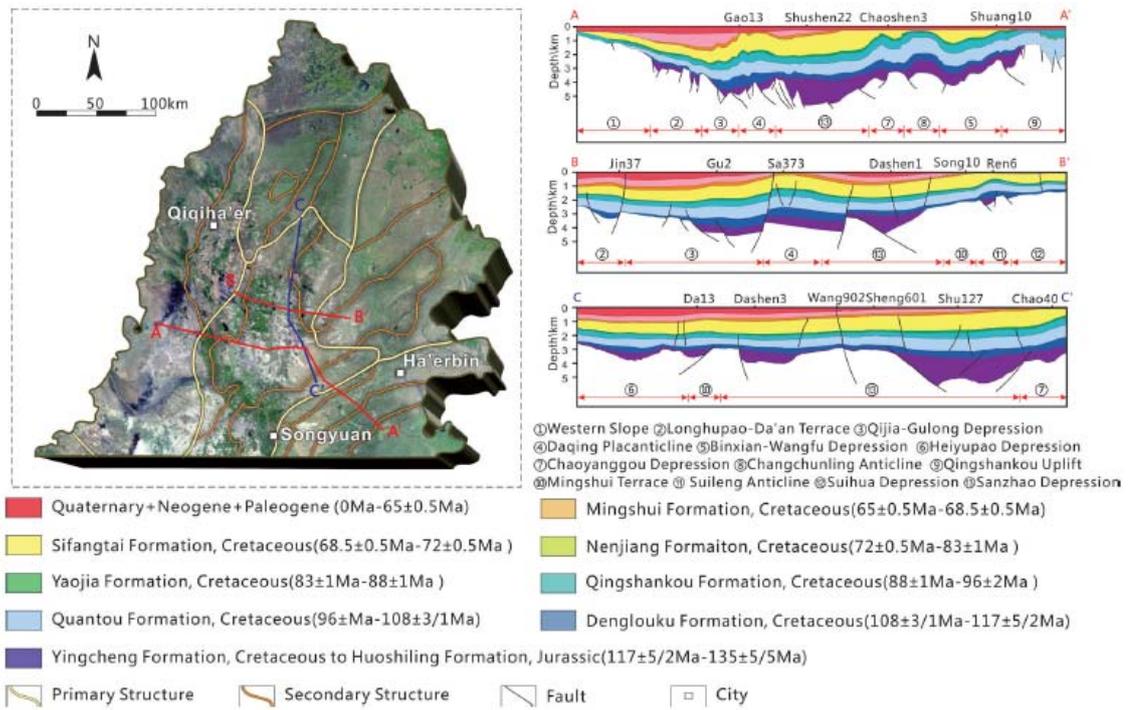
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1 Table 5 CO₂ storage potential of HFSA in Songliao Basin

		S _{CO2} (kg/m ³)	Φ (%)	Swi (%)	ρ _{CO2} (Kg/m ³)	M _{CO2s} (10 ⁶ t)	M _{CO2a} (10 ⁶ t)	M _{CO2} (10 ⁶ t)
Primary Potential Area	Max(HFS-1)	57.28	25.50	0.13	743.38	4645.2	219.03	4864.2
	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	7272.5	438.15	7710.6
						2		7
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	1562.8	510.03	2072.9
						9		2

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1 **Figures**



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4 Fig.1 Tectonic units and cross-section of the northern Songliao Basin (Section A-A' was modified
5 from Chen J et al., 2009;¹⁹ Section B-B' and C-C' were modified from Lei P et al., 2010²⁰)

Period	Formation	Member	Age (Ma)	Thick (m)	Column	Facies	Hydrocarbon			CO ₂		
							Source	Seal	Reservoir	Seal	Reservoir	
Cretaceous	k2m	II	65±0.5	0~381		Fluvial	•					
		I		0~243		Lacustrine	•	•		•		
	k2s		68.5±0.5	0~413		Fluvial	•	•		•		
		V	72±0.5	0~355		Fluvial Shore	•	•		•		
	k2n	IV		0~300		Lacustrine			•		•	
		III		35~131		Deep lacustrine			•		•	
		II		85~252		Turbidite	•	•		•	•	
	k2y	I	83±1	40~222		Fluvial, Delta	•		•		•	
		II-III		60~150		Delta, Turbidite	•		•		•	
	k2qn	I	88±1	0~78		Delta, Turbidite			•		•	
		II-III		300~552		Lacustrine			•		•	
	k2q	I		96±2	60~112		Deep lacustrine, Turbidite		•		•	•
			IV		0~128		Delta Turbidite	•		•		•
		III		0~692	Lacustrine			•		•		
		II		0~479	Fluvial	•	•		•			
		I		0~885	Lacustrine	•						
k1d	IV		108±3/1	0~212		Fluvial		•				
		III		0~612		Fluvial Lacustrine			•			
	II		0~700	Lacustrine	•							
	I	117±5/2	0~215	Fluvial								

k2m: Mingshui Formation k2s: Sufangtai Formation k2n: Nenjiang Formation
 k2y: Yaojia Formation k2qn: Qingshankou Formation k2q: Quantou Formation
 k1d: Dengloulou Formation

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2 Fig.2 Summary stratigraphy column of Cretaceous sediments in the northern Songliao Basin. (The

3 size of circle under 'source' column indicates the scale of source rock; the size of circle under

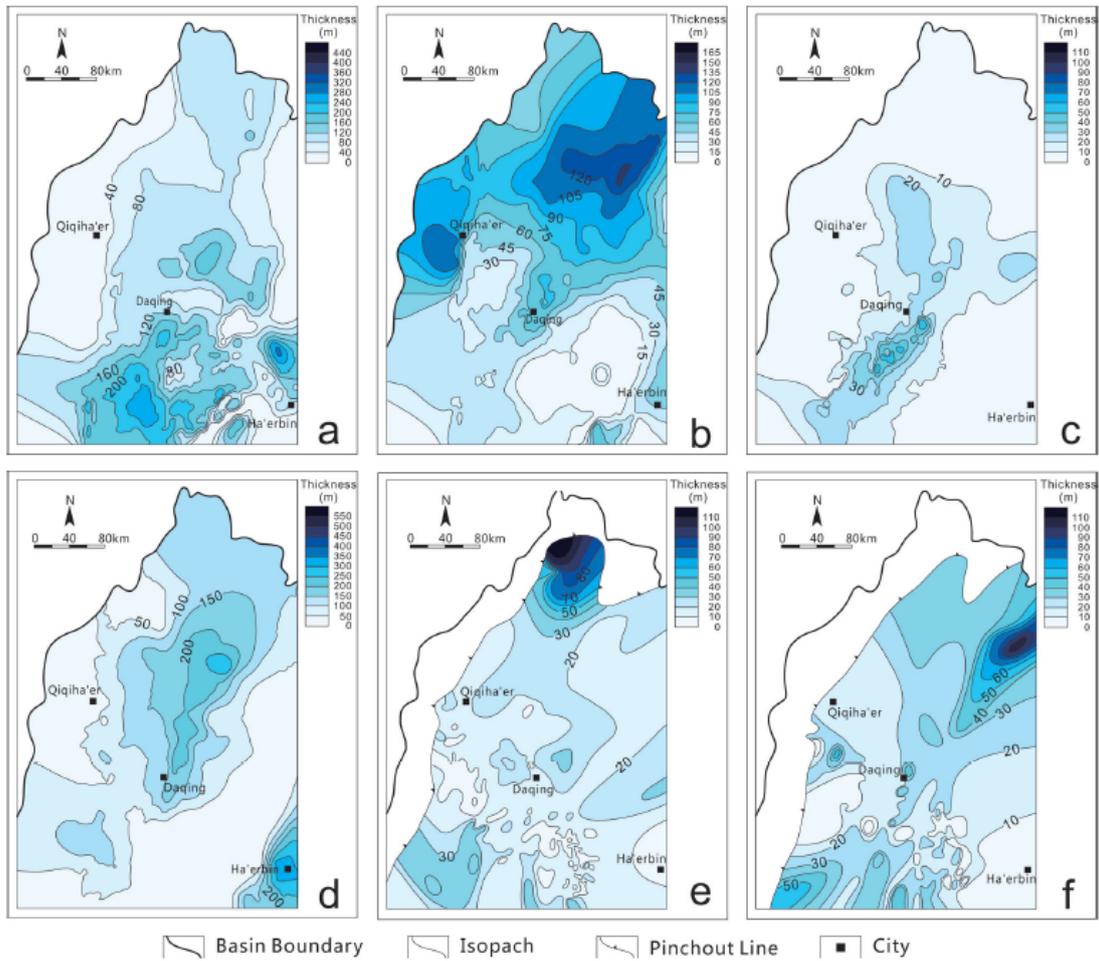
4 'seal' column indicates the ability of seals to trap hydrocarbon/CO₂; the size of circle under

5 'reservoir' column indicates the suitability and potential for hydrocarbon trapping/CO₂ storage.)

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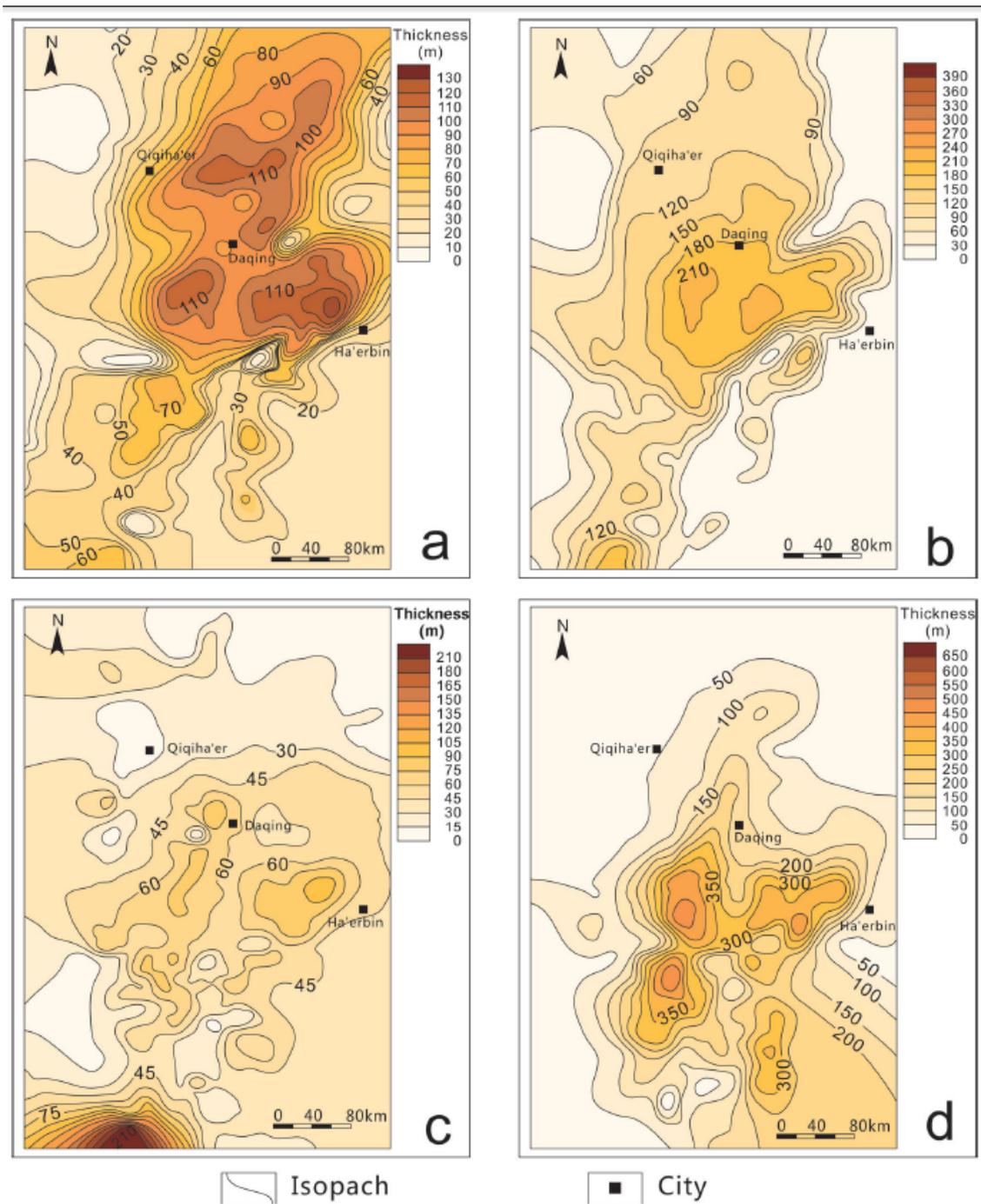
3 Fig. 3 Isopach maps of sandstone thickness in potential storage formations in the northern
4 Songliao Basin (Modified after Hou Qijun, 2009³³) (a) 3rd, 4th member of Nenjiang Formation (b)
5 2nd, 3rd member of Yaojia Formation (c) 1st member of Yaojia formation (d) Qingshankou
6 Formation (e) 4th member of Quantou Formation (f) 3rd member of Quantou Formation

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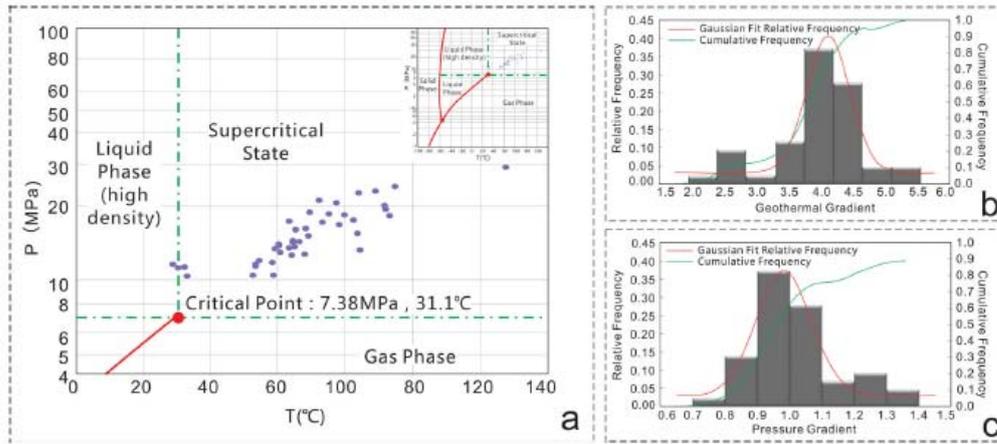
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2 Fig. 4 Isopach map of mudstones in the northern Songliao Basin (Modified after Hou Qijun,

3 2009³³) (a) 1st member of Nenjiang Formation (b) 2nd member of Nenjiang Formation (c) 1st

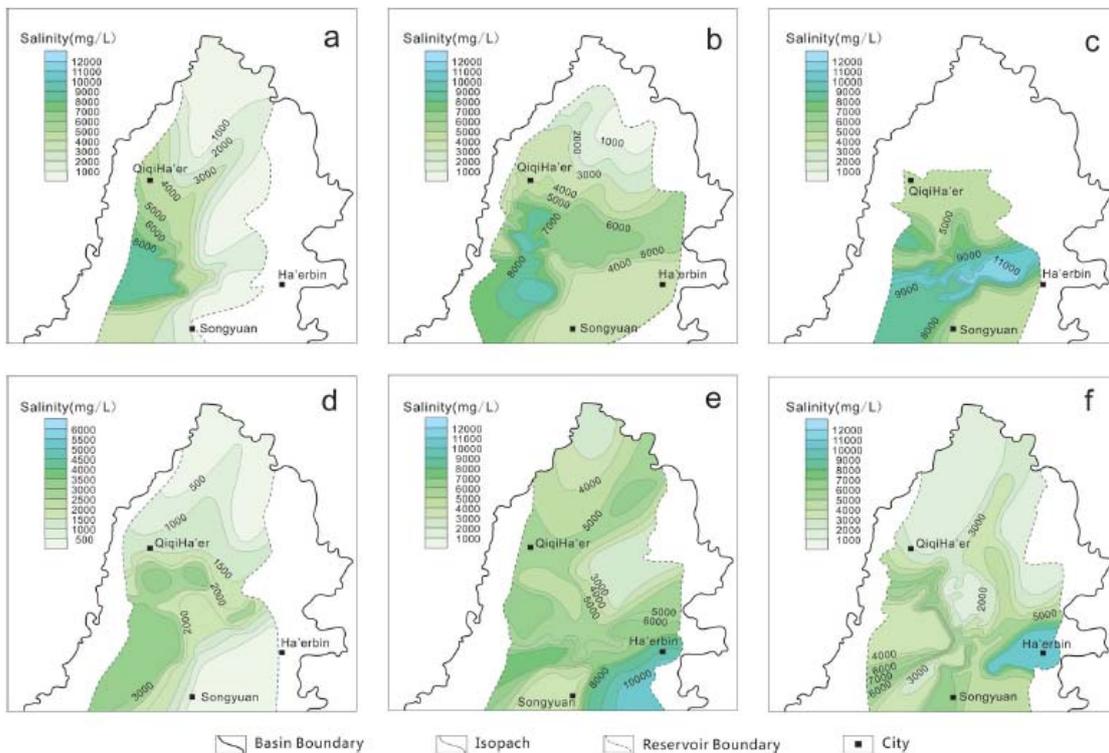
4 member of Qingshankou Formation (d) 2nd, 3rd members of Qingshankou Formation

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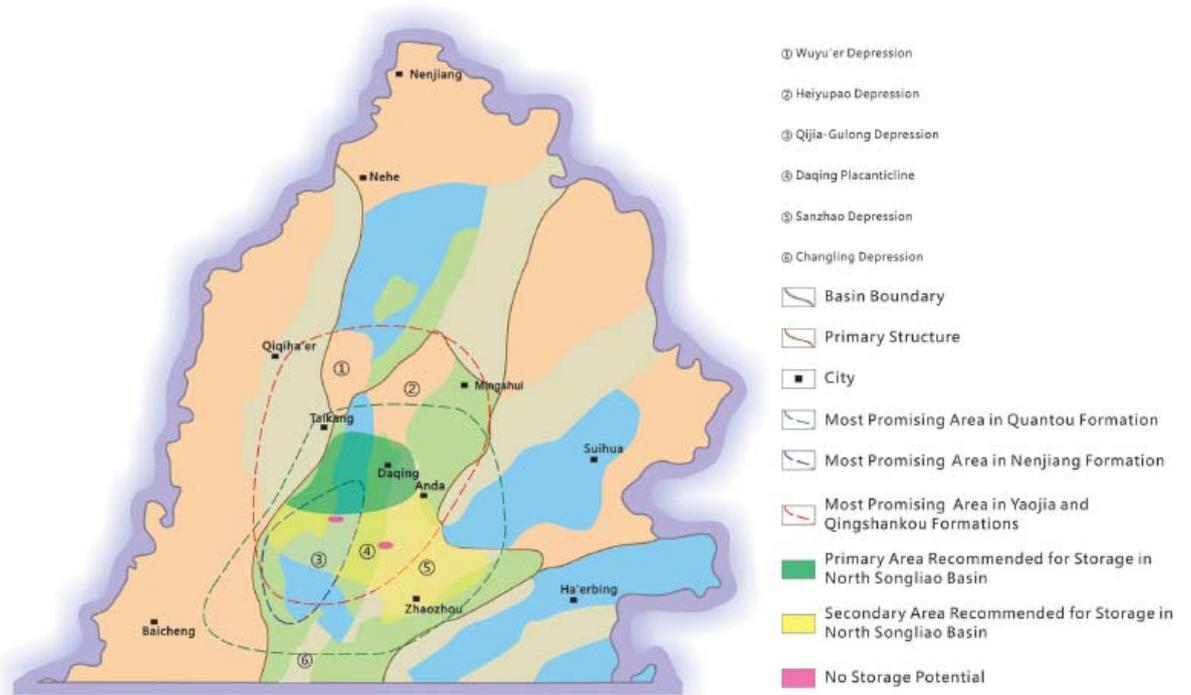
Fig. 5. Statistical analysis of PT conditions in northern Songliao Basin (a) distribution of temperature and pressure in different oilfields (b) statistical analysis of geothermal gradient (c) statistical analysis of pressure gradient



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Fig.6 Salinity of HFSA in different formations in northern Songliao Basin⁴⁴ (a) 3rd, 4th member of Nenjiang Formation (b) 2nd, 3rd member of Yaojia Formation (c) 1st member of Yaojia formation (d)

- 1 Qingshankou Formation (e) 4th member of Quantou Formation (f) 3rd member of Quantou
- 2 Formation
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- 5 Fig.7 Areas recommended for geological storage of CO₂ in northern Songliao Basin
- 6

1 **Author biographies**

2 **Shu Wang**



4 Shu Wang has studied as a PhD candidate in the Institute of Geology and Geophysics, Chinese
5 Academy of Sciences for six years. Current research interests include CO₂ storage and Enhanced Oil
6 Recovery potential in the sedimentary basins of East China

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8 **Ceri Vincent**



10 Ceri J Vincent has worked for the British Geological Survey for over 12 years on geological storage of
11 CO₂. Current research interests include storage potential in the Europe, China and South Africa.

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13 **Mike Stephenson**



15 Mike Stephenson is the Director of Science and Technology at the British Geological Survey (BGS).
16 He is Editor-in-Chief of an Elsevier geological journal and has honorary professorships at the
17 Universities of Nottingham and Leicester.

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2 **Zeng Rongshu**



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4 Zeng Rongshu is participating in the Chinese National Basic Research Program on a project relating to

5 geological storage of CO₂. He is also involved in three international projects studying geological

6 storage of CO₂. Zeng is a member of the International Advisory Panel of the Global CCS Institute.