Front. Earth Sci. 2023, 17(3): 727–738
https://doi.org/10.1007/s11707-022-1043-9

RESEARCH ARTICLE

CO_2 geological sequestration potential of the low-rank coals in the southern margin of the Junggar Basin

Qun ZHAO (✉)[1], Ze DENG[1], Meng ZHAO[2], Dexun LIU[1]

1 Research Institute of Petroleum Exploration & Development, PetroChina, Beijing 100083, China
2 PetroChina Southwest Oil & Gasfield Company, Chengdu 610051, China

Abstract Carbon capture, utilization, and storage (CCUS) is considered one of the most effective measures to achieve net-zero carbon emissions by 2050, and low-rank coal reservoirs are commonly recognized as potential CO_2 storage sites for carbon sequestration. To evaluate the geological CO_2 sequestration potential of the low-rank coal reservoirs in the southern margin of the Junggar Basin, multiple experiments were performed on coal samples from that area, including high-pressure mercury porosimetry, low-temperature N_2 adsorption, overburden porosity and permeability measurements, and high-pressure CH_4 and CO_2 isothermal adsorption measurements. Combined with the geological properties of the potential reservoir, including coal seam development and hydrodynamic characteristics, the areas between Santun River and Sigong River in the Junggar Basin were found to be suitable for CO_2 sequestration. Consequently, the coal-bearing strata from Santun River to Sigong River can be defined as "potentially favorable areas for CO_2 sequestration". To better guide the future field test of CO_2 storage in these areas, three CO_2 sequestration modes were defined: 1) the broad syncline and faulted anticline mode; 2) the monoclinic mode; 3) the syncline and strike-slip fault mode.

Keywords CO_2 geological sequestration, coalbed methane, low-rank coal, coal reservoir, Junggar Basin

1 Introduction

Geological sequestration of CO_2 has been widely recognized as an effective strategy that may contribute significantly to reducing CO_2 emissions. Three key factors contribute to improving the effectiveness of CO_2 geological sequestration: 1) sufficient thickness and permeability of the reservoir to ensure the effective injection of CO_2, 2) sufficient pore volume to inject economically viable volumes of CO_2, and 3) sufficiently safe and environmentally friendly conditions for long-term sequestration of CO_2 (Chen et al., 2021; Gholami et al., 2021; Lyu et al., 2021; Sharma et al., 2021). Low-rank coal seams have been found to meet these three key criteria and are recognized as potential reservoirs for CO_2 sequestration (Kang et al., 2020; Zhang et al., 2021; Ma et al., 2022). Since the Junggar Basin has a large number of low-rank coal reservoirs (Ma et al., 2022), it is necessary to evaluate the CO_2 geological sequestration potential of these low-rank coal reservoirs in order to select the ones with the greatest sequestration potential.

Previous research mainly focused on static parameters, such as the CO_2 adsorption capacity of coal reservoirs (Zhang and Hu, 2020; Ma et al., 2022) However, the retention of CO_2 in coal seams is a dynamic process that involves the on-going coupling of multiple parameters (Sun et al., 2021). For example, the changes in temperature and pressure conditions during CO_2 injection will dynamically cause the expansion of matrix structure, the deterioration of coal strength, and the destruction of coal integrity (Tan et al., 2016; Xu et al., 2019) As these changes accumulate over an extended period, the gas flow paths in the sequestrated area will be significantly reduced, and negatively influence the effectiveness of the geological storage of CO_2. Therefore, a suitable CO_2 geological sequestration site should consider not only the adsorption capacity of coal reservoirs but also their stability and safety after sequestration.

A coalbed reservoir with a high sealing capacity and a specific macroscopic distribution range can effectively trap and retain CO_2, which will minimize the risk of leakage (Mi and Ma, 2019; Dai et al., 2019). Consequently, deep coal seams with thick caprocks should be selected to prevent fractures and seal damage caused by

Received May 10, 2022; accepted August 1, 2022

E-mail: zhaoqun69@petrochina.com.cn

long-term CO_2-H_2O-rock interaction (Zhang et al., 2021). Due to the migration of CO_2 after sequestration, the effects of stress, and geochemical interaction, new fractures can be developed and existing fractures can be re-activated in the caprock, which can increase the permeability of the caprock and so increases the risk of CO_2 leakage (Gheibi et al., 2017). Many of the factors influencing the storage of CO_2 in coal seams have been identified previously. For example, (Tan et al., 2016) concluded that burial depth, coal rank, and coal thickness were the primary controlling factors, while the reservoir tectonic environment and hydrogeological characteristics were the secondary factors. Other significant influencing factors include the mechanical properties of caprocks (Al-Ameri et al., 2016), tectonism, hydrogeology, and the geothermal regime of the sedimentary basin (Bachu and Stewart, 2002). In particular, there are numerous experimental studies on CO_2 sequestration in different rank coals (Ranathunga et al., 2017; Zheng et al., 2020; Zhang and Hu, 2020; Liu et al., 2021; Ma et al., 2022; Sun et al., 2021) that demonstrate that the low-rank coal reservoirs have excellent potential for the geological sequestration of CO_2. However, only a few studies have considered both the physical properties and the geological settings of coal reservoirs when evaluating the CO_2 geological sequestration potential of the southern margin of the Junggar Basin.

To evaluate the CO_2 geological sequestration potential of sites in the southern margin of the Junggar Basin, multiple experiments were conducted using coal samples from this area to analyze the physical characteristics, CH_4 and CO_2 adsorption characteristics, and stress sensitivities. The experiments included high-pressure mercury porosimetry, low-temperature N_2 adsorption, overburden porosity and permeability analyses, and high-pressure CH_4 and CO_2 isothermal adsorption. The results of the experimental data were integrated with the analysis of the geological setting in order to delineate the favorable areas for CO_2 sequestration in the southern margin of the Junggar Basin.

2 Geological setting

The Junggar Basin is a sizeable coal-rich basin in Mesozoic and Cenozoic, China. The early Junggar Basin was formed after compression and collision during the Hercynian movement, and deposition continued until the Triassic. The southern margin of the Junggar Basin is the Yilinhabil Mountains, and the coal mines occur mainly in the fault-fold belt on this margin. The southern margin of the Junggar Basin was strongly deformed by the Himalayan movement, forming the Bogda fault fold belt and the northern Tianshan thrust belt. The significant faults developed in the area include the northern Tianshan piedmont fault (F1), the Bogda piedmont fault (F2), and the Urumqi-Miquan strike-slip fault, followed by the F3 strike-slip faults and the F4, F5 and F6 reverse faults. Anticlines and small-scale fault structures in the southern margin of the basin are also highly developed and are often manifested as folds and reverse faults (Fig. 1).

In the Early-Middle Jurassic, there were two principal coal accumulation periods along the southern margin, and the Badaowan Formation and the Xishanyao Formation are the primary coal-bearing strata (Fig. 2). The lower intervals of the Badaowan Formation were principally

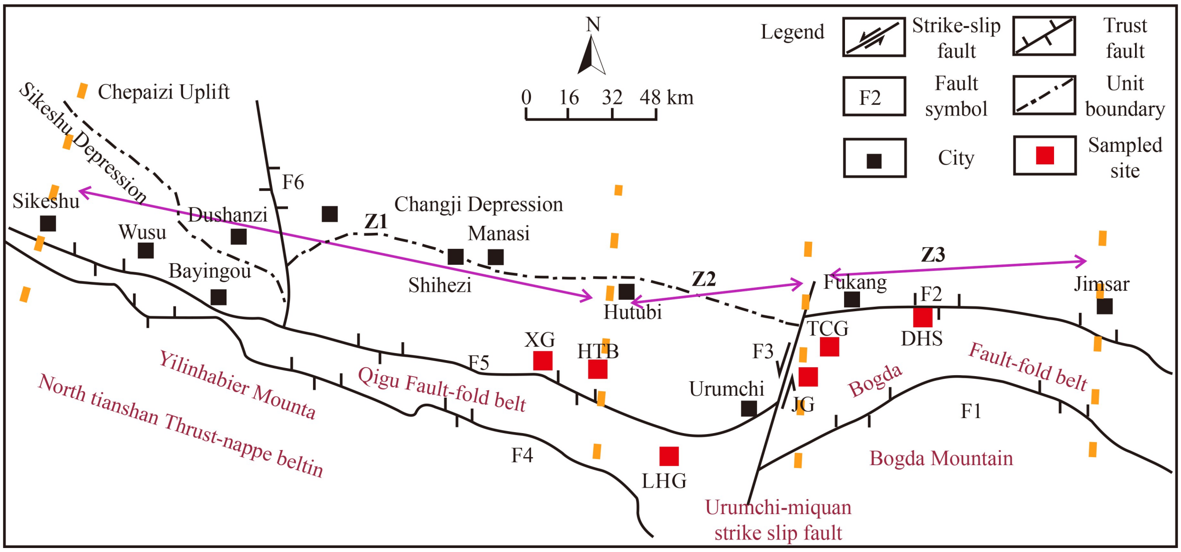


Fig. 1 Location and geological framework of the southern margin of the Junggar Basin (modified after Mi and Ma, 2019; Dai et al., 2019; Zhang et al., 2021). The delineation of the Z1, Z2, and Z3 ones is based on a comprehensive consideration of the structural characteristics, hydrodynamic characteristics, petrological compositions, and coal maturation. Z1 is the area from Sikeshu coal mine to HTB coal mine, Z2 area is from HTB coal mine to JG coal mine, and Z3 area is from JG coal mine to Jimsar coal mine.

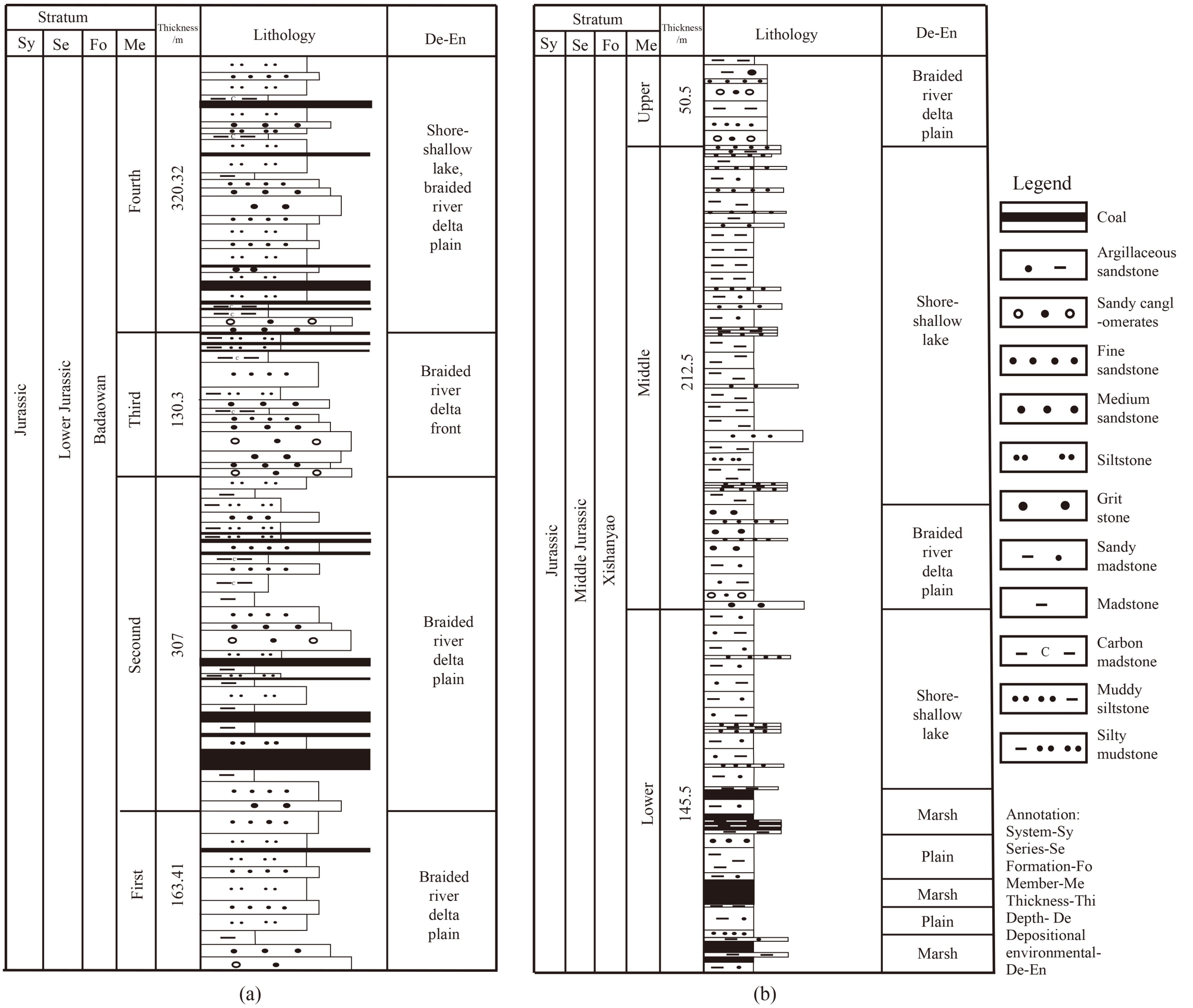


Fig. 2 Stratigraphy, lithology, and environments of deposition of (a) Badaowan Formation; (b) Xishanyao Formation.

alluvial fan and fan delta facies, while the upper parts developed river-lake, delta, and shallow lake facies. The Badaowan Formation contains coal seams in both the lower and upper sections, with the seams in the lower section being relatively thick. The total minable thickness in the Fukang-Baiyang River area is 46 m, and the Xishanyao Formation has 47 mineable coal seams with a total thickness of 184.09 m.

3 Experimental methods

Coal block samples were collected from the coal mines in the southern margin of the Junggar Basin (Fig. 1), including Hutubi (HTB), Jiangou (JG), Liuhuanggou (LHG), Xigou (XG), Tiechanggou (TCG), Dahuangshan (DHS). 20 cm × 20 cm × 20 cm block samples were sampled from the fresh working face of each coal seam, then sealed and transported to the laboratory. The vitrinite reflectance (R_o) and coal maceral composition analyses were performed using a TIDAS MSP200 microscopic spectrophotometer and an Axio Scope A1 Pol polarizing microscope, respectively. The pore characteristics were analyzed using high-pressure mercury porosimetry and low-temperature N_2 adsorption methods. The high-pressure mercury porosimetry was performed using a Micromeritics AutoPore 9500 automatic mercury intrusion instrument. The low-temperature N_2 adsorption measurements were conducted using a Tristar 3020 physical adsorption instrument. The high-pressure CH_4 and CO_2 isotherm adsorption experiments were carried out using the GAI high-pressure adsorption instrument. Gas permeability was measured by the AP-608 overburden porosity-permeability instrument.

4 Results and discussion

Effective CO_2 sequestration is the result of the coupling the reservoir, sealing, preservation, and the dynamic sequestration processes. Therefore, effective CO_2 sequestration is influenced by the cumulative effects of many factors, including 1) the coal composition and pore characteristics; 2) the thickness of the coal reservoir; 3) the sealing capacity of the caprock; and 4) the hydrogeological conditions. These factors will be used to evaluate the CO_2 sequestration potential in the southern margin of the Junggar Basin. The coal beds in the southern Junggar Basin will also be compared to those in the Ordos Basin and the Qinshui Basin discuss the advantages of CO_2 sequestration in the Junggar Basin (Sections 4.1–4.3). The favorable zones for CO_2 sequestration in the Junggar Basin will then be delineated using the reservoir properties and the geological conditions (Sections 4.4 and 4.5).

4.1 Reservoir physical characteristics

Pore parameters such as pore volume, pore size, and surface area significantly impact gas adsorption capacity (Sun et al., 2021; Liu et al., 2021; Ma et al., 2022). Since CO_2 storage capacity increases with increasing pore volumes, pore sizes, surface areas, and porosity, it is necessary to examine the pore parameters of different coals to understand the potential effects of variations in these parameters.

The pore parameters of the coal samples from the southern Junggar Basin were determined (Fig. 3), and compared to the pore parameters of coal samples from the eastern margin of the Ordos Basin and from the Qinshui Basin (Qiao, 2009; Sun, 2015; Ma et al., 2022). For coals from the southern Junggar Basin, the average surface area value is 0.63 m^2/g, the average adsorption pore size is 16.01 nm, seepage pore volume is 0.21 cm^3/g, the average seepage pore diameter is 5.04 µm, and the average porosity is 8.56%. For coals from the Ordos Basin, the average surface area value is 0.37 m^2/g, average adsorption pore size is 16.11 nm, seepage pore volume is 0.13 cm^3/g, average seepage pore diameter is 0.15 µm, and the average porosity of the coal samples is 5.22%.

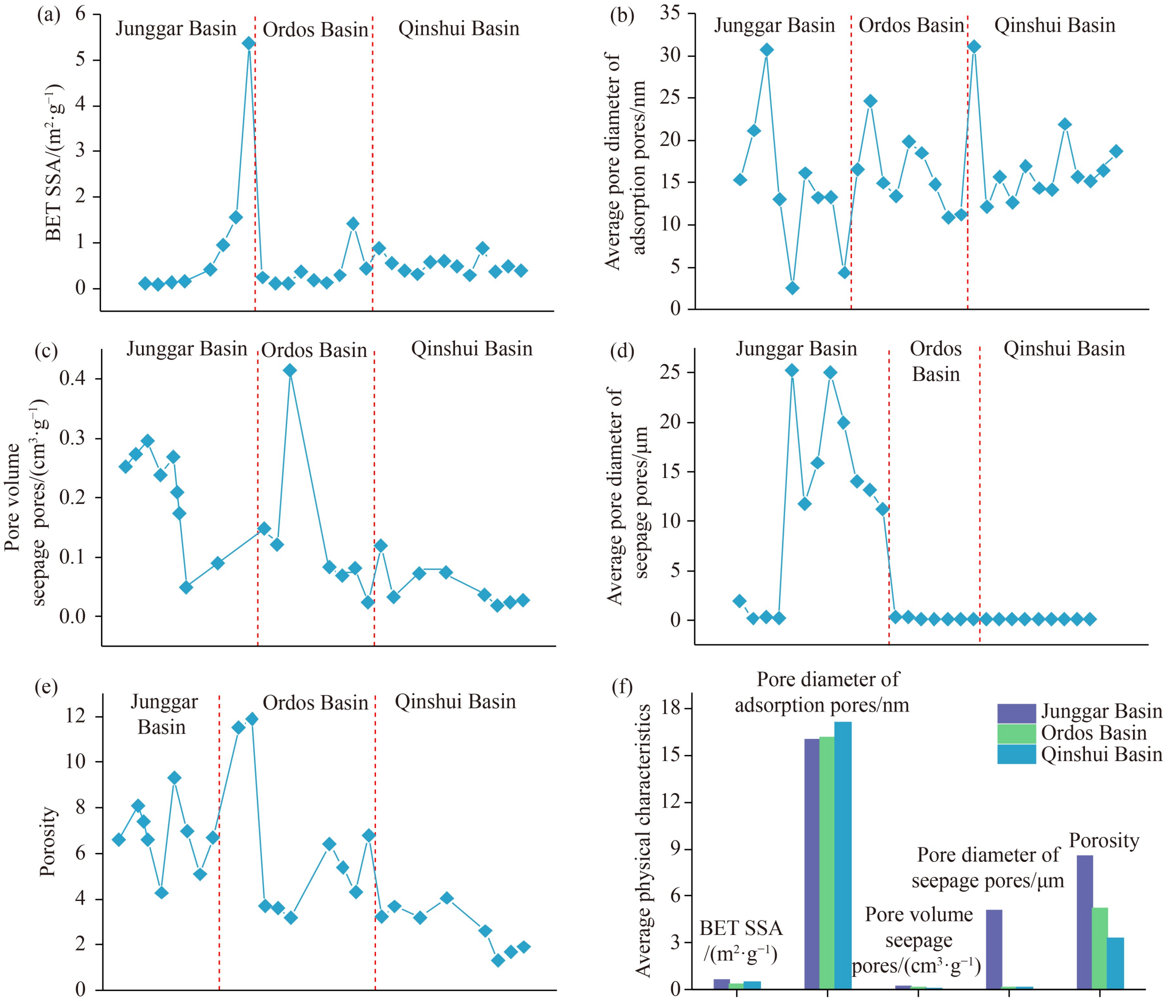


Fig. 3 Pore properties and porosities of coal samples from different basins (Data for the samples from the Ordos and Qinshui Basins are from Qiao, 2009; Sun, 2015; Ma et al., 2022). (a) BET SSA; (b) pore diameter of adsorption pores; (c) pore volume of seepage pores; (d) pore diameter of seepage pores; (e) porosity of coal samples; (f) average values of these parameters.

For coals from the Qinshui Basin, the average surface area value is 0.52 m^2/g, average adsorption pore size is 17.09 nm, seepage pore volume is 0.05 cm^3/g, average seepage pore diameter is 0.13 μm, and the average porosity is 3.31%. These data suggest that coals from Junggar Basin may be more suitable for CO_2 storage, since the Junggar Basin coals have a relatively higher surface area, seepage pore volume, seepage pore size, and porosity than coals from the other two basins (Fig. 3(f)).

4.2 Stress sensitivity of reservoir permeability

The sensitivity of reservoir permeability to subsurface stress can affect the migration of gas in coal, and a higher stress sensitivity will enhance CO_2 sequestration (Ma et al., 2020a). It has been shown (Chen, 2018; Cheng et al., 2018; Huang et al., 2019; Ma et al., 2020a) that the porosity and permeability of coal reservoirs will decrease with an increase in effective stress:

$$Q_i = Q_0 e^{-C_{\mathrm{p}}\sigma_i} + \mathrm{C}, \tag{1}$$

where Q_i is the porosity under effective stress σ_i, %; Q_0 is the initial porosity, %; C_{p} is the porosity compression coefficient, MPa^{-1}; C is a constant.

$$K = \mathrm{B}e^{-\alpha\sigma_i} + \mathrm{C}, \tag{2}$$

where K is the permeability under effective stress σ_i, mD; B and C are constants; α is the stress sensitivity coefficient, MPa^{-1}.

Previous work has shown that the porosity compression coefficients of low-rank, medium-rank, and high-rank coal samples were 0.235–0.307 MPa^{-1}, 0.038–0.153 MPa^{-1}, and 0.037–0.041 MPa^{-1}, respectively (Cheng et al., 2018; Huang et al., 2019; Ma et al., 2020a) The average stress sensitivity coefficients of the low-rank, medium-rank, and high-rank coal samples were 0.377 MPa^{-1}, 0.175 MPa^{-1}, and 0.223 MPa^{-1}, respectively, and the average stress sensitivity coefficient of low-rank coals was greater than those of medium- and high-rank coals. The porosity compression coefficient and stress sensitivity coefficient were found to decrease initially and then increase with increasing coal rank (Fig. 4). Consequently, during the CO_2 sequestration process, the permeability of low-rank coal reservoirs is restricted by increases in effective stress, which will reduce the fluid migration capacity of CO_2 and so enhance the preservation of CO_2. Consequently, low-rank coals in the southern Junggar Basin will have higher potentials for CO_2 sequestration than higher rank coals in the Ordos and Qinshui Basins.

4.3 Adsorption selectivity between CH_4 and CO_2

Since coal seams contain large amounts of CH_4, injecting CO_2 is a competition adsorption process between CH_4 and CO_2. As a result, it is necessary to compare and analyze the differences between the adsorption capacities of CH_4 and CO_2 for different rank coals.

In this section, the selectivity coefficient (α) is introduced (Ma et al., 2022). If α is greater than 1, it means CO_2 has a stronger adsorption affinity than CH_4, and α is expressed as

$$\alpha = \frac{a_2 \cdot b_2}{a_1 \cdot b_1}, \tag{3}$$

where a_1 is the maximum theoretical adsorption capacity of CH_4 (m^3/t); a_2 is the maximum theoretical adsorption capacity of CO_2 (m^3/t); b_1 is the Langmuir equilibrium constant of CH_4 (MPa^{-1}); and b_2 is the adsorption Langmuir equilibrium constant of CO_2 (MPa^{-1}).

Experimental data indicate that low-rank coals have lower adsorption capacities for CH_4 and CO_2 than medium- and high-rank coals (Fig. 5). Based on Eq. (3), the calculated average α of medium and high-rank coals is 3.21, while the calculated average α of low-rank coals was 5.17, which indicates that the low-rank coals have a stronger affinity for CO_2 than CH_4. In addition, CO_2 can

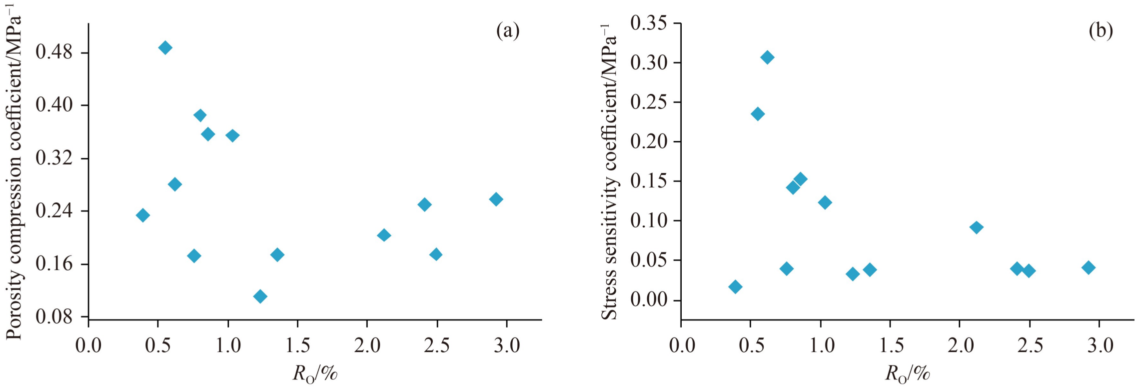


Fig. 4 Stress sensitivity of different rank coal reservoirs (data for the medium-and high-rank coals are from Cheng et al., 2018; Huang et al., 2019; Ma et al., 2020a). (a) Relationship between porosity compression coefficient and R_{o}; (b) Relationship between stress sensitivity coefficient and R_{o}.

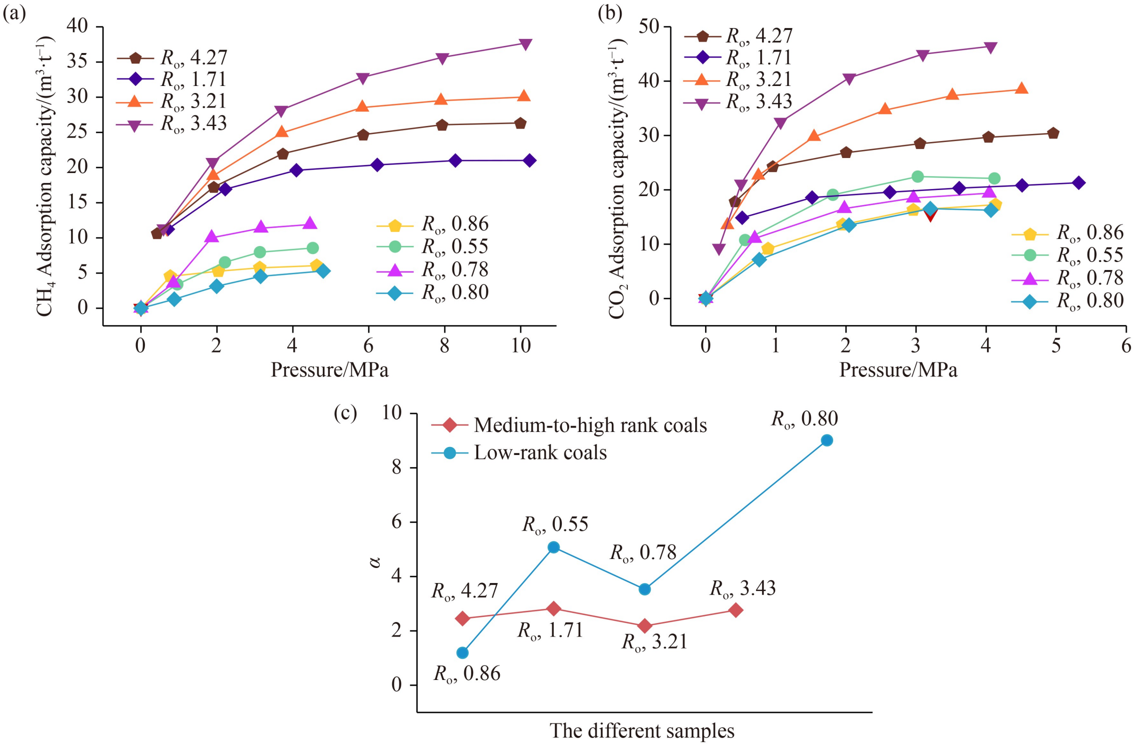


Fig. 5 CH_4 and CO_2 adsorption capacities and adsorption selectivity in different coal rank samples (data for the high-rank coals are from (Yu et al., 2014; Ma et al., 2022)). (a) CH_4 adsorption; (b) CO_2 adsorption; (c) adsorption selectivity coefficient of α of different rank coals.

be injected into low-rank coal reservoirs using lower injection pressures than for medium-and high rank coal reservoirs (Ma et al., 2022). From this it can be concluded that the low-rank coal reservoirs in the southern Junggar Basin have better potential for CO_2 sequestration and related CO_2-ECBM than the reservoirs in the Ordos and Qinshui Basins.

4.4 Petrological compositions and levels of maturation

As demonstrated above, low-rank coal reservoirs in the Junggar Basin are more suitable for CO_2 storage. Consequently, the petrological compositions and levels of maturity of these coals can be used to compare the sequestration potential of possible CO_2 storage sites in the Junggar Basin.

Higher gas adsorption capacity is generally thought to indicate a higher CO_2 sequestration potential (Kang et al., 2020; Gholami et al., 2021; Zhang et al., 2021; Ma et al., 2022). Since different coal petrological compositions can have different gas adsorption properties (Sun et al., 2021; Ma et al., 2022), it is necessary to quantify the impact of coal compositions on gas adsorption capacities. Correspondingly, the relationship of the Langmuir volume to moisture content, ash content, volatile content, fixed carbon content, vitrinite content, inertinite content, and exinite content was studied using both the experimental data in this study and data from the literature (Qiao, 2009; Li, 2015; Sun, 2015; Zhang et al., 2015; Zhou, 2015; Li, 2016; Li et al., 2016; Zhang, 2016; Zhang and Jiang, 2016; Zhang, 2018; Cheng, 2017; Wei, 2017; Dou, 2018; Lin et al., 2018; Yi, 2018; Zheng et al., 2018; Li, 2020; Gao et al., 2020; Ma et al., 2020b; Zou, 2020). In addition, the variations in moisture content, fixed carbon yield, organic components and R_o from east to west in the southern margin of the Junggar Basin were delineated.

Variations in coal compositions and properties can affect Langmuir volumes in different ways (Fig. 6). For example, moisture content negatively impacts the Langmuir volume, while fixed carbon content and vitrinite content positively impact it (Fig. 6). Since the oxygen-containing functional groups of coal are generally hydrophilic, the polar water molecules will preferentially occupy adsorption sites compared with the nonpolar CH_4, reducing the adsorption of CH_4 (Xu et al., 2019; Zhang et al., 2020; Ma et al., 2022). Because the strength of the gas adsorption increases with decreasing pore size, increasing concentrations of vitrinite will generally enhance gas adsorption since vitrinite has higher concentrations of micro-pores than inertinite, which has more mesopores (Li, 2016; Li, 2020; Ma et al., 2022). There was also a positive correlation between coal maturation and Langmuir volume (Fig. 6(h)), indicating that CO_2 sequestration potential will be enhanced with increasing coal rank. However, there were no clear correlations between ash content, volatile content,

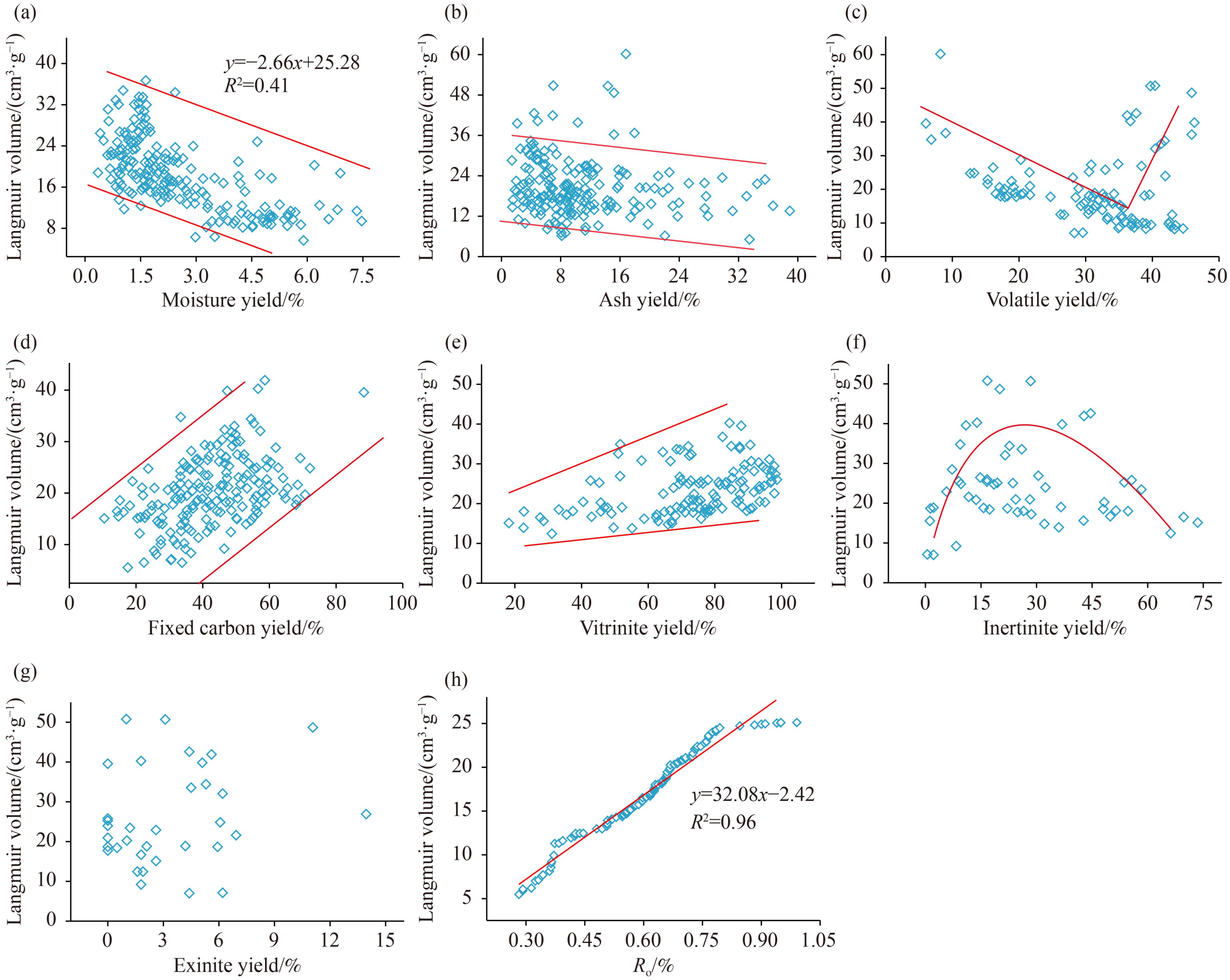


Fig. 6 The relationship between coal compositional and maturity parameters to Langmuir Volume (literature values are from Qiao, 2009; Sun, 2015; Zhou, 2015; Zhang, 2015; Li, 2015; Li, 2016; Li et al., 2016; Zhang, 2016; Zhang and Jiang, 2016; Zhang, 2018; Cheng, 2017; Dou, 2018; Lin et al., 2018; Yi, 2018; Zheng et al., 2018; Gao et al., 2020; Li, 2020; Ma et al., 2020b; Zou, 2020). (a) Moisture content and Langmuir Volume; (b) ash yield and Langmuir Volume; (c) volatile matter yield and Langmuir Volume; (d) fixed carbon content and Langmuir Volume; (e) vitrinite concentration and Langmuir Volume; (f) inertinite and Langmuir Volume; (g) exinite and Langmuir Volume; (h) R_o and Langmuir Volume.

inertinite content, exinite content, and Langmuir volume (Fig. 6). These data indicate that lower moisture content, higher fixed carbon content, and higher vitrinite content will enhance the potential for CO_2 sequestration.

The compositions of the coals vary significantly among the different areas of the southern Junggar Basin (Fig. 7). Evaluation of the coals from west to east in the Junggar Basin (Fig. 7) indicated that the coal reservoirs in the Z2 area (Fig. 1) have the highest potential for gas adsorption and CO_2 storage, since they have a lower moisture content, higher fixed carbon content, higher vitrinite content, and higher maturity than the coals in the other areas of the southern Junggar Basin.

4.5 Stratigraphic and hydrogeological trapping of gas

The analysis of the physical properties of the coals in the reservoirs in Sections 4.1–4.4 indicate that the coal seams in the Z2 area have the best sequestration potential in the southern Junggar Basin. As noted above, in addition to the compositions and physical properties of the coals, the geological conditions can also significantly impact the potential for CO_2 storage. To analyze the hydrogeological elements of the southern margin of the Junggar Basin in more detail, the study area was divided into six areas, A: West of Manas River; B: Manas River and Santun River; C: Santun River and Urumqi River; D: Urumqi River and Sigong River; E: Sigong River and Dahuangshan; F: Jimusaer (Figs. 8 and 9). In particular, areas C and D correspond to the Z2 area defined and discussed above in Sections 4.1–4.4. In this analysis, the trapping capacity of coal measures and the hydrogeological conditions were investigated to delineate the favorable storage areas in the Junggar Basin.

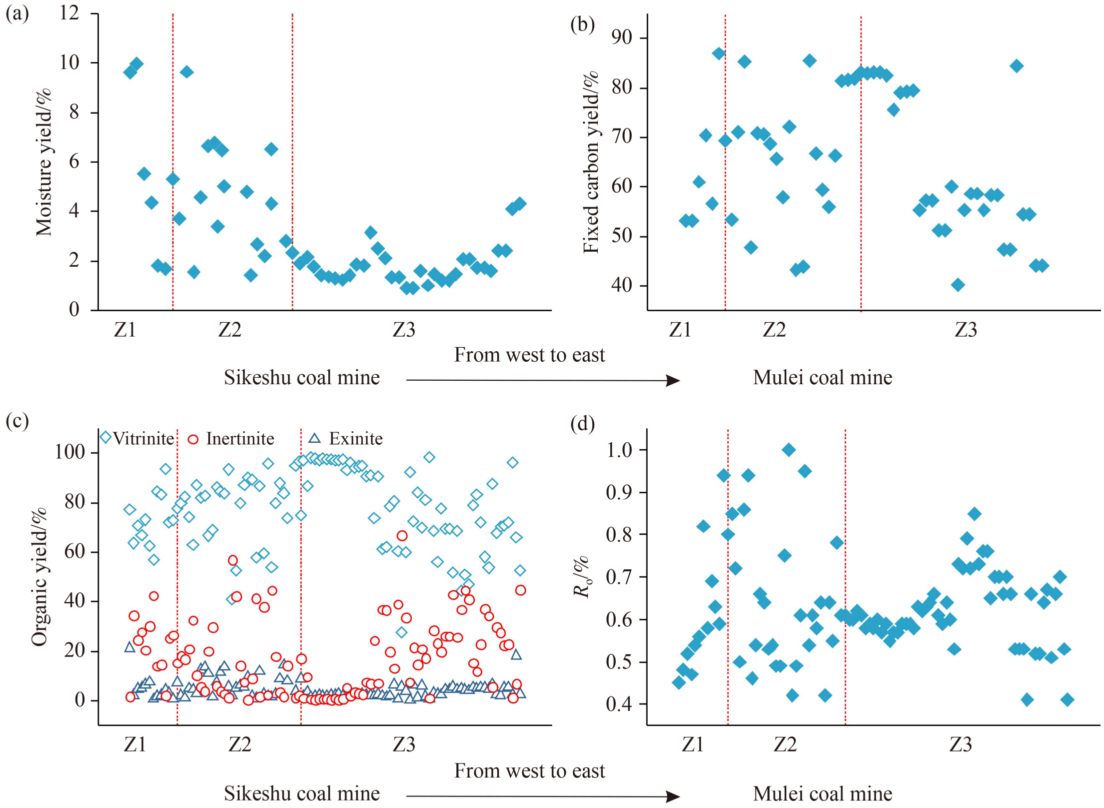


Fig. 7 Variation in coal compositional parameters in the southern Junggar Basin (literature data are from Qiao, 2009; Sun, 2015; Zhou, 2015; Zhang, 2015; Li, 2016; Li et al., 2016; Zhang, 2016; Cheng, 2017; Dou, 2018; Li, 2018; Yi, 2018; Zheng et al., 2018. See Fig. 1 for locations of the three geographic zones). (a) Moisture content; (d) fixed carbon yield; (c) maceral composition; (d) R_o.

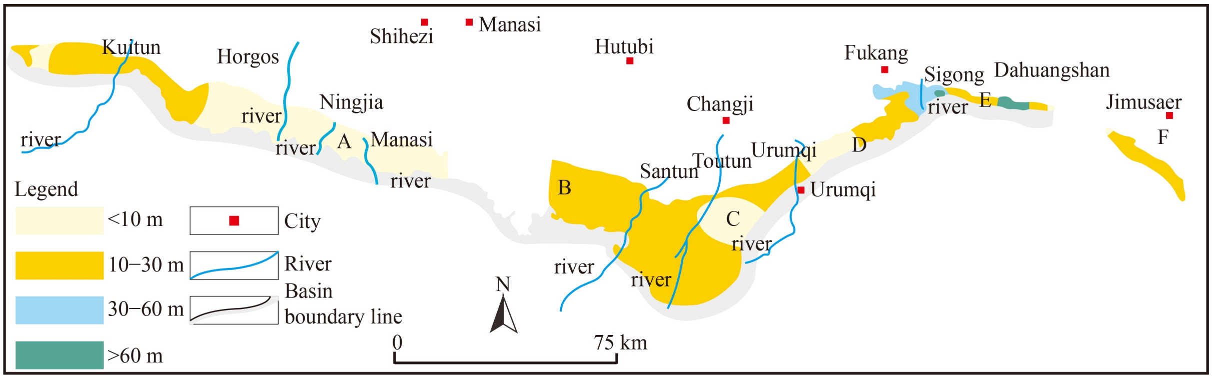


Fig. 8 Coal seam isopach of Badaowan Formation in the southern margin of the Junggar Basin. A: West of Manas River; B: Manas River to Santun River; C: Santun River and Urumqi River; D: Urumqi River and Sigong River; E: Sigong River and Dahuangshan; F: Jimusaer.

4.5.1 Coal seam development characteristics

Since the geological sequestration of CO_2 requires a robust seal, the loss of CO_2 can be effectively reduced if the caprock has a large thickness and low permeability (Sun, 2015; Zhao, 2019). In general, fine-grained clastic rocks have low permeabilities and are usually regarded as good seals.

The coal-bearing strata of the Badaowan Formation are about 800 m thick and are mainly located in the Kuitun river area, although they are also well-developed in areas from the Santun river to Jimusaer (Fig. 8). In contrast, the coal-bearing strata of the Xishanyao Formation are about 900 m thick and are more or less continuously distributed across the southern margin (Fig. 9), being best developed in the vicinity of the Urumqi river (Fig. 9). Fine-grained clastic rocks comprise greater than 60% of the roof and floor rocks of these coal-bearing strata, while coarse-grained clastic rocks are less than 40% of these intervals (Fig. 10).

The Badaowan and Xishanyao Formation contain thick

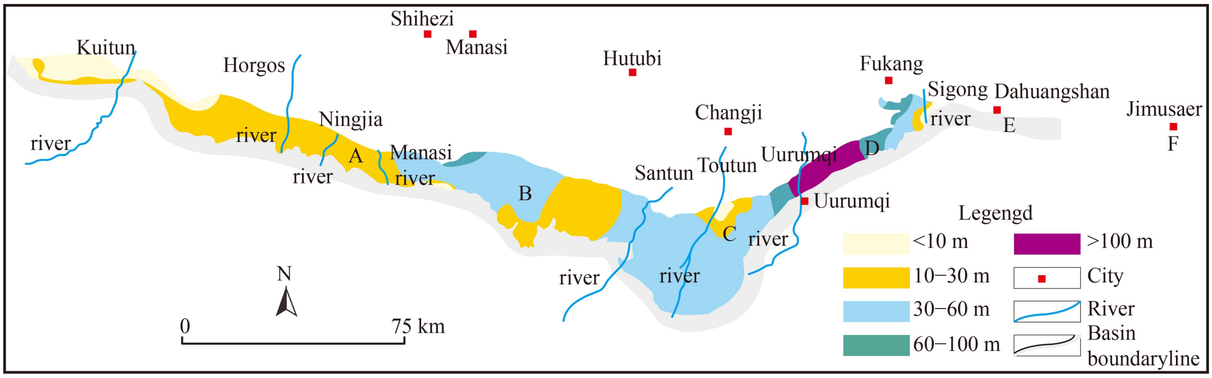
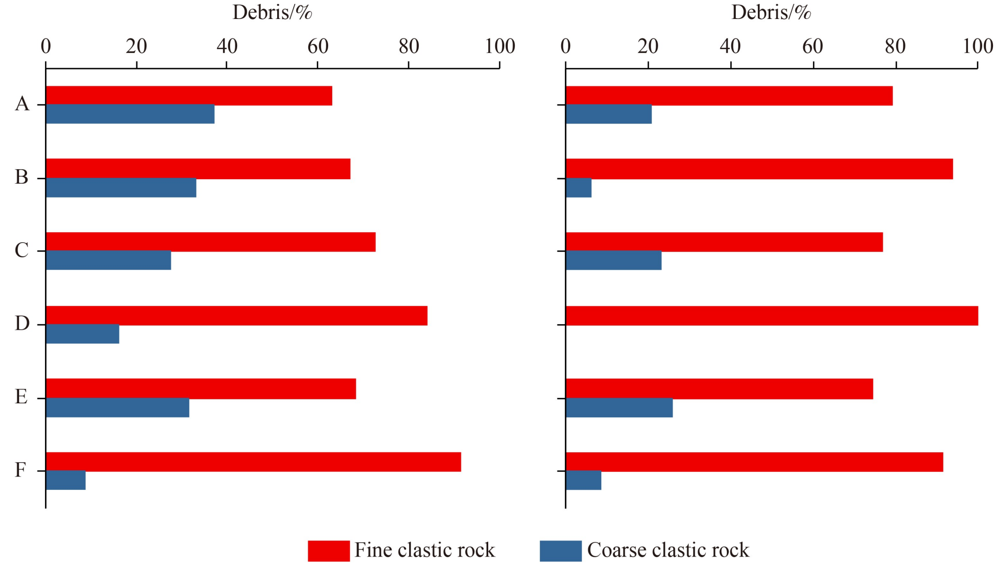


Fig. 9 Coal seam isopach of Xishanyao Formation in the southern margin of the Junggar Basin.



(a) Roof (b) Floor

Fig. 10 Proportion of fine-grained and coarse-grained lithologies in coal seam roof and floor rocks, southern Junggar Basin.

coal-bearing strata with fine-grained clastic rocks, which can inhibit CO_2 leakage. Since areas C, D, and F have thick coal-bearing strata with fine-grained clastic roof and floor rocks (Fig. 10), they are considered to have favorable potential for CO_2. Note that areas C and D correspond to the Z2 area discussed previously.

4.5.2 Hydrodynamic characteristics of coal-bearing strata

Hydrodynamic characteristics have a significant influence on CO_2 storage (Bachu and Stewart, 2002). The water in the coal reservoirs can occlude the pores and so hinder the migration of gas molecules (Wu et al., 2021). In addition, water in coal reservoirs can affect the pore pressure and consequently influence the adsorption and desorption of CO_2 and CH_4 (Wu et al., 2021).

The water in the coal reservoirs in the southern margin of Junggar Basin is supplied by atmospheric precipitation and the resulting runoff. During periods of rainfall, surface water flows down into the coal seam in the direction of differences in water levels. In the dry season, the pore pressure decreases due to the water level falling, which can cause gas leakage through desorption and diffusion. Therefore, some catchment areas need to be defined for better CO_2 storage. It was found that the groundwater in the southern margin of the Junggar Basin tends to flow from west to east, and also from south to north (Fig. 11). Consequently, it is easier to form several local catchment areas in the C and D areas than in the other areas in the southern margin.

In addition, the Urumqi-Miquan strike-slip fault cannot only lead to the formation of a regional stagnant hydrodynamic environment, but also can form several local catchment areas (e.g., synclinal structures) in the C and D areas. Consequently, the C and D areas can be regarded as potentially favorable areas for CO_2 sequestration because the catchment area has a good sealing capacity for CO_2. In contrast, although the F area has good coal seam development characteristics, it does not have stable hydrodynamic conditions, so it is unsuitable for CO_2 sequestration.

4.6 Modes for geological CO_2 sequestration in the Junggar Basin

The above analyses show that areas C and D (area Z2) in the southern margin of the Junggar Basin are suitable for CO_2 geological sequestration. The Urumqi-Miquan strike-slip fault resulted in the development of anticlines and synclines in the C and D areas (Zhou, 2015; Zhang, 2018; Yi, 2018). To better guide the future field tests of CO_2 storage in C and D areas, three modes of CO_2 sequestration that incorporated strike-slip fault factors were defined (Fig. 12): 1) the broad syncline and faulted anticline mode (Fig. 12(a)); 2) the monoclinal mode (Fig. 12(b)); 3) the syncline and strike-slip fault mode (Fig. 12(c)).

The broad syncline and fault anticline mode requires that the broad syncline and faulted anticline be deeply buried and have abundant surface water. The burial depth of the broad syncline is significant, which is beneficial in retaining stored CO_2. At the same time, the axis of the anticline can easily form a closed reverse fault due to extrusion, which will inhibit the diffusion of CO_2. In addition, surface water is abundant due to runoff of snow meltwater from the North Tianshan Mountains, and the migration of groundwater cannot only prevent CO_2 migration but also carry some CO_2 into to the deep areas. Consequently, this mode is conducive to CO_2 storage.

The monoclinal mode is more affected by hydrogeological conditions. Due to the abundant supply of river and glacier water in the southern Junggar Basin, the pores

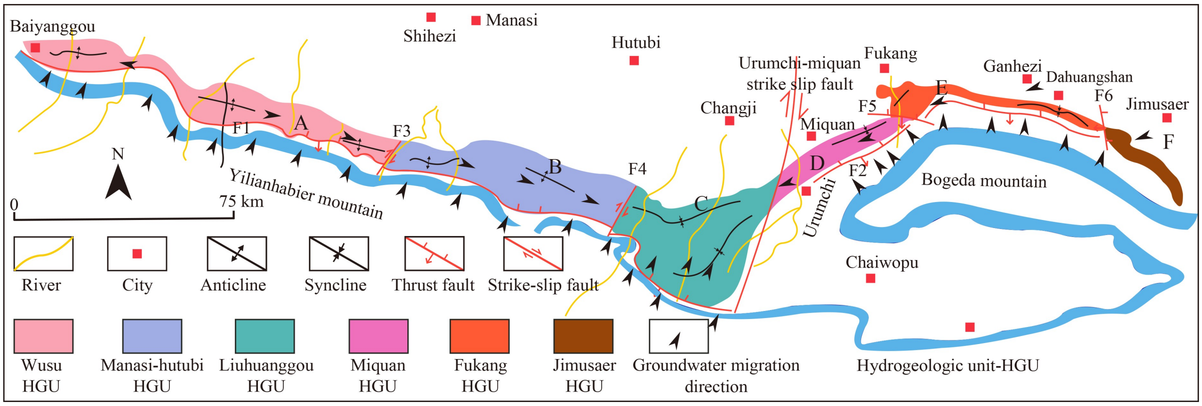


Fig. 11 Patterns of groundwater migration in the southern margin of the Junggar Basin.

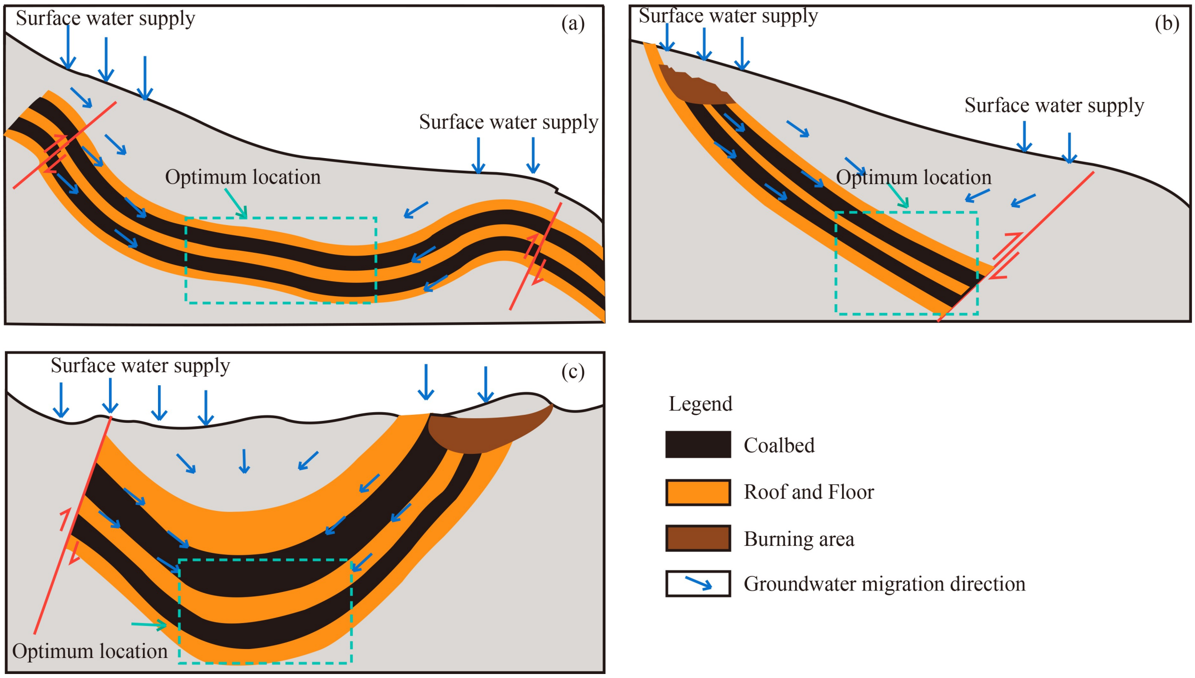


Fig. 12 CO_2 sequestration modes in the southern margin of the Junggar Basin. (a) Broad shallow-sloping syncline and + faulted anticline + fault + hydrology combinations, (b) monoclinal + faulted anticline + fault + hydrology combinations, and (c) syncline + faulted anticline + fault + hydrology combinations.

and fractures of shallow coal seams are quickly filled, thus blocking the migration pathways of CO_2 and preventing the diffusion of CO_2. This area is favorable for CO_2 sequestration exploration below 500 m depth (the wind oxidation zone in this area).

The syncline and strike-slip fault mode is significantly affected by extrusion activities. Most of the faults are thrust faults affected by the extrusion, and the fault plane of the reverse fault has sealing capacity. As a result, the fractures generated by the faulting are closed, which will inhibit the diffusion of CO_2. In addition, the surface water in the region is concentrated, and the coal seams have larger thicknesses and inclinations, which can further trap CO_2. In this mode, the area below the reverse fault and the wind oxidation zone depth (about 600 m) can also be regarded as a potential CO_2 sequestration area.

5 Conclusions

By analyzing the pore parameters, stress sensitivity, and adsorption properties of CH_4 and CO_2 of coal samples of different maturities from different basins, low-rank coal reservoirs in the Junggar Basin were demonstrated to have a high potential for CO_2 sequestration. Comparisons of the petrological compositions and levels of maturity of coal samples from different areas in the Junggar Basin were combined with analysis of the geological settings to show that areas C and D (the coal-bearing strata from the Santun River to the Sigong River) in the Junggar Basin have the highest potential for CO_2 sequestration. To better guide the future field test of CO_2 storage in these areas, three CO_2 sequestration modes were defined: 1) the broad syncline and faulted anticline mode; 2) the monoclinic mode; 3) the syncline and strike-slip fault mode.

Competing interests The authors declare that they have no competing interests.

References

Al-Ameri W A, Abdulraheem A, Mahmoud M (2016). Long-term effects of CO_2 sequestration on rock mechanical properties. J Energy Resour Technol, 138(1): 012201

Bachu S, Stewart S (2002). Geological sequestration of anthropogenic carbon dioxide in the Western Canada sedimentary basin: suitability analysis. J Can Pet Technol, 41(2)

Chen Y, Fu H Y, Ma D M, Duan Z H, Zhang Y P, Yang F, Li W B, Zheng C, Teng J X (2021). Differences of the pore structure and methane adsorption/desorption between vitrain and durain of low-rank coals: case study in the Huanglong Coalfield, southern Ordos Basin, China. J Energy Eng, 147(5): 04021038

Chen Z S (2018). Dynamic Change of physical property of coal reservoir during drainage in West Fukang Area. Dissertation for Master’s Degree. Beijing: China University of Mining and Technology (in Chinese)

Cheng B (2017). Experimental research on adsorption pore characteristics and gas radiation performance of low-rank coal in Xinjiang Fukang mining area. Dissertation for Master’s Degree. Xi’an: Xi’an University of Science and Technology (in Chinese)

Cheng M, Fu X H, Zhang M, Cheng W P, Qu L Z (2018). Comparative study on porosity and permeability in net confining stress of three natural gases in coal series reservoirs in Guxian County, Qinshui Basin. Nat Gas Geosci, 29(8): 1163–1171 (in Chinese)

Dai X G, Wang M, Wei C T, Zhang J J, Wang X Q, Zou M J (2019). Factors affecting shale microscopic pore structure variation during interaction with supercritical CO_2. J CO_2 Util, 38: 194–211

Dou X D (2018). Dynamic study of the displacement of adsorbed CH_4 on shales by injecting CO_2. Dissertation for Doctoral Degree. Chongqing: Chongqing University (in Chinese)

Gao Z, Ma D M, Chen Y, Zhang H, Zhang L (2020). Effect of water content on adsorption/desorption of methane of different macroscopic lithotypes. Coal Sci Technol, 48(8): 97–105 (in Chinese)

Gheibi S, Holt R M, Vilarrasa V (2017). Effect of faults on stress path evolution during reservoir pressurization. Int J Greenh Gas Control, 63: 412–430

Gholami R, Raza A, Iglauer S (2021). Leakage risk assessment of a CO_2 storage site: a review. Earth Sci Rev, 223: 103849

Huang Q, Fu X H, Zhang Q H, Li Y S (2019). Experimental study on overburden pore permeability of medium and high-rank coal reservoirs in Qinshui Basin. Coal Sci Technol, 47(6): 164–170 (in Chinese)

Kang J H, Wan R, Zhou F B, Liu Y K, Li Z Q, Yin Y S (2020). Effects of supercritical CO_2 extraction on adsorption characteristics of methane on different types of coals. Chem Eng J, 388: 123449

Li D D (2020). Study on influence of industrial analysis parameters of coal on adsorption performance of multi-rank coal. Coal, 29(6): 62–65 (in Chinese)

Li Y Y (2016). Coalbed methane accumulation models and resources evaluation in the southern margin of Junggar Basin. Dissertation for Master’s Degree. Jiaozuo: Henan Polytechnic University (in Chinese)

Li Y, Cao D Y, Wei Y C, Wang A M, Zhang Q (2016). Middle to low-rank coalbed methane accumulation and reservoir in the southern margin of Junggar Basin. Acta Petrol Sin, 37(12): 1472–1482 (in Chinese)

Li Z T (2018). Evolution of pore-fractures of coal reservoir and its impact on CBM microcosmic flow. Dissertation for Doctoral Degree. Beijing: China University of Geosciences (in Chinese)

Li Z W(2015). Study on microstructure characteristics of low-rank coal and its control mechanism on gas adsorption/desorption. Dissertation for Doctoral Degree. Beijing: China University of Mining and Technology (in Chinese)

Lin H F, Wei W B, Li S G,Yan M, Bai Y (2018). Experimental study on thermodynamics characteristics of CH_4 and CO_2 adsorption on coal. China Safe Sci J, 28(6): 129–134 (in Chinese)

Liu D M, Zou Z, Cai Y D, Qiu Y K, Zhou Y F, He S (2021). An updated study on CH_4 isothermal adsorption and isosteric adsorption heat behaviors of variable rank coals. J Nat Gas Sci Eng, 89: 103899

Lyu Q, Tan J Q, Li L, Ju Y W, Busch A, Wood D A, Ranjith P G, Middleton R, Shu B, Hu C, Wang Z H, Hu R N (2021). The role of supercritical carbon dioxide for recovery of shale gas and sequestration in gas shale reservoirs. Energy Environ Sci, 14(8): 4203–4227

Ma D M, Gao Z, Chen Y, Zhang H, Shao K (2020b). Differences in methane adsorption and desorption characteristics of low, medium and high rank coal reservoirs at different temperatures. Reserv Evaluation Development, 10(4): 17–24+38 (in Chinese)

Ma R Y, Wang M, Bake A, Jia T F, Zhu J Q (2020a). Experimental study of overburden pore porosity and permeability of low-rank coal reservoirs in southeastern Junggar. J China Univ Min Technol, 49(6): 1182–1192 (in Chinese)

Ma R Y, Yao Y B, Wang M, Dai X, Li A (2022). CH_4 and CO_2 adsorption characteristics of low-rank coals containing water: an experimental and comparative study. Nat Resour Res, 31(2): 993–1009

Mi J F, Ma X F (2019). Development trend analysis of carbon capture, utilization and storage technology in China. Proceedings of the CSEE, 39(09): 2537–2544 (in Chinese)

Qiao J W(2009). Research on the low-rank coal of pore characteristics and desorption laws. Dissertation for Master’s Degree. Xi’an: Xi’an University of Science and Technology (in Chinese)

Ranathunga A S, Perera M S A, Ranjith P G, Wei C H (2017). An experimental investigation of applicability of CO_2 enhanced coal bed methane recovery to low rank coal. Fuel, 189: 391–399

Sharma S, Agrawal V, McGrath S, Hakala J A, Lopano C, Goodman A (2021). Geochemical controls on CO_2 interactions with deep subsurface shales: implications for geologic carbon sequestration. Environ Sci Process Impacts, 23(9): 1278–1300

Sun X R(2015). Experimental research on pore structure and desorption characteristics of the low-rank coal for Fukang mining area in Xinjiang. Dissertation for Master’s Degree. Xi’an: Xi’an University of Science and Technology (in Chinese)

Sun X X, Yao Y B, Liu D M (2021). The behavior and efficiency of methane displaced by CO_2 in different coals and experimental conditions. J Nat Gas Sci Eng, 93: 104032

Tan X T, Zhang S J, Tian T D, Zhang H S (2016). Research status and development on CO_2 sequestration in deep coal seams. Shandong Chem Indust, 45(18): 31–34 (in Chinese)

Wei W B (2017). Experimental study on pore structure of low-rank coal affected to gas adsorption thermodynamics characteristics Zhunnan. Dissertation for Master’s Degree. Xi’an: Xi’an University of Science and Technology (in Chinese)

Wu H, Yao Y B, Liu D M, Zhang Y, Chang Y (2021). DLVO-based analyses of the water vapor adsorption and condensation in hydrophilic nanopores of low-rank coal. Energy Fuels, 35(15): 11920–11929

Xu J Z, Zhai C, Ranjith P G, Sun Y, Qin L (2019). Petrological and ultrasonic velocity changes of coals caused by thermal cycling of liquid carbon dioxide in coalbed methane recovery. Fuel, 249: 15–26

Yi Z J (2018). Permian geological architecture and formation mechanism of eastern Junggar Basin. Dissertation for Doctoral Degree. Beijing: China University of Geosciences (in Chinese)

Yu H G, Jing R X, Wang P P, Chen L H, Yang Y J (2014). Preferential adsorption behavior of CH_4 and CO_2 on high-rank coal from Qinshui Basin, China. Int J Min Sci Technol, 24(4): 491–497

Zhang C (2016). Reservoir forming condition and favorable prediction in the area of east Junggar Basin. Dissertation for Doctoral Degree. Beijing: China University of Geosciences (in Chinese)

Zhang D F, Hu Z C (2020). Effects of ethanol-mixed supercritical CO_2 fluid on CO_2 adsorption on coals: implications for CO_2 geologic storage in coal seams. Int J Glob Warm, 21(3): 274–286

Zhang K, Sang S X, Zhou X Z, Liu C J, Ma M Y, Niu Q H (2021). Influence of supercritical CO_2-H_2O-caprock interactions on the sealing capability of deep coal seam caprocks related to CO_2 geological storage: a case study of the silty mudstone caprock of coal seam No. 3 in the Qinshui Basin, China. Int J Greenh Gas Control, 106: 103282

Zhang Q, Jiang W P (2016). Study on coalbed methane surface development and production potential of low-rank coal in China. Coal Sci Techn, 44(6): 211–215+187 (in Chinese)

Zhang T (2018). Analysis on geological control factors and models of coalbed mathane in the eastern segment of south margin of Junggar Basin. Dissertation for Master’s Degree. Beijing: China University of Geosciences (in Chinese)

Zhang W J, Ju Y W, Wei M M, Wang G C (2015). Study on characteristics and mechanism of adsorption/desorption on different metamorphic-deformed coal reservoirs. Earth Sci Front, 22(2): 232–242 (in Chinese)

Zhao S H (2019). The coal quality and its controlling factors in the main coalfields of Junggar and Yili Basins, northern Xinjiang province. Dissertation for Doctoral Degree. Beijing: China University of Geosciences (in Chinese)

Zheng S J, Yao Y B, Cai Y D, Liu Y (2018). Characteristics of movable fluid and pore size distribution of low-rank coals reservoir in southern margin of Junggar Basin. Coal Geo Explor, 46(1): 56–60+65 (in Chinese)

Zheng S J, Yao Y B, Elsworth D, Liu D M, Cai Y D (2020). Dynamic fluid interactions during CO_2-ECBM and CO_2 sequestration in coal seams. Part 2: CO_2-H_2O wettability. Fuel, 279: 118560

Zhou X Z (2015). Study on the occurrence regularity of CBM at eastern Urumqi River mining area in southern Junggar Basin. Dissertation for Master’s Degree. Xi’an: Xi’an University of Science and Technology (in Chinese)

Zou Z (2020). Adsorption characteristics and their thermodynamic evolution in variable rank coals. Dissertation for Master’s Degree. Beijing: China University of Geosciences (in Chinese)