Impact assessment of interlayers on geological storage of carbon dioxide in Songliao Basin

Deping Zhang^{1,2}, Chengkai Fan^{3,*}, and Dongqin Kuang³

¹ Department of Petroleum Engineering, Northeast Petroleum University, 163318, Daqing, Heilongjiang, PR China

² PetroChina Jilin Oilfield Company, Songyuan, 138000, PR China

³ State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Xiaohongshan 2, Wuchang, 430071, Wuhan, Hubei, PR China

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Abstract. Reservoirs in the Songliao Basin are characterized by strong heterogeneity, which increases the difficulty of exact reservoir prediction. The clay interlayer developed in the reservoir is an important factor affecting the heterogeneity of the reservoir. Using the reservoir numerical simulation technology, an attempt has been made to investigate the storage efficiency during CO₂ sequestration in Songliao Basin considering different types of interlayer in underground formations. Results indicate that type I interlayer, with a large thickness embedded between the two sand bodies has function of shunting and blocking to alleviate the impacts on cap rock. The type II interlayer has a small thickness and locates inside a single sand body, with poor physical properties and continuity, which has the same blocking effect on CO₂ distribution and moderating influence on the cap rock. The physical properties of type III interlayer are same as the type II interlayer, but it has uneven distribution and poor continuity. In addition, three schemes of perforated zone were designed and their effects on CO₂ storage efficiency and stability were studied. For a single reservoir, the scheme I is to perforate a whole reservoir, which is more conducive to maintain the reservoir's stability. For multiple sets of "single-reservoir", the scheme II can be preferentially selected to perforate the reservoir section below the interlayer when the injection volume is small. However, the scheme III can be used to perforate the interlayer and the reservoir below that when the injection volume is large. The study is beneficial to provide guidance and advice for selecting a suitable CO₂ geological storage and reduce the risk of CO₂ leakage.

1 Introduction

Songliao Basin is a large Meso-Cenozoic sedimentary basin in eastern China and a composite basin with dual fault-depression structure (Fig. 1). The basin is divided into seven first-level units, namely the Western Slope, Northern Dumping, Central Depression, Northeast Uplift, Southeast Uplift, Southwest Uplift and Kailu Depression. The tectonic evolution of the basin generally controls the distribution of source rocks, reservoir distribution and combination characteristics of generation, reservoir and cap (Han *et al.*, 2019; Hu *et al.*, 2019). Songliao Basin has the characteristics of multi-source and multi-sedimentary systems, forming a wide distribution of sandstone reservoirs. The large delta sand body from the northern provenance area extends to the central depression of Changyuan, which provides a good reservoir condition for forming a huge oilfield (Wu *et al.*, 2001). Nearly 100 oil and gas fields have been discovered

in the north and south areas of the basin, where is the most important petroliferous basin in China. The Songliao Basin is the most primary petroliferous basin in China. Since 1995, the field test of CO₂ flooding has been implemented in *Jilin Oilfield*. In 2007, the research and demonstration project of 100 000 tons/year CO₂ flooding and storage was officially put into operation (Zhang *et al.*, 2009). In the recent years, *Jilin Oilfield* has gradually carried out the research and construction of the project expansion. At present, it has equipped with about supporting injection facilities of about 500 000 tons/year and realized annual CO₂ utilization of about 200 000 tons/year (Ren *et al.*, 2016; Zhang *et al.*, 2014). However, in the process of sedimentation and diagenesis of the reservoir, the interlayer with different genesis and distributions are formed. It will affect the distribution of sand bodies, oil and water in the reservoir, which makes the detailed description of the reservoir more complicated. In the later stage of the reservoir prediction, if the interlayer is not considered, the flooding process of reservoir will be abnormal, and the prediction can be not accurate (Shan *et al.*, 2007; Zhang *et al.*, 2009).

* Corresponding author: fanchengkai16@mails.ucas.ac.cn

Fig. 1. (A) Schematic map showing the Songliao Basin and its adjacent regions. (B) Geological map of the Songliao Basin. (C) Stratigraphic cross sections through the Songliao Basin (Yu *et al.*, 2019; Zhi-qiang *et al.*, 2010).

The different definitions of interlayer have been put forward since the last century (Qiu, 1992; Wang and Li, 1996). At present, it is generally accepted that a non-permeable rock in the reservoir that blocks fluid's movement is aquifuge; a relatively non-permeable layer within the sandstone is impermeable interbed, which together constitute the structure of interlayer. Due to the irregular spatial distributions of interlayer, it is significant to study interwell prediction and its effect on post-development prediction (Rao *et al.*, 2013). The previous studies were centered on the identification technology of interlayer and divided it into three classic models, namely the continuous aquifuge, the continuous impermeable interbed and the discontinuous impermeable interbed (Yan and Duan, 2008). Additionally, the interlayer's characteristics of distribution and morphology were also the research focuses. The above series of studies will eventually serve the development of oil and gas reservoirs, for investigating the effects of interlayer on waterflooding, drilling and reservoir distribution. To clarify the characteristics of interlayer, some scholars have adopted the scheme of selective perforation and partial subdivision to carry out the repair production, such as profile

control, water plugging and layered water injection (Zhu, 2013). Currently, most oil and gas reservoirs belong to post-development stage and the interlayer is an important factor affecting and even controlling the distribution of remaining oil. Moreover, the strong randomness and heterogeneity of the interlayer increase the difficulty on its research.

Based on previous studies, for oilfield development, the interlayer has a blocking effect and affects the reservoir connectivity and oil production (Fan *et al.*, 2015; Sun, 2013). And the interlayers are classified into three basic types based on the typical characteristics in Songliao Basin. In this paper, the interlayer is introduced into Geological CO₂ Storage (GCS) engineering project to study its role in CO₂ storage process to facilitate the optimization of GCS project storage scheme. In this paper, the effect of interlayers including three types on CO₂ geological storage was studied. Where the reservoir is defined as "single-reservoir collective". The numerical simulation method was used to explore the influence of interlayer on CO₂ storage efficiency, for further analysis and evaluation of the space utilization and stability of CO₂ storage.

2 Characteristics of interlayer

The previous studies have shown that the north and south oilfields of the Songliao Basin are developed with different interlayers, including argillaceous, sandy and calcareous interlayers in the North Sabei III area (Zhang, 2014). There are three types of interlayer like argillaceous, calcareous and gravelly in a single distributary channel of the II–I group in the Sanzhao Depression. The blocking effect of the interlayer that belongs to Putaohua oil layer in *South Daanbei Oilfield* controls the distribution of remaining oil (Yu, 2009).

The oilfields of *Jilin Oilfield Company* are mainly located in the south of the basin. Many sets of gas–water cycles in Dengloulou Formation of Wangfu Fault Depression are controlled by the interlayers (Deng et al., 2015). The interlayer of *Xinli Oilfield* affects the remaining oil in a plane, which deteriorates the physical properties of the reservoir and causes the remaining oil to be enriched (Hu et al., 2013). The strong heterogeneity caused by the non-permeable interlayer in the reservoir is a factor in the formation of ultra-low permeability reservoirs in *Haituozi Oilfield* (Li et al., 2015). The dawsonite cement in the Cretaceous sandstone of *Honggang Oilfield* is widely distributed, and the reservoir is characterized by multi-layer cementation separated by mudstone interlayer in a longitudinal direction (Liu et al., 2016). Three sets of interlayers are developed stably in the Heidimiao oil layer in block 208 of *Honggang Oilfield*, which is mainly composed of interbedded mudstone and calcareous cemented compact siltstone with thicknesses of 10–15 m, 15–20 m and 30 m, respectively (Fig. 2). In addition, three different distribution patterns of interlayer exist in Hei59 Block, where is the CO₂-EOR pilot test zone of the original reservoir (Yan et al., 2016), including the type of mud rolling in the sand, the stable interbed type of sand mud, and the type of sand rolling in the mud.

Considering the above lettuces, the complex reservoir was simplified using a single-reservoir group and the effect of interlayers during the process of CO₂ storage was analyzed. Finally, the research method was applied to the complex reservoir. In order to facilitate the calculation, the interlayer is simplified according to the real stratigraphic data of the existing oil area and the interlayer was classified into three types in this study:

- Type I interlayer, thickness greater than 0.4 m, between two sand bodies, with continuity and isolation.
- Type II interlayer, thickness greater than 0.4 m, located in a single sand body Internal, with a certain continuity and isolation.
- Type III interlayer, thickness less than 0.4 m, located inside a single sand body, without continuity and isolation, and the distribution is unstable.

3 Numerical model

Based on previous studies, for oilfield development, the interlayer has a blocking effect and affects the reservoir

Fig. 2. Diagram of clay interlayers distribution.

connectivity and oil production (Fan et al., 2015; Sun, 2013). In this paper, the interlayer is introduced into GCS engineering project to study its role in CO₂ storage process to facilitate the optimization of GCS project storage scheme. In this study, a CO₂ based on three types of interlayer, injection well was set, with the same injection conditions and the injection volume. To study the effect of interlayer on CO₂ storage, we simulate different schemes in this paper by a commercial simulator (ECLIPSE 2012, *The Eclipse Foundation*).

A model was set up with length, width and height of 2000 m × 2000 m × 54 m in three directions, respectively. The grid block in *x*, *y*, and *z* directions is 200 × 200 × 18, respectively. In other words, each grid in the *x* and *y* directions is 10 m, the *z* direction is 3 m. The permeability of 1–2 and 17–18 layers along the *z* direction is set as 1.0×10^{-5} mD, the permeability of other grids is set as 8 mD. For interlay, a layer is added between layers 12 and 13 of the model, specific parameter Settings are shown in Table 1. The injection well located in the middle of the model, as shown in Figure 3. In this study, the current reservoir pressure is 16.7 MPa, reservoir temperature is 65 °C, water saturation is 0.32, total compressibility is 1.1×10^{-4} MPa⁻¹. The liquid-gas relative permeability curve used in this simulation is shown in Figure 4. In this paper, the injection rate of CO₂ is 3000 m³/Day. The injection time was considered for duration of 20 years.

4 Results and discussion

4.1 Effect of the interlayer on CO₂ distribution

According to the distribution of residual oil in reservoir engineering, the effect of interlayer is mainly manifested as the blocking, sealing ability and high displacement pressure, which can form the multiple seepage barriers. There is less residual oil in a positive rhythm reservoir area, while the negative rhythm reservoir area belongs to a residual oil rich area (Wang, 2010). By referring to the above ideas and combining the objectives of GCS project, it is critical to investigate the effect of the interlayer on CO₂ storage.

Table 1. The properties of interlayer.

Types	Thickness (m)	Porosity (%)	Permeability (mD)	Scheme
I	0.8	0.164	0.12	Perforating
II	0.4	0.04	0.08	Perforating
III	0.3	0.04	0.08	Half well spacing

Fig. 3. Conceptual model diagram of three types of interlayer.

Through the reservoir numerical simulation software ECLIPSE, the influence of interlayer on the migration and distribution of CO₂ was studied and the distribution pattern of CO₂ in sand bodies was predicted.

The red line in Figure 5 corresponds to the interlayers in Figure 3. According to the simulation results of gas saturation distribution after CO₂ injection for 20 years (Fig. 5), CO₂ is isolated by the interlayer into two V-shaped plumes and some CO₂ penetrates through the interlayer to form two inverted V-shaped plumes on both sides of the interlayer. For the same type of interlayer, when the injection time is longer, the more CO₂ will penetrate the interlayer, which indicates that the blocking effect of the interlayer is weaker. For the three different types of interlayer, the type I has the best blocking effect. However, the blocking effect of the type III interlayer is the weakest. Generally, the stronger the blocking effect, the maximum utilization of plane space. For example, the plane migration distance (Y direction) of the small V-shaped CO₂ plume at the

Fig. 4. Liquid-gas relative permeability curve.

type I interlayer is the longest. On the contrary, the V-shaped CO₂ plume plane (Y direction) migrates the shortest distance at the type III interlayer. On the other hand, the stronger the blocking effect, the maximum utilization of vertical space. For example, the longitudinal migration distance (Z direction) of inverted V-shaped CO₂ plume is the longest at the type I interlayer, that in the type III interlayer is the shortest. Among the three kinds of interlayer set up in this model, the physical property and continuity of the type I interlayer is the best, the type II interlayer is the second and the type III interlayer is the worst.

4.2 Effect of perforation on the interlayer (GSAT)

The interlayer affects the distributions of the reservoir and oil–water, which also makes the selection of the perforation scheme difficult. Xu *et al.* (2012) pointed out that if the perforation section is in the interlayer, a certain amount of injected water may change its microstructure, permeability and blocking effect, even causes water logging. In this paper, three perforation schemes are designed based on the interlayer in the single-reservoir group (Fig. 6), among which the scheme 1 is to perforate the whole reservoir; the scheme 2 is only to perforate the lower section of the interlayer; the scheme 3 is to perforate the interlayer and the reservoir section.

From Figures 7–9, for each type of the interlayer, after perforating the whole reservoir (scheme 1), the CO₂ plume occupies the smallest space and has the lowest spatial utilization rate. The CO₂ plumes takes up the same space in scheme 2 and 3, that is, they have the same space utilization rate. The permeability of packer was set as the same as the caprock. There is still a pressure difference in the packer section and CO₂ leaks out of the packer after 20 years.

Therefore, it is recommended to adopt the scheme 2, which is only to perforate the reservoir section under the interlayer. For different types of the interlayer under the same scheme, the less CO₂ penetrates the stability

Fig. 5. Distribution of gas saturation after gas injection of three types of interlayer. (a) Distribution of gas saturation after 10 years of gas injection in type I interlayer. (b) Distribution of gas saturation after 20 years of gas injection in type I interlayer. (c) Distribution of gas saturation after 10 years of gas injection in type II interlayer. (d) Distribution of gas saturation after 20 years of gas injection in type II interlayer. (e) Distribution of gas saturation after 10 years of gas injection in type III interlayer. (f) Distribution of gas saturation after 20 years of gas injection in type III interlayer.

Fig. 6. Schematic diagram of three perforation schemes (Scheme 1: perforate the whole reservoir section; Scheme 2: perforate the reservoir section under the interlayer; Scheme 3: perforate the interlayer and the reservoir section).

Fig. 7. Distribution of gas saturation after 20 years of gas injection for three perforation schemes of the class I interlayer. (a) Full reservoir perforation. (b) Perforate the lower section of the interlayer. (c) Perforating the interlayer and its lower reservoir section.

Fig. 8. Distribution of gas saturation after 20 years of gas injection for three perforation schemes of the class II interlayer. (a) Full reservoir perforation. (b) Perforate the lower section of the interlayer. (c) Perforating the interlayer and its lower reservoir section.

Fig. 9. Distribution of gas saturation after 20 years of gas injection for three perforation schemes of the class III interlayer. (a) Full reservoir perforation. (b) Perforate the lower section of the interlayer. (c) Perforating the interlayer and its lower reservoir section.

interlayer when the blocking effect tends to be stronger. At the same injection volume, the space above the type I interlayer occupied by CO_2 is the smallest, indicating that its blocking effect is the strongest. However, the CO_2 occupies the space above the type III interlayer is the largest, indicating that the blocking effect of the type III interlayer is the weakest.

4.3 Effect of the interlayer on stability

The interlayer not only affects the distribution of CO_2 , but also has an impact on the distribution of reservoir pressure. Zou *et al.* (2010) studied the effects of interlayer's type and thickness on sealing capacity. During the development process, the interlayer with poor sealing

Fig. 10. Diagram of the upper pressure.

Fig. 11. Left: pressure changes of the top layer under different schemes of three types of the interlayer; Right: the top layer pressure changes under three different perforation schemes.

capacity will be broken through due to the rising pressure, causing the oil and gas upwelling and coexisting with water. Based on the single-reservoir group (Fig. 10), the

interlayer can mitigate the upper pressure and reduce the risk of cap breakthrough under the consideration of reservoir stability and caprock security.

As shown in Figure 11, the pressure changes at the center of the upper layer in a single-reservoir group. From Figures 11a–11c, for the three types of single-reservoir group, the ultimate overlying pressure all attains to be maximum under the action of scheme 1. From Figures 11d–11f, at three schemes of perforation, the overlying pressure of single-reservoir group III is the highest. Although in the beginning, the pressure of single-reservoir group II is slightly larger than the type I, but both are higher than that of type III. However, the pressure of type III gradually exceeds the other types and reaches the maximum from the 18th year.

For a single-reservoir group, the scheme 1 is more conducive to reservoir stability, blocking effect on gas and oil, and sequestration of CO₂. In addition, it can alleviate or even avoid the coexistence of oil, gas and water in the same layer. For multiple sets of single-storage groups, the scheme 2 can be preferred when the injection volume is small, because the interlayer can be as a barrier layer blocking CO₂ migration. However, when the injection amount is large, the scheme 3 is the optimal solution. Because the blocking effect of the interlayer is limited when the injected volume is huge. At the time, a large amount of CO₂ penetrates the interlayer, indicating the reservoir space utilization will increase and more CO₂ will be storage.

In a word, although the pressure change in the single-reservoir group is small, the actual reservoir is composed of thousands of single-reservoir groups. Therefore, such a small change cannot be ignored, which is of research significance.

5 Conclusion

In this paper, the numerical simulation method was used to study the effects of three different types of interlayer on CO₂ storage efficiency in a single-reservoir group. In addition, the different perforation schemes are discussed for the effects on CO₂ distribution and overburden pressure changes as well. The following conclusions can be obtained from the studies:

1. Among the three kinds of interlayer set up in this model, the physical property and continuity of the type I interlayer is the best, the type II interlayer is the second and the type III interlayer is the worst.
2. Based on the effect of the interlayer on CO₂ distribution, the stability interlayer can play a role in blocking the migration of CO₂.
3. If the reservoir storage capacity is considered, the unstable interlayer should be selected first in the target layer; if the reservoir stability is considered, the stability interlayer should be preferentially selected as the target layer.
4. For CO₂ storage, it is recommended to select the interlayer and its below reservoir as the perforation layer.
5. Considering the safety and stability, it is necessary to analyze the pressure of the upper pressure in a single-reservoir group. Generally, perforating the whole reservoir is more stable and secure.

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