GHGT-11

Reservoir evaluation for the Moebetsu Formation at Tomakomai candidate site for CCS demonstration project in Japan

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Abstract

A reservoir evaluation study for the Moebetsu Formation at Tomakomai candidate site for carbon dioxide capture and storage (CCS) demonstration project in Japan was conducted. Geological interpretation, such as 3D seismic interpretation, sedimentary facies interpretation, and 3D seismic facies analysis was carried out to clarify the geological structure, sedimentary facies, 3D seismic facies of Moebetsu Formation. Geological model and simulation model were constructed by using the results of geological interpretation. Reservoir simulation study for CCS was carried out using simulation model. As a result, it was confirmed the possibility of injection CO\(_2\) at the target amount (2.5×10\(^5\) tonne/year \(\times\) 3 years, based on demonstration plan) and it was confirmed that caprock have sufficient seal capacity to CO\(_2\) long-term storage. From the results of this study, it is confirmed that Moebetsu Formation has desirable properties as the injection target of CCS Demonstration Project.

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Selection and/or peer-review under responsibility of GHGT

*Keywords; CO\(_2\) geological storage; simulation study; sequence stratigraphic analysis*

1. Introduction

Carbon Dioxide Capture and Storage (CCS) is a key technology to reduce carbon dioxide emission to the atmosphere and needed to be widely deployed in the world as early as possible. A number of CCS
demonstration projects are started in many areas. As in Japan, the Ministry of Economy, Trade and Industry (METI) started investigations for the CCS Demonstration Project in 2008.

In offshore Tomakomai, which is located at the south of Hokkaido (Fig.1), fan delta sediments are known in the Miocene to Quaternary sections. The Quaternary Moebetsu Formation is among them, and is divided into two members. The lower "Sandstone Member" mainly consists of sandstone, and the upper "Mudstone Member" consists of silty mudstone. The division has been confirmed by previous exploration activities for oil and gas around this area. These activities have suggested that the formation is widespread in this area. It is considered that the Sandstone Member has good properties for a reservoir and the Mudstone Member has good properties for a cap rock. So, the Sandstone Member is considered as a candidate of reservoir for CO2 geological storage in this project. But the data from previous activities are insufficient for reservoir evaluation. Therefore, as a part of the project, 3D seismic survey and two survey wells drilling were carried out by Japan CCS Co., Ltd (JCCS). And a reservoir evaluation study for the Moebetsu Formation such as seismic interpretation, geological modeling and reservoir simulations, using the 2D and 3D seismic data and the well data was carried out.

This paper discusses storage capacity of the Moebetsu Formation for CCS.

Fig.1 Location map for Tomakomai CCS candidate site

2. Geological Interpretation by 3D seismic and well data

2.1. Geological Structure

The time structure map of surface of unconformities and boundaries of each formations, using data set obtained by the 3D seismic survey, shows that the structure morphology of the Moebetsu Formation in this area is monoclinal without any remarkable faults cutting the formation. The Mudstone Member is about 200m, Sandstone Member is about 100m in thickness.

2.2. Sequence Stratigraphic Analysis by well and seismic data

For sequence stratigraphy definition of the Moebetsu Formation, sedimentary facies classification and the sequence boundary definition was carried out using well log and FMI data (Fullbore Formation MicroImager; a trademark of Schlumberger), and the 3D seismic geomorphology analysis was created by
Paradigm’s 3D seismic interpretation software (Stratimagic™ and VoxelGeo™). The 3D seismic interpretation results and well facies interpretation results were integrated for the depositional system definition and estimation of the reservoir and seal rocks in the Moebetsu Formation.

2.2.1. Sedimentary facies identification using FMI image and well log data

Continuous geological column in the Moebetsu Formation was created by lithofacies identification using FMI image and conventional well logs (Fig.2). The Moebetsu Sandstone Member has been recognized as the fan delta systems from the previous geological studies. Comparing geological column and SP/GR logs, we confirmed two patterns, one is upward thickening and coarsening, and the other is upward thinning and fining. These trends indicate the fan delta systems moved forward (progradation) and backward (retrogradation). And also pebbly sandstone intervals showing upward fining pattern with sharp base can be recognized near the base and top of the Moebetsu Sandstone Member, they can be interpreted as channel fill deposits in the fan delta system.

From the sequence stratigraphy concepts, the Moebetsu Sandstone Member is interpreted as HST (Highstand Systems Tract) and the basal part of the Moebetsu Mudstone Member is interpreted as TST (Transgressive Systems Tract), so the boundary between HST and TST can be identified as the sequence boundary (SB) (Fig.2). The coarse-grained fan delta deposits developed during HST stage with high sediment supply, and the most proximal fan delta facies were developed near the top of the Moebetsu Sandstone Member caused by the falling relative sea-level. During the TST stage, the development of the fan delta systems declined gently after the SB was generated at the latest HST stage, and changed into muddy sediments caused by the transgression. A few upward thickening and coarsening units above the SB are interpreted as transgressive sandstones. Probably the changes of the relative sea level and sediment supply ratio influenced to the development of the Moebetsu fan delta systems.

2.2.2. Depositional systems in the Moebetsu Formation from 3D Seismic facies analysis

As the first step of the 3D seismic sequence and seismic facies analysis and geomorphology analysis, sequence boundaries (SB) and the boundaries of the fan deltas were interpreted in the 3D seismic data. The second step, the seismic facies maps and isochron maps were created by Stratimagic™ and horizon cut maps were created by VoxelGeo™ in the Moebetsu Formation HST and TST members. Moreover the distributions of the fan deltas were identified in the Moebetsu Formation HST member.
In the 3D seismic sections, the distinct downlapping patterns of the seismic reflectors from the northeast to the southwest are recognized in the Moebetsu Formation HST Member, and they can be interpreted as progradation of the fan deltas onto the shelf.

The seismic facies map of the Moebetsu Formation HST Member indicates that each fan delta is prograding from the northeast to the southwest on the shelf (Fig.3 left). The isochron map of the same interval indicates the thick area in the northeast is the area where five fan deltas are overlapped, and the thickness is decreasing toward the southwest because of the distal part of the fan delta systems (Fig.3 right). From those results, it can be interpreted that the sedimentary basin is deepening toward the southwest, and the trend of the shelf-break line is the northwest-southeast direction.

The lithology of the Moebetsu HST fan delta developing in the northeast area can be estimated pebbly sandstones, coarse grained sandstones and interbedded thin mudstone beds. The fan delta sediments are gradually changing into fine-grained siltstones or mudstones on the shelf-slope area. In addition, the Moebetsu TST fan delta system is also developing in the northeast area, and the fan delta sediments are changing into siltstones or mudstones in the shelf-slope area.

3. Geological Modeling

3.1. Framework Modeling

Framework model was constructed by using depth structure map; it has 8km wide (East-West) and 12km long (North-South). In addition, it is classified to six zones by seven depth structure maps (Table 1).

The Moebetsu Mudstone Member (considered to be main caprock) has enough seal ability to seal CO₂ in gas phase in terms of formation thickness. On the other hand, the structure is upward to the northeast, and the trend is gradually thinner toward to the onshore area is confirmed. However, salinity of formation water in the Moebetsu Formation is clearly different from it in the Mukawa Formation. Therefore, the Moebetsu Mudstone member has been set across the entire model.

For the Moebetsu TST, the upper coarse grained facies (sandy facies) and lower fine-grained facies (muddy facies) are observed in survey wells (Fig.2). Therefore, these two layers are set for the Moebetsu TST to represent both phases.

For the Moebetsu HST (considered to be injection target), the layer thickness is set smaller than the upper and lower formations for the purpose of detailed fluid flow simulation. And taking into consideration depositional system, follow base layering is applied to the Moebetsu HST upper, and follow top layering is applied to the Moebetsu HST lower (Table 1). Total number of cells of the framework model is 129,000, and number of active cells is 90,017.

3.2. Property Modeling

Property model (facies model) was constructed from framework model. Sedimentary facies of the Moebetsu TST and HST were realized of results of attribute analysis of 3D-seismic data.
Fig. 4 shows the schematic of facies classification in property model. The Moebetsu HST is classified into four facies by sedimentary environment, slope (No.6), shelf (No.7), upper delta (No.8) and lower delta (No.9). Lower delta (No.9) is coincident with the Moebetsu HST lower. Westernmost point of the delta is almost consistent with the boundary between the Moebetsu HST lower and the Moebetsu HST upper.

For the Moebetsu TST, two lithofacies (sandy facies and muddy facies) are confirmed from survey wells. And two sedimentary environments are confirmed. Therefore, the Moebetsu TST is classified into three facies, offshore side (No.3), land side upper (No.4), land side lower (No.5).

4. CO₂ Injection simulation and long-term simulation

4.1. Simulation Parameters and Settings

4.1.1. Simulation parameters

It is desirable to set different simulation parameters to each sedimentary facies. However, reservoir parameters of shelf and slope are unknown because the survey wells have not been drilled into them yet. Usually, the fandelta has a tendency to be coarser grained in the proximal side, and to become finer grained towards offshore. In addition, we did not have enough data to evaluate heterogeneity in the same facies. So, we assumed two lithofacies (high and low permeability rocks) and categorized ten parts into them. No.1,2,3,5,6,7,10 in Fig. 4 are categorized as low permeability rocks (Mudstone), and No.4,8,9 are categorized as high permeability rocks (Sandstone). Then the reservoir parameters were decided from well test data and core analysis data of survey wells and the other wells. Table 2 shows simulation parameters. Fig 5 Shows permeability distribution of simulation model.

<table>
<thead>
<tr>
<th>Porosity</th>
<th>Horizontal Permeability (×10^-15 m²)</th>
<th>Vertical Permeability (×10^-15 m²)</th>
<th>Compressibility (1/kPa)</th>
<th>Salinity (ppm- NaCl)</th>
<th>Sg</th>
<th>S_w</th>
<th>S_grm</th>
<th>Threshold Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sandstone 0.281</td>
<td>16.78</td>
<td>1.678</td>
<td>1.532×10⁶</td>
<td>18000</td>
<td>0.05</td>
<td>0.49</td>
<td>0.275</td>
<td>404</td>
</tr>
<tr>
<td>Mudstone 0.342</td>
<td>0.0017</td>
<td>0.0017</td>
<td>1.678×10⁶</td>
<td>0.05</td>
<td>0.838</td>
<td>0.838</td>
<td>-</td>
<td>750</td>
</tr>
</tbody>
</table>

- Parameters for Sandstone

Porosity is given Φ=28.1% from core analysis and well log from survey well. Horizontal permeability is given 16.78×10⁻¹⁵ m² (17.0mD) from injection test of survey well. Vertical permeability is assumed to be 1.678×10⁻¹⁵ m² (1.7mD). Hysteresis is considered to Sandstone. Maximum residual gas saturation (S_grm) is given 0.275 from correlation equation between the maximum gas saturation and porosity (Holtz, 2002). Capillary pressure curve is obtained from rock-fluid centrifuge core analysis.
• Parameters for Mudstone
  Porosity is given $\Phi=34.2\%$ from core analysis. Vertical and Horizontal permeability is given $1.707\times10^{-18}$ m$^2$ (1.73 μD) from core analysis. Residual water saturation ($S_{wr}$) is assumed to be 0.638 from CO$_2$-water core flood analysis by Bennion et al (2007)\cite{2}. Critical gas saturation ($S_{gc}$) is assumed to be 0.05. Threshold capillary pressure was given $Pc = 750$ kPa from threshold capillary pressure measurement.

• Other parameters
  Reservoir pressure and temperature gradient are given from the survey well. Average reservoir pressure is about 10,669 kPa and average temperature is about 44.8 degree. Aquifer size is estimated from prediction of spread in a wide area of Moebetsu Formation.

4.1.2. Simulation Overview

CO$_2$ geological storage simulation was carried out using CMG’s GEM-GHG reservoir simulator. Three trapping mechanism, structural trapping, residual trapping, and solubility trapping are considered in this simulation study.

Model size is approximately 8000m×15000m×1500m. Typical grid size of the model is 200m×200m×15~150m. Local grid refinement is applied to near the injection well to represent CO$_2$ injection behavior.

Injection target is set to the point where good injectivity is expected from Acoustic Impedance value. Injection well was about 4000m in drilling depth, 3400m in departure length, and about 84 degree in maximum inclination angle.

4.2. CO$_2$ Injection simulation and long-term simulation

A reservoir simulation study to confirm the possibility of the injection of target amount ($2.5\times10^5$ tonne/year × 3 years, based on demonstration plan) and the stability of CO$_2$ in reservoir were carried out using above model. The target rate was determined based on the plan of “Demonstration of CO$_2$ Reduction Technology” conducted by the Ministry of Economy, Trade and Industry.

• Running simulation without CO$_2$ injection.
• $2.5\times10^5$ tonne/year of CO$_2$ (about $3.66\times10^5$ Sm$^3$/day) are injected continuously for 3 years. However, maximum injection pressure is set to 13410 kPa. This limit is estimated from leak off pressure of caprock which was measured at survey well.
• Running no CO$_2$ injection for about 1000 years to confirm long-term behavior of CO$_2$ in the model.

Fig.6 shows injection rate, cumulative injection volume, and bottomhole pressure of injection well. Injection rate drops below target injection rate in the early stage of injection period because of the limit of
bottomhole injection pressure. But injection rate increases to the target rate in a few months. Finally, about 7.5×10^5 tonne of CO₂ (2.5×10^5 tonne/year×3 years) has been injected.

Fig.7 shows CO₂ saturation and molality of CO₂ at Grid (23,30,15). This grid is the grid with most quantity of invasion of CO₂ in caprock. As shown in Fig.7, CO₂ is continuously entering the bottom of caprock after injection period. However, saturation of CO₂ rises up to only about 0.01%. In addition, saturation of CO₂ and molality has reached equilibrium in about 400 years after injection. Therefore, it is considered that caprock has enough seal capacity for CO₂ storage.

Fig.8 shows the distribution of gas (CO₂) saturation at top of reservoir at after 3 years (end of injection period), 200 years, and 1000 years. CO₂ plume (gas phase and dissolved CO₂) has been spread in the range of about 200m in diameter centered on injection well at the end of injection period. CO₂ plume continues to spread to 600m in diameter in 200 years. Thereafter, CO₂ doesn’t migrate.
4.3. Parameter Sensitivity Analysis

A sensitivity analysis for investigating the effects of reservoir parameters, such as permeability of reservoir and seal capacity of cap rock was carried out.

4.3.1. Effect of permeability of reservoir

From the results of the brine injection test of survey well, horizontal permeability of sandstone is considered within the range of $8.882 \times 10^{-15} \text{m}^2$ to $24.673 \times 10^{-15} \text{m}^2$ (9mD to 25mD). In order to identify the injectivity in the case of maximum permeability and minimum permeability, sensitivity study in both cases was carried out. $k_h/k_v$ ratio is same as the base case ($k_h/k_v = 0.1$), vertical permeability of sandstone is $0.8882 \times 10^{-15} \text{m}^2$ and $2.4673 \times 10^{-15} \text{m}^2$ respectively. Other parameters are the same as the base case.

Fig.9 shows injection rate and cumulative injection volume of base case, high permeability case, and low permeability case. For low permeability case, bottomhole injection pressure reach injection pressure limit immediately. Injection rate is range of $1.1 \times 10^3 \text{tonne/year}$ to $1.6 \times 10^3 \text{tonne/year}$, cumulative injection volume is $4.52 \times 10^4 \text{tonne}$. In high permeability case, $2.5 \times 10^5 \text{tonne/year}$ of injection is possible in all injection period.

![Fig.9 Injection rate and cumulative injection volume of base case, high permeability case, and low permeability case](image)

4.3.2. Effect of seal capacity of caprock

In order to understand the behavior of CO$_2$ when caprock has inferior seal capacity (high permeability and low threshold capillary pressure), a simulation of inferior seal capacity case was carried out.

Parameters of caprock are decided from the worst measurement results of the threshold capillary pressure measurement for the core obtained from survey well (However, we think that this significantly worse result is caused by failure of the measurement). In this case, horizontal and vertical permeability of caprock is $0.007 \times 10^{-15} \text{m}^2$ (7μD) and threshold capillary pressure is 12kPa. Other parameters are the same as the base case.

Fig.10 shows CO$_2$ saturation and molality of CO$_2$ of grid (23,30,15) and grid (23,30,14) in inferior seal capacity case. Compared to the base case, molality of CO$_2$ is three times higher and gas saturation is five times higher in caprock. The amount of invasion of CO$_2$ increases. But absolute amount of invasion of CO$_2$ is very small in base case and inferior seal capacity case, and gas saturation and molality of CO$_2$ do not increase at the upper layers.

Consequently, it shows that cap rock has sufficient seal capacity even in the case of low threshold pressure and high permeability.

![Fig.10 CO$_2$ saturation and molality of CO$_2$ of grid (23,30,15) and grid (23,30,14) in inferior seal capacity case.](image)
5. Conclusion

A reservoir evaluation study for CCS at Moebetsu Formation was carried out. The results of geological interpretation are as follows.

- The sedimentary environments for the Sandstone Member are interpreted to be fan delta, shelf and slope within the High Stand System Tract. On the fan delta, total of five lobes are detected. Lithology of the fan delta is sandstone dominant. Lithology of shelf and slope are considered to be siltstone dominant. Reservoir thickness is about 100m near the target area.
- Sedimentary Environment for Mudstone member is interpreted to be shelf within the Transgressive System Tract. This member is about 200m in thickness and consists of siltstone and mudstone. This member has a sufficient thickness and good seal capacity around storage area.

Simulation model was build based on the results above. Thereafter CO₂ long-term storage simulation was conducted using this simulation model. As a result, it is possible to inject CO₂ at the rate of $2.5 \times 10^5$ tonne/year $\times$ 3 years was confirmed. In addition, it was confirmed that caprock have sufficient seal capacity to CO₂ long-term storage.

A sensitivity study about the parameter of the reservoir and caprock were also conducted. In the case of low permeability for reservoir, it was not possible to inject CO₂ at the rate of $2.5 \times 10^5$ tonne/year. But the injection rate was above the minimum planned injection rate in this project. And caprock had sufficient seal capacity even in the case of low threshold pressure and high permeability.

From the results of this study, JCCS concluded that Moebetsu Formation has suitable properties as a CO₂ reservoir for CCS Demonstration Project.

6. Acknowledgements

This study was a part of the “CCS Demonstration Project in Japan” conducted by the Ministry of Economy, Trade and Industry (METI). The authors would like to thank METI for their permission to disclose the result of the study.

7. References
