CO$_2$ Storage Experience in Japan
including Impacts of Earthquakes

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### Purpose of Nagaoka Pilot Project

- **World CCS Projects (@2000)**
  - **Sleipner** (Norway, Aquifer, Associated CO₂)
  - **Weyburn** (Canada, EOR, Coal Gasification)

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- **Nagaoka Project**
  - 1st on-shore aquifer CO₂ injection test

   (Verification of CO₂ Storage in Complex Geology)
Site Selection

Geological Factors

- Continuity of cap rock
- Gentle tilted reservoir
  - Depth (800-1200m),
  - Thickness (>10m)
- No faults within 1.5km²
- Details data for subsurface

Operational Factors

Social Acceptance, Well yard etc.
Overview of the Nagaoka Site

Well Configuration at the Reservoir Depth

- OB-4: Injection Well
- IW-1: Observation Well
- OB-2
- OB-3
- Dip 15°
- 60m
- 40m
- 120m

- Total amount: 10,400 ton CO₂
- Rate: 20~40 ton/day

Reservoir: Haizume Formation (Pleistocene Sand)
- Injec. Layer: Zone 2, 12m-thick
- Porosity: 23%
- Permeability: ave. 7mD (Pump-test)
- Conditions: 48°C, 11MPa
Reservoir Modelling & Simulation
- Summing up all Knowledge of Injection Site -

Reservoir (Haizume Formation)

- Injection point is Edge of Anticline

Based on seismic, logging, and core

Pre-Injection: Evaluate injection plan (Injectivity)
(Reservoir model is build based on the seismic and well data)

During Injection: History matching with pressure & logging data
(Reservoir model is updated by the monitoring data)

Post-Injection: Long-term prediction of CO2 distributions
(Based on the accurate reservoir model considering with trapping mechanisms, long-term prediction is acceptable)
Detection of CO2 breakthrough by time-lapse logging

Elapsed time from 7 July 2003 (day)

Seismic tomography
Well Loggings
- Neutron
- Sonic
- Induction

Injection rate (t-CO₂/day)
Rate; 20~40 ton/day
Total; 10,400 ton

Cumulative amount (t-CO₂)
Sonic Logging @ OB-2

Vp changes

14th 16th 18th 20th 22nd 24th 26th 28th 30th 32nd 34th 36th

End of CO₂ injection (24th)

BL Average up to 13th

37th

Vp: -23%

Post-injection

1.5 2.5 3.5

Vp (km/sec)

1108 1112 1116 1120
Neutron Logging @ OB-2

End of CO₂ injection (24th)

Post-injection

ϕn changes
Induction Logging @ OB-2

Resistivity changes

End of CO₂ injection (24th)

Post-injection

BL
Time Series of Logging Data
(1116.0m @ OB-2)

Breakthrough

Imbibition

Vp (km/sec)

ρ (ohm-m)

SCO₂ max. 63%

SCO₂

CO₂ injection period

Date

2003/01/01
2005/01/01
2007/01/01
2009/01/01
2011/01/01
P-wave Velocity and Resistivity vs CO₂ saturation
(1116.0m @ OB-2)

Joint monitoring is key to understand CO₂ behavior.

SCO₂ max. 63%
Time-lapse Tomography
OB2 – OB3 Section (160m)

Injection Period

Injection Rate: 20~40 ton/day
Total Injection: 10,400 ton

- BLS: Base Line
- MS1: After 3,200t
- MS2: After 6,200t
- MS3: After 8,900t
- MS4: After 10,400t (End Injection)
- MS5: After 9 months
- MS6: After 2 years 9 months

2002/01/01 to 2008/01/01
Seismic Tomography

(Feb. 2003 : BLS)

(Jan. 2004 : MS1)

Max: - 3.0%
(Feb. 2003 : BLS)

8,900 t

(Max: -3.5%)

(Nov. 2004 : MS3)
Time-lapse seismic tomography

Post-Injection: 10,400 t-CO₂

Max. Velocity Change = -3.5%

Velocity Change = (V_{MS4} - V_{BLS}) / V_{BLS}
3D Reservoir Model

\[ k_h = (k_x \cdot k_y)^{-0.5}, \quad k_y/k_x = 1.2 \]
Results of Reservoir Simulation

CO2 Distribution at Terminating Injection
Distribution of Injected CO2
(Comparison Reservoir simulation and Tomography)

Simulation Results

<table>
<thead>
<tr>
<th>Anomaly Size</th>
<th>Δh (m)</th>
<th>Δz (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OB-3</td>
<td>105</td>
<td>22</td>
</tr>
<tr>
<td>OB-2</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

Ray paths: no travel time difference

Garcia (2009)
Evolution of Reservoir Model by History Matching

Reservoir Model → CO2 Distribution Simulation → History Matching

- Bottom hole pressure
- Reservoir pressure
- CO2 Breakthrough time
- Seismic tomography

✓ Accurate Reservoir Model
✓ Anisotropic Permeability
CHDT* (Cased Hole Dynamic Tester)

Fluid sampling from reservoir ➔➔➔ Geochemical Reactions
Formation Fluid Sampling at OB-2

- Depth@OB-2 (mMD) vs Time since injection started (year)
- Resistivity change (%)

- Without CO₂
- Free CO₂
- Dissolved CO₂

1st fluid sampling

2nd fluid sampling

- Injection
- Post-injection
Successful measurement of dis-CO$_2$ & pH under in-situ pressure condition

![Graph showing dis-CO$_2$ and pH measurements at different depths.]

- **1112.0m**: 33 (dis-CO$_2$) and 7.95 (pH)
- **1118.0m**: 241 (dis-CO$_2$) and 5.67 (pH)
- **1119.5m**: 44 (dis-CO$_2$) and 5.01 (pH)

Partial pressure at the reservoir depth:
- **1112.0m**: 0.05 (CO$_2$)
- **1118.0m**: 1.0 (CO$_2$)
- **1119.5m**: 0.2 (CO$_2$)
Concentrations of Ca, Mg, Fe and Si in fluid sampled at 1118.0m are much higher than other two depths.

→ **Neutralization of pH by mineral dissolution**
Calcite shows a tendency of re-precipitate at 1118.0m.

→ Mineral trapping of CO2?
Nagaoka CO$_2$ Storage Project Workflow

**Pre-Injection Phase:** 3-5 years
- Site selection
- Characterization
- Design

**Injection Phase:** 10-50 years
- Construction
- Monitoring
- CO$_2$ injection

**Post-Injection Phase:** 100+ years
- Ceasing injection
- Decommissioning
- Surveillance

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**Commercialized CCS**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>2000.12</td>
<td>Nagaoka (pilot test site)</td>
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<tr>
<td></td>
<td>(2.5 years)</td>
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<tr>
<td>2003.7</td>
<td>CO$_2$ injection</td>
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<tr>
<td></td>
<td>(1.5 years) 10,400 Ton</td>
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<tr>
<td>2005.1</td>
<td>Decommissioning</td>
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<tr>
<td></td>
<td>(10 years)</td>
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<tr>
<td>2015.3</td>
<td>Surveillance</td>
</tr>
</tbody>
</table>

The First Case on Post-Injection Monitoring
Field measurements during and post CO$_2$ injection

(Geophysical monitoring)

Elapsed time from 7 July 2003 (day)

Seismic tomography

Well Loggings
- Neutron
- Sonic
- Induction

Earthquake Oct.23, 2004
Earthquake Jul.16, 2007

Rate: 20~40 ton/day
Total: 10,400 ton

Injection rate (t-CO$_2$/day)
Cumulative amount (t-CO$_2$)
Changes in Bottom Hole Pressure

Earthquake Oct.23, 2004
Earthquake Jul.16, 2007

Pressure (MPa)

Injection rate (t-CO₂/day)
Cumulative amount (t-CO₂)

Date

2003/01/01 2004/01/01 2005/01/01 2006/01/01 2007/01/01 2008/01/01
The Mid Niigata Prefecture Earthquake in 2004

Main shock: 23 Oct 2004
M6.8 at 10km depth
Seismic intensity: 7
→ Injection was automatically stopped at the main shock.

Access road was damaged.

CO₂ detector (No leak)

Injection was carefully resumed after confirming safety (6 Dec 2004)
Injection rate: 40t-CO₂/day

(GSJ, 2004 http://www.gsj.jp/jishin/chuetsu_1023/)

For detail: Xue et al. (2006)
3rd Monitoring Network Meeting (Melbourne)
Main Shock: 2004/10/23 17:56 M6.8

- NS (gal)
- Vertical (gal)
- EW (gal)

Max: 705 gal
Sonic Logging (Vp) @ OB-2

Vp (km/sec)

Changes of the Vp

-1.0  0.5

15th 17th 19th 21st 23rd 25th 27th 29th 31st 33rd 35th 37th

14th 16th 18th 20th 22nd 24th 26th 28th 30th 32nd 34th 36th

End of CO₂ injection

BL

Latest

Post-injection

Depth (mMD)

1108

1112

1116

1120

E2004

E2007
Results of Crosswell Seismic Tomography

MS1/BL 3,200t

MS2/BL 6,200t

MS3/BL 8,900t

E2004

MS4/BL 10,400t

MS5/BL 10,400t

MS6/BL 10,400t

E2007
Pilot scale, **Large scale**, Commercial scale (1)

- CO₂ plume size
  (the reservoir scale vs CO₂ plume size, reservoir heterogeneity, permeability anisotropy)

- formation pressure buildup
  (fracture pressure, micro-seismicity, geo-mechanical deformation, controlled injection)

⇒⇒ **Alarm system according to magnitude and number of microseismic events.**
Pilot scale, Large scale, Commercial scale (2)

- CO$_2$ trap mechanism
  (field or lab data of residual CO$_2$ saturation, CO$_2$ dissolution, geo-chemical reaction)

- technical feasibility of CO$_2$ monitoring
  (geo-physical and -chemical monitoring, quantitative evaluation of CO$_2$)

⇒⇒ Same technology but Different geology, Different interpretation. No Silver Bullet!
Large-scale Demonstration: 2012 - Offshore Tomakomai

- **CO₂ source**
  - PSA (Hydrogen production unit)
  - PSA off gas containing CO₂ corresponding to more than 100,000 t/year

- **Capture facility**
  - Activated amine process
  - Capturing CO₂ of more than 100,000 t/year

- **Injection facility**
  - Compressor
  - Injection wells

- **Existing oil refinery**

- **Transportation**
  - Pipeline, approx. 2.5km

- **Reservoir**
  - Sandstone layers of Moebetsu Fm. 1,000~1,200m under the seabed
  - T1 Member of Takinoue Fm. 2,400~3,000m under the seabed

*Tanase et al., 2013*
Overview of the Tomakomai Project

- **OBC**: Ocean Bottom Cable used for 2D seismic survey and monitoring of micro-seismicity and natural earthquakes
- **OBS**: Ocean Bottom Seismometer used for monitoring of micro-seismicity and natural earthquakes

Tanase et al., 2013
# Time Schedule for the Tomakomai Project

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<tr>
<td>Ground</td>
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<td>Equipment</td>
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<tr>
<td>Injection Well</td>
<td>Engineering, Procurement, and Construction</td>
<td>Site work</td>
<td>Commissioning</td>
<td>Operation</td>
<td>Injection</td>
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<tr>
<td>Offshore Monitoring Facilities</td>
<td>Observation well for Takinoue Formation</td>
<td>Drilling</td>
<td>Observation well for Moebetsu Formation</td>
<td>Retrofitting</td>
<td>Observation</td>
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<tr>
<td>Offshore</td>
<td>Onshore seismometer</td>
<td>Installation</td>
<td>Offshore 2D seismic survey</td>
<td>Baseline survey</td>
<td>Baseline observation (Seismicity)</td>
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<tr>
<td>Offshore</td>
<td>Marine environmental survey</td>
<td>Baseline survey (Seasonal)</td>
<td>Test measurement</td>
<td>OBS Installation</td>
<td>Baseline observation (Seismicity)</td>
</tr>
</tbody>
</table>

*Tanase et al., 2013*
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