Second Edition

Research Report on Impacts of Hokkaido Eastern Iburi Earthquake on CO_2 Reservoir

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Japan CCS Co., Ltd.

Report

Table of Contents

		Page
1. Executive Summary		1
2. Overview of Tomakomai CCS Demonstration Project		
2.1	Objectives and issues of Demonstration Project	3
2.2	Schedule of Demonstration Project	3
2.3	CO_2 reservoir and injection condition	3
3. Hokkaido Eastern Iburi Earthquake (Overview)		
3.1	Triggering mechanism of the earthquake	5
3.2	Actions after the earthquake	8
4. Risk management regarding Earthquake and Tomakomai CCS Demonstration Project		
4.1	Condition of Tomakomai CCS Demonstration Project facilities before and after the Earthquake	9
4.2	Framework of manuals for risk management	10
4.3	Risk management for onshore capture/injection facilities and present status	11
4.4	Risk management of CO_2 reservoir and present status	12
4.5	Relationship to Act for the Prevention of Marine Pollution and Maritime Disasters	12
5. Relationship of CO_2 Injection and Earthquake		
5.1	Mechanism of earthquake induction	13
5.1.1	Examination of earthquake induction in the reservoir and cap rock by CO_2 injection	13
5.1.2	Examination on impacts of CO_2 injection on earthquake source fault	13
5.2	Impacts on reservoir	
5.2.1	Monitoring results of micro-seismicity/natural earthquakes	15
5.2.2	Monitoring results of temperature and pressure	18
6. Future Plan		22

1. Executive Summary

This report (hereinafter referred to as “Report”) compiles the circumstances of local actions taken by the “Large scale CCS Demonstration Project in Tomakomai” (hereinafter referred to as the “the Demonstration Project”) when the Hokkaido Eastern Iburi Earthquake (hereinafter referred to as “the Earthquake”) occurred, as well as the content and the opinions received from the committee members of the “Review Meeting on the Tomakomai CCS Demonstration Project” (October 19, 2018) held by Japan CCS Co., Ltd. (hereinafter referred to as “JCCS”).

JCCS is compiling and disclosing this Report in accordance with its principle to widely share information on the project, to which it has adhered to since the project startup.

Prior to the start the project, JCCS conducted a detailed evaluation of the effects of the underground storage of CO_2 on the geological formations of the Tomakomai area through such methods as simulation analysis. In view of the occurrence of the Earthquake, JCCS once again held discussions on whether the Earthquake had any impact on the project, whether there was any relationship between the project and the Earthquake, and sought the opinions of external experts. JCCS herein reports the results.

(1) Overview of Tomakomai CCS Demonstration Project

The Demonstration Project being implemented by JCCS under consignment by the New Energy and Industrial Technology Development Organization (NEDO; METI until the last Japanese fiscal year; hereafter “JFY”). This project aims to achieve the practical use of CCS technology (separation, capture, injection and storage of CO_2) by around 2020 in accordance with the Basic Energy Plan (latest plan approved by Cabinet on July 3, 2018) by demonstrating the safe and stable implementation of the first integrated CCS system in Japan. CO_2 injection into the reservoir located about 3 km offshore of Tomakomai at a depth of about 1.0 to 1.2 km below the seabed (the Moebetsu Formation) started in April 2016, and the cumulative CO_2 injection volume exceeded 200,000 tonnes by the middle of August 2018. In addition, test injection into the reservoir located about 4 km offshore of Tomakomai at a depth of about 2.4 to 3.0 km (Takinoue Formation) was started in February of 2018, and 98 tonnes of CO_2 has been injected.

(2) Hokkaido Eastern Iburi Earthquake (Outline)

On September 6, 2018, at 03:07, a M6.7 earthquake occurred at a depth of 37 km in the central eastern Iburi region (announcement by Japan Meteorological Agency), and an intensity of 7 was registered at Atsuma Town, Hokkaido, and an intensity of lower 5 (158 gal) at the Tomakomai CCS Demonstration Center. Regarding this earthquake, the Earthquake Research Committee of the Japanese government expressed the view, “In areas from around the eastern part of the Iburi/Hidaka regions to offshore of Urakawa, many earthquakes have historically occurred in regions deeper than where earthquakes usually occur in the onshore earth crust, and the recent seismic activity occurred in such region.” Thus, it is believed that the Earthquake is not beyond the scope of seismic activities expected in this region.

(3) Risk management for the Earthquake and the Demonstration Project

The Demonstration Project Center adopts a security system that entails an emergency shutdown of the CO_2 capture/injection facilities for seismic tremors exceeding 150 gal. However, the supply of the

CO_2 containing gas had been stopped since September 1 due to circumstances of the CO_2 supplier and operations of the surface facilities and injection had been suspended when the Earthquake occurred, and no emergency shutdown due to the Earthquake occurred. JCCS, in accordance with its in-house emergency response rules, confirmed that there were no abnormalities in the facilities and equipment of the Center immediately after the occurrence of the Earthquake, and communicated with NEDO, METI and local stakeholders. On the other hand, a power shutdown occurred 18 minutes after the Earthquake, and the entire power supply was lost after the uninterruptible power supply (UPS) operated for about 90 minutes, resulting in a blackout for about 55 hours before power restoration. In order to enable full-time acquisition of data of the injection well even during a power outage, improvement countermeasures with redundant means to deal with power outages comprising the installation of emergency power generators in the Demonstration Center to ensure minimum operation of the facilities, and installation of batteries for the continuous measurement data recorders for the injection wells will be implemented as a first step.

(4) Relationship with Earthquake

In 2011 before the startup of the project, it was confirmed that there was no possibility of slipping along cracks in the geological formation (which would cause a micro-earthquake) by evaluating the impacts on cracks in the reservoir and cap rock caused by CO_2 injection, on the basis of a calculation of pressure rise of geological layers for the case where an injection of 750,000 tonnes CO_2 (250,000-tonnes per year for three years) has been implemented.

On this occasion, in order to examine the impact of the CO_2 injection on the source fault of the Earthquake, simulations on CO_2 behavior were conducted based on an updated reservoir model (as of July 2018) when the cumulative injection amount (300,000 tonnes into the Moebetsu Formation and 750 tonnes into the Takinoue Formation) reaches the amount expected at the time of injection completion. The pressure increase in the geological formations due to the rise in injection pressure (about 5 MPa in the Takinoue Formation and 0.7 MPa in the Moebetsu Formation) with regard to the Takinoue Formation was 2 MPa at 50m from the injection well and decreased to about 0.25 MPa or less 1 km away from the well, and the variation in stress[*1] at the hypocenter about 30 km in epicenter distance was calculated to be about 1/1,000 of the pressure change in the earth's crust caused by the tidal force of the earth (several kPa). In addition, micro-seismicity has been continuously monitored in the vicinity of the injection point, and no micro-seismicity had been detected since the start of injection. As a result, the committee members reached a common understanding that no data suggesting any relationship between the CO_2 geological storage and the Earthquake occurring at a location about 30 km away could be confirmed.

Although part of the pressure and temperature data of the reservoirs is lost by the power outage, resumption of data acquisition after power restoration revealed that the data follows the same trend as that before the power outage, identical to that seen in past stoppages of CO_2 injection. Furthermore, a rise in pressure (1.8 kPa) in the CO_2 reservoir (Takinoue Formation) at the injection well was temporarily observed just after the Earthquake. This value is consistent with the theoretical solution (1.9 kPa) of stress variations associated with fault activity at the hypocenter, and it does not indicate an abnormality of the CO_2 reservoir. Therefore, the committee members reached a common understanding that no CO_2 leakage attributable to the Earthquake could be recognized. [*1] The force that is generated inside an object as a result of applying a force to the object. Pressure is the force applied to the object.

(5) Future Plan

The committee members confirmed their understanding that the resumption of CO_2 injection would be conducted pending the restart of supply of CO_2 gas from the CO_2 source, observation of the situation regarding the integrity of injection facilities and wells, explanation to local stakeholders, and trends of aftershocks of the Earthquake.

2. Overview of Tomakomai CCS Demonstration Project

The Demonstration Project is being implemented by JCCS under consignment by NEDO (METI until JFY 2017).

2.1. Objectives and issues of Demonstration Project

The Demonstration Project, as a countermeasure against global warming, aims to achieve the practical use of CCS technology by around 2020 in accordance with the Basic Energy Plan (latest plan approved by Cabinet on July 3, 2018), and sets out to demonstrate that CCS can be implemented safely and stably at a practical usage technical level. To this end, as the first integrated CCS system in Japan, CO_2 will be captured, injected, and stored at the rate of about 100,000 tonnes per year, and the subsurface behavior of CO_2 will be monitored.

Although most of the elemental technologies that are required in the respective steps of CCS (capture, injection/storage, and monitoring) are already in use in various types of industries, it will further be demonstrated that the combined elemental technologies will function as an integrated system.

2.2. Schedule of Demonstration Project

The entire schedule of the Demonstration Project is shown in Figure 1. CO_2 injection was started in April 2016 and is scheduled for the 3 years of JFY 2016 through 2018.

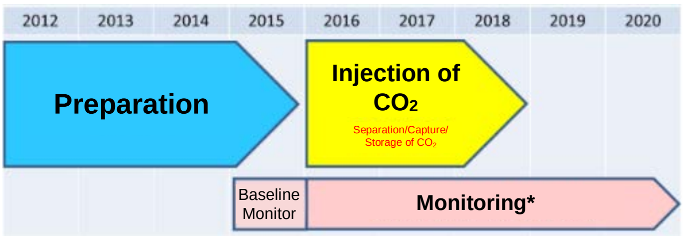


Figure 1: Entire Schedule of Demonstration Project
(as of November 2018)

* Investigation of the subsurface condition of the injected CO_2, the surrounding sea and seabed conditions to obtain information for the adequate management of CO_2 injection.

2.3. CO_2 reservoir and injection condition

The CO_2 source of the Demonstration Project is CO_2 containing gas supplied by an existing oil refinery, and the capture volume of CO_2 is dependent on the CO_2 volume supplied by the CO_2 gas source. The capture facility of the Demonstration Project has been confirmed to have a capture capacity of up to 220,000 tonnes per year (approx. 600 tonnes per day) at a CO_2 concentration of 99% or greater. The captured CO_2 will be injected entirely into sub-seabed reservoirs located offshore Tomakomai (Moebetsu and Takinoue Formations). In April 2016, injection was started into the Moebetsu Formation, evaluated to be highly permeable for CO_2, located 1.0 to 1.2 km below the seabed about 3 km offshore of Tomakomai. The cumulative injected CO_2 amount as of September 1, 2018, is 207,209 tonnes. On the other hand, test injection into the Takinoue Formation, located 2.4 to 3.0 km below the seabed about 4 km offshore was also started in February 2018, and 98 tonnes of CO_2

has been injected. The testing of simultaneous injection of CO_2 into the two reservoirs has also been conducted.

Placing importance on the safe implementation of CO_2 injection, JCCS measured the leak-off pressure of the cap rock (not the pressure at which the geological layer is actually ruptured, but the pressure at which cracks are to be formed before rupturing occurs) in advance, and designated 90% of this pressure as the upper limit of the operational pressure. We also installed a comprehensive monitoring system. To implement CCS safely and stably, it is necessary to grasp the behavior (movement, distribution, etc.) of the CO_2 stored, as well as to continuously monitor for any CO_2 leakage/seepage out of the reservoirs. For this purpose, we are implementing seismic surveys to grasp the distribution of CO_2, and are monitoring the pressure and temperature of the reservoirs (Figure 2). In addition, natural earthquakes and underground micro-seismicity are continuously monitored. Furthermore, in Japan, the Act on the Prevention of Marine Pollution and Maritime Disasters (Maritime Pollution Prevention Act) is applied for sub-seabed CO_2 storage, and in accordance with the “Monitoring Plan” associated with the act, marine environmental surveys (seasonal surveys implemented four times a year) are being conducted.

As for the behavior of stored CO_2, a 3D seismic survey was implemented in 2017 at cumulative CO_2 injection of 65,000 tonnes into the Moebetsu Formation, and a comparison with the reflected waves of a baseline 3D survey conducted before the start of CO_2 injection detected a difference in the seismic waves (Figure 3). This difference is believed to indicate the distribution of the stored CO_2, which shows a distribution similar to the prediction results of CO_2 behavior simulation at cumulative injection of 61,238 tonnes implemented in advance. Calibration of the reservoir model by a comparison of the prediction and the actual measurement is expected to improve the accuracy of the model and contribute to the prediction of the future CO_2 distribution.

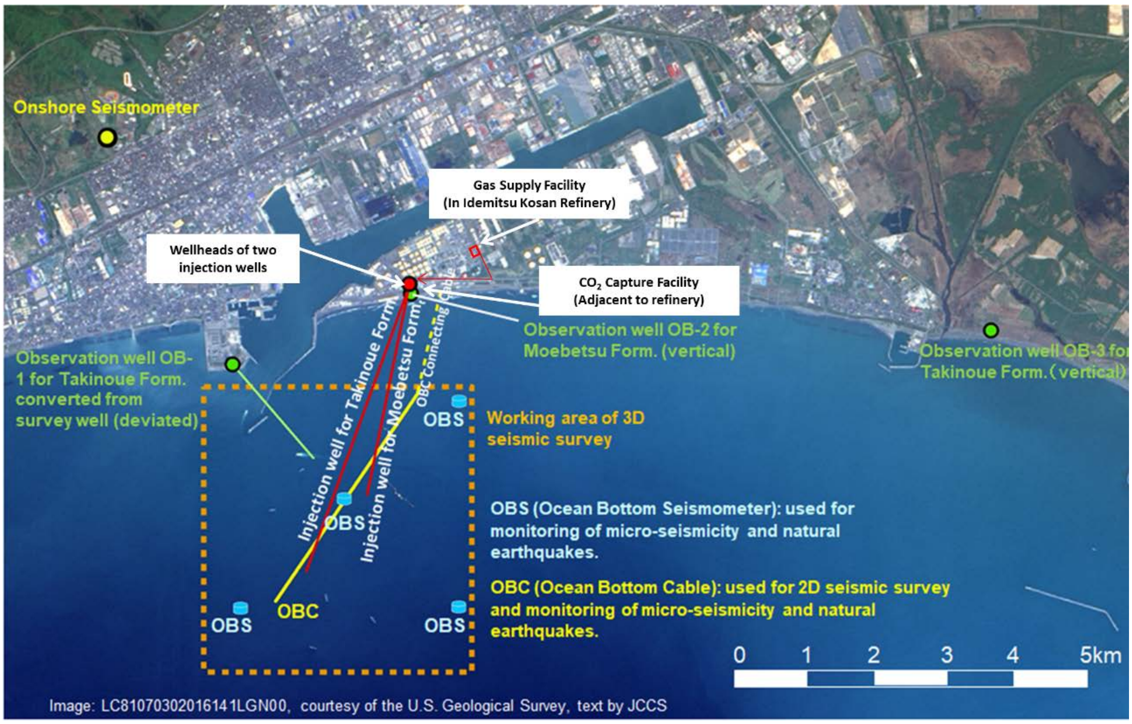


Figure 2: Positional Relationship of Demonstration Project Facilities

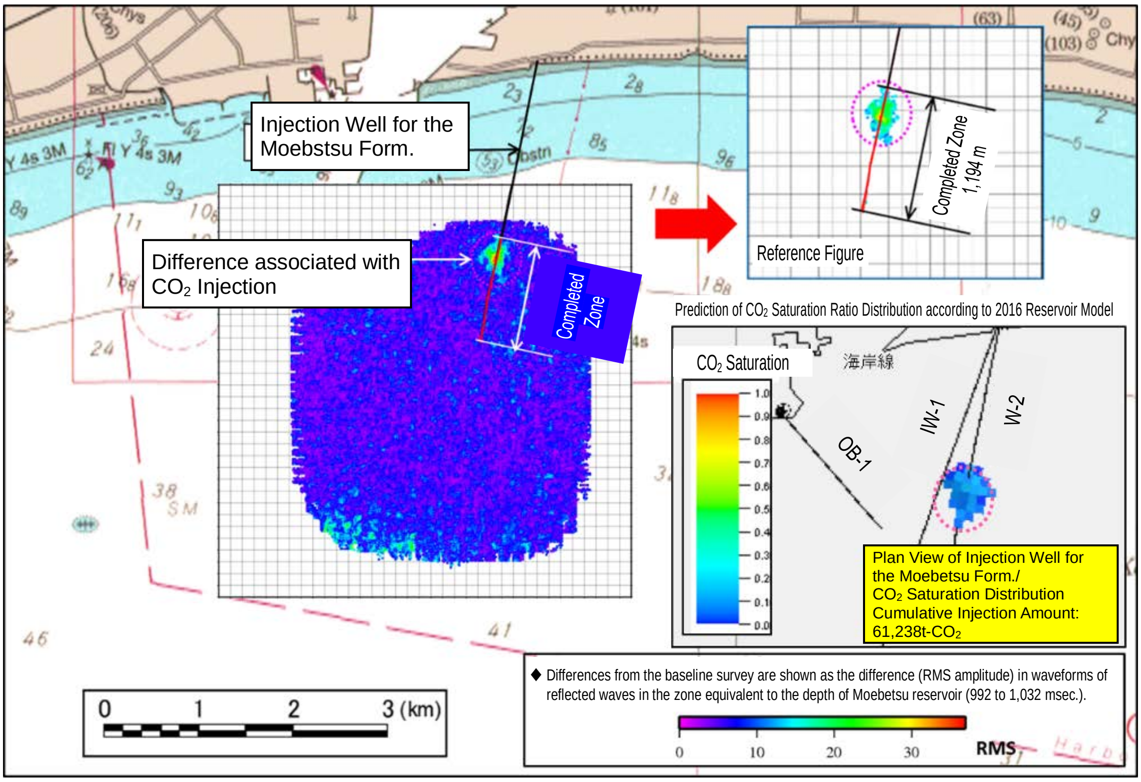


Figure 3: Results of Monitor 3D Seismic Survey

3. Hokkaido Eastern Iburi Earthquake (Overview)

3.1. Triggering mechanism of the earthquake

On September 6, 2018, at 03:07, an M6.7 earthquake occurred at a depth of 37 km in the central eastern Iburi region (announcement by Japan Meteorological Agency), and a seismic intensity of 7 was recorded at Atsuma Town, Hokkaido, while the intensity was lower 5 (158 gal) at the Demonstration Project Center. According to material released by the Japan Meteorological Agency, if we take a look at seismic activity since October 1997, earthquakes of around M4.0 and greater have occurred from time to time around the hypocenter of the Earthquake, and on July 1, 2017, an M5.1 earthquake occurred at a depth of 27 km (Figure 4). According to public material, the regional subsurface structural framework is believed to be that the Pacific plate is moving obliquely into the Kuril Trench, dragging the earth’s crust of the Kuril Islands (Kuril Arc) from the east, which pushes and collides with the NE Japan Arc (Figure 5). It is believed that when this happens, the upper crustal part of the Kuril Arc is thrust upwards and forms the Hidaka Mountain Range, and the lower part splits and slides downwards beneath the NE Japan Arc, which is also dragged downwards. As a result, the earth’s crust is thicker around the Hidaka Mountain Range and to the west (Figure 5).

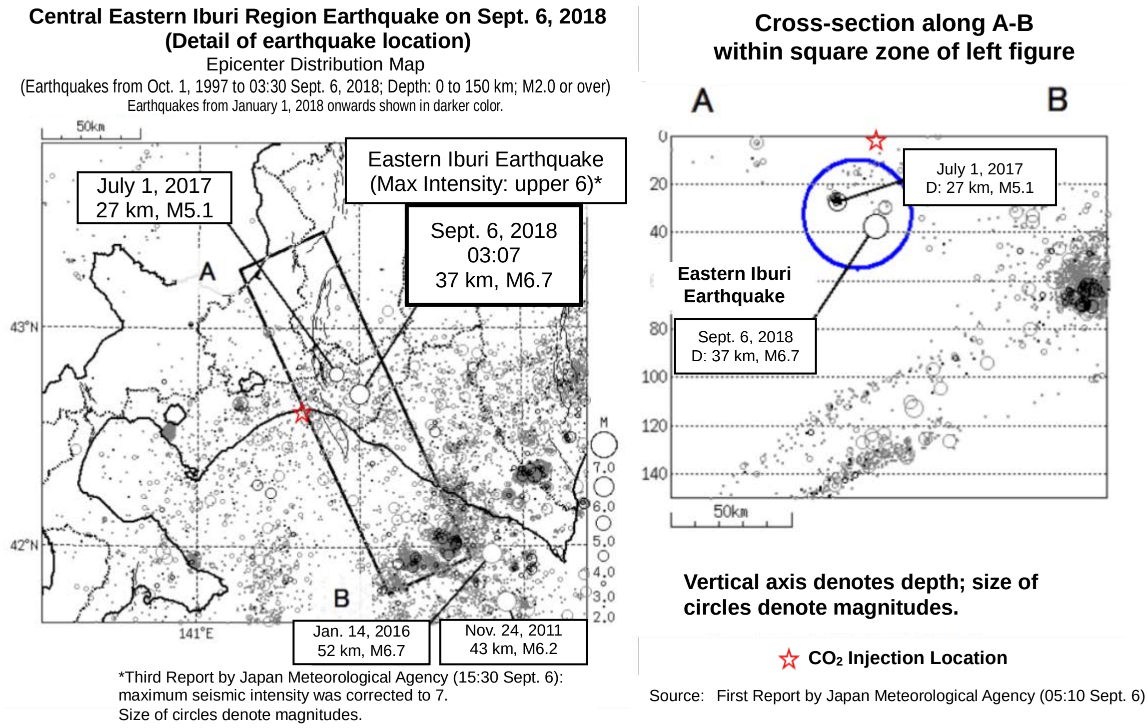


Figure 4: Hypocenter of Hokkaido Eastern Iburi Earthquake

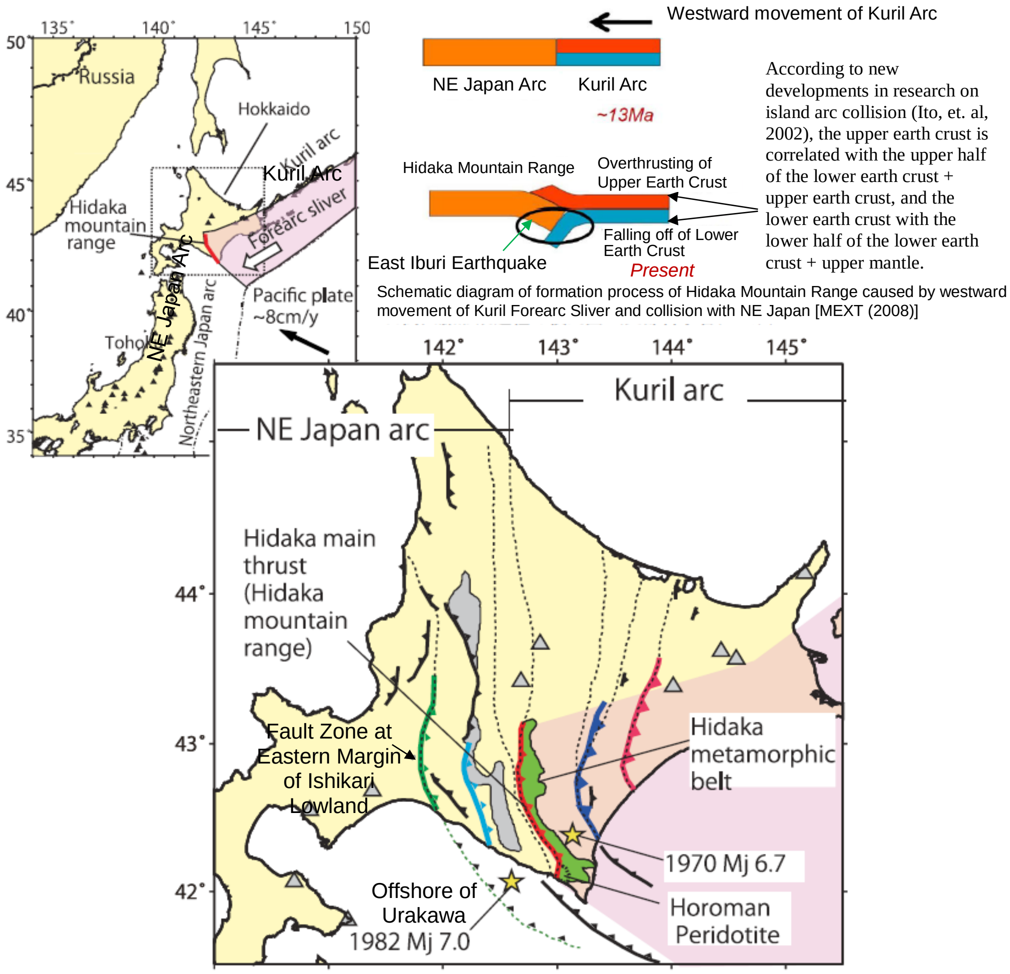
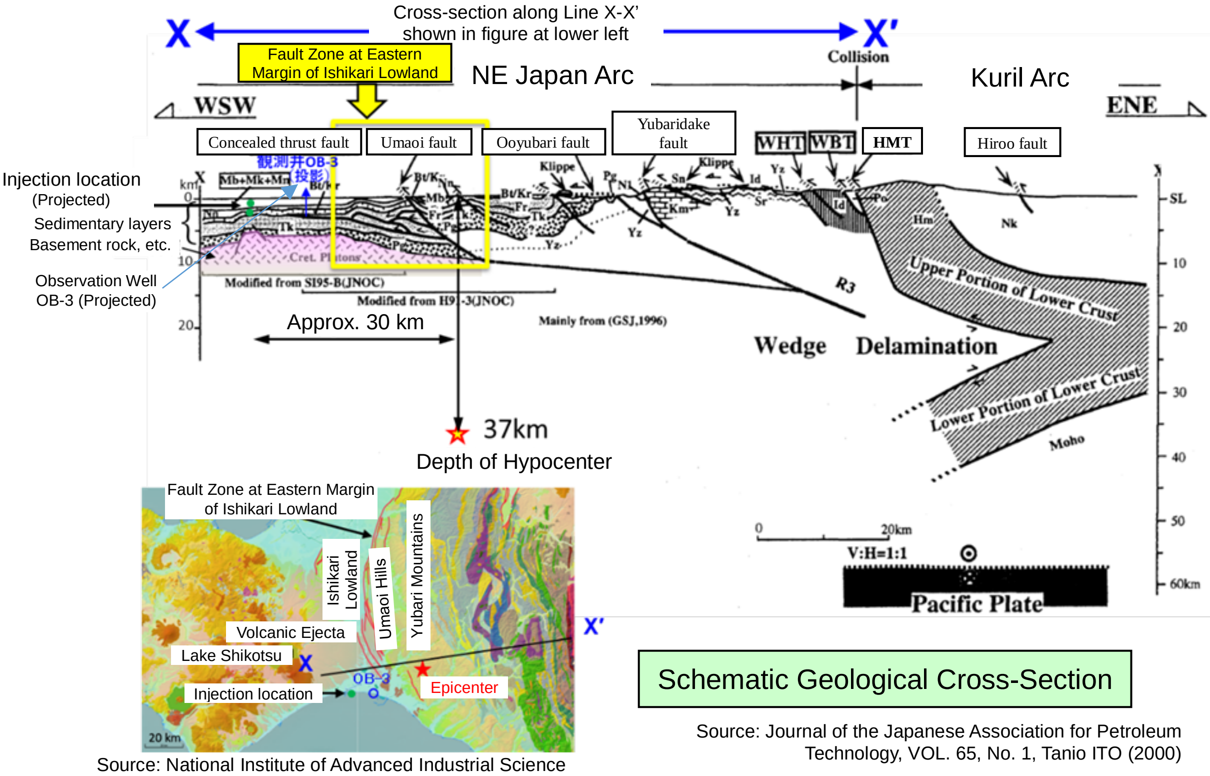


Figure 5: Tectonic Structure Image of Southern Hokkaido

Source: High-resolution seismic velocity structure beneath the Hokkaido corner, northern Japan (Saeko Kita et al., 2012), Estimation of 3D Inhomogeneous Crustal Structure at Plate Boundaries and Peripheral Regions (MEXT, 2008)

The Earthquake is believed to have occurred in the vicinity of the bend of the earth's crust, and the government's Earthquake Research Committee expressed the view on September 6 that "the regions around eastern Iburi, Hidaka to offshore Urakawa are characterized by many earthquakes also occurring in locations deeper than where earthquakes usually occur in the onshore earth crust, and the latest seismic activity occurred in the areas having such characteristics." As described above, the Earthquake is believed be within the range of seismic activities expected in the areas concerned.

In addition, the hypocenter of the Earthquake officially announced by the Japan Meteorological Agency is located at a depth of 37 km in basement rock, which has no continuity with the sedimentary layers into which CO_2 is being injected (Figure 6).



Source: National Institute of Advanced Industrial Science and Technology; additions made by JCCS

Source: Journal of the Japanese Association for Petroleum Technology, VOL. 65, No. 1, Tanio ITO (2000)

Figure 6: Hypocenter of Hokkaido Eastern Iburi Earthquake and schematic geological cross-section

3.2. Actions after the earthquake

Following the Earthquake on September 6, JCCS implemented actions according to in-house emergency response rules, and provided reports and disclosed information to the relevant stakeholders as follows:

- 03:07 Following the Earthquake, the operations personnel on duty first executed evacuation, roll-call, and information collection, and then implemented an on-site inspection according to the "Inspection List" (on items stipulated in "Procedures for countermeasures against natural disasters"), confirmed that there was no accident/disaster and abnormality regarding the capture and injection facilities, and reported the situation to the General Manager of the Tomakomai CCS Demonstration Project Center.
- 07:03 In accordance with in-house rules, the General Manager of the Storage Engineering Department of JCCS Head Office, followed by the General Manager of the Plant Division, reported by e-mail that there was no abnormality at the plant to the Global Environment Partnership Office, Industrial Science and Technology Policy and Environment Bureau of METI, and the Environment Department of NEDO.
- 08:00 After confirming that there was no abnormality regarding personnel safety, facilities, buildings and the entire premises, which were not listed on the "Inspection List", the General Manager of the Tomakomai CCS Demonstration Project Center once again reported to the JCCS Head Office Plant Division that "no property damage or abnormality to personnel or facilities was detected as a result of inspection".
- The Tomakomai CCS Demonstration Project Center provided the first report via mobile phone at

08:50 to Tomakomai Fisheries Cooperative Association, 09:00 to Tomakomai Industry and Economics Department, and 09:15 to Hokkaido Federation of Fisheries Cooperative Associations, reporting that there was no abnormality of the project facilities.

- 09:37 JCCS posted that there was no abnormality of the onshore capture/injection facilities on “Information” section of homepage.
- 09:50 Reporting to the Energy Policy Division, Hokkaido Bureau of Economy, Trade and Industry, was made by the General Affairs Department, JCCS Head Office due to the disconnection of landline phones caused by the Hokkaido power outage and the recharging status of mobile phones.
- As no human casualties or property damage of facilities were incurred, JCCS judged there was no need to make an emergency call to the fire department and police station, and reported the situation after the Earthquake as follows:
  - September 12 (Wed) Electric Power Safety Division, Hokkaido Industrial Safety and Inspection Department (Reporter: Plant Headquarters)
  - September 13 (Thu) Commerce, Industry, Labor and Tourism Section, Industry Promotion Division, Hokkaido Iburi General Sub-prefectural Bureau (General Manager of Tomakomai CCS Demonstration Project), Hokkaido Tomakomai Regional Environment Monitoring Office, Tomakomai City Environment Preservation Division (Manager of Environment and Safety Group), Tomakomai Fire Department (Manager of Environment and Safety Group)
- September 12 (Wed) 19:40 JCCS posted its view regarding CCS and the Earthquake on “Information” section of homepage.
- September 13 (Thu) Although JCCS in-house rules did not require disclosure of information because the hypocenter was outside the Tomakomai Project monitoring area, from the viewpoint of appropriately providing adequate information, JCCS communicated the contents of the “Information” section of its homepage to major local stakeholders, including the Tomakomai Fisheries Cooperative Association, Tomakomai Industry and Economics Department and the Hokkaido Federation of Fisheries Cooperative Associations.

4. Risk management regarding Earthquake and Tomakomai CCS Demonstration Project

4.1. Condition of Tomakomai CCS Demonstration Project facilities before and after the Earthquake

Although CO_2 capture and injection operations were being implemented smoothly until September 1, the supply of CO_2 containing gas was stopped due to conditions at the CO_2 source as shown below, and accordingly, CO_2 injection was suspended. The CO_2 capture and injection facilities were kept in standby mode in order that injection could be restarted as soon as the supply of gas was resumed. However, the CO_2 source informed us on September 5 that the resumption of gas supply would be delayed, and the facilities were switched from standby to stop mode, after which the Earthquake occurred. Thus, although tremors exceeding 150 gal which would have activated emergency shutdown were detected, emergency shutdown of the entire facilities was not implemented.

Sept. 1 (Sat)	2:25	Supply of CO_2 containing gas feeding was stopped due to conditions of the CO_2 source, and CO2 injection was suspended. Facilities were maintained in standby mode.
Sept. 5 (Wed)	11:00	It became apparent that resumption of gas supply from the CO_2 gas source would be delayed.

	17:00	Operational mode of facilities transferred from standby to stop.
Sept. 6 (Thu)	3:07	Occurrence of Earthquake
	3:08	Detection of the Earthquake (local seismometer in the capture facility: 158 gal); outage of special high voltage electricity of Hokkaido Electric Power (Hoku-Den).
	3:25	Total blackout
	4:40	Uninterruptible power supply (UPS) of the capture and injection facilities stopped.
	Around 5:37	Monitoring operation stopped.
	8:00	Confirmation that there was no abnormality of facilities.
Sept. 8 (Sat)	11:18	Restoration of special high voltage electricity from Hokkaido Electric Power.
	12:15	Confirmation of power distribution to Tomakomai CCS Demonstration Center completed.
	14:50	Restoration of stop mode of capture and injection facilities prior to Earthquake (air, nitrogen, industrial water operation).
Sept. 9 (Sun)	15:00	Restoration of access to Internet.

Sept.10 (Mon) around 11:45: Monitoring operation of the project was resumed, except for Observation Well OB-3 (monitoring devices under routine inspection).

4.2. Framework of manuals for risk management

Prior to the startup of injection in April 2016, JCCS formulated in-house rules with regard to measures to be taken when emergencies such as disasters occur, on the basis of assumptions on actions required for possible emergencies. As for the framework of manuals, a set of risk management manuals (Figure 7) for each project element (onshore capture/injection facilities, offshore reservoirs, public relations) was established around a Basic Risk Management Manual. When the Earthquake occurred, this framework of manuals was applied, and actions were taken accordingly.

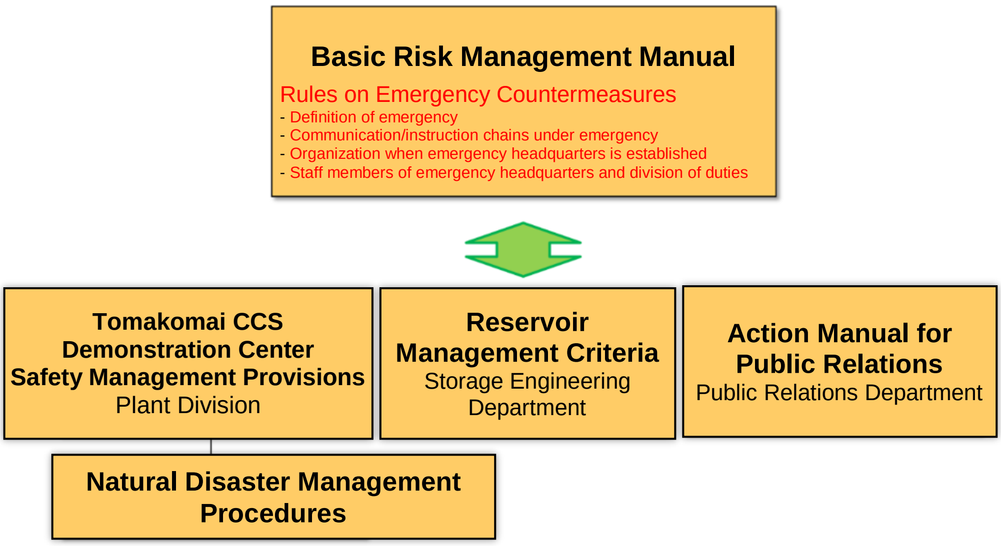


Figure 7: Risk Management Manual Framework

4.3. Risk management for onshore capture/injection facilities and present status

The framework of safety management provisions of the Demonstration Project Center is shown below (Figure 8). Relevant business laws are applied to the onshore capture/injection facilities, and CO_2 capture operations are implemented after obtaining permits and authorization from the relevant government ministries and agencies. Upon the occurrence of the Earthquake, the Natural Disaster Management Procedures were applied, and various actions were taken.

Regarding the onshore capture/injection facilities, JCCS had established an independent system employing an emergency shutdown system (ESD) that would safely stop, shut-off, and isolate when the facilities are in operation in case of occurrence of factors causing serious disasters (explosion, fire, environmental damage, human damage, important equipment breakage) or abnormal operation of the facilities. On this occasion, the capture facility was in a shutdown mode when the earthquake occurred. However, had the facilities been in normal operation mode, the ESD would have been activated as the accelerometer of the facility actually detected 158 gal, exceeding the in-house standard for shutdown of 150 gal.

In addition, regarding the safety equipment, we had set out multiple items for hypothetical abnormalities including the occurrence of a huge earthquake, and had implemented actions including installation of devices required for the safety equipment.

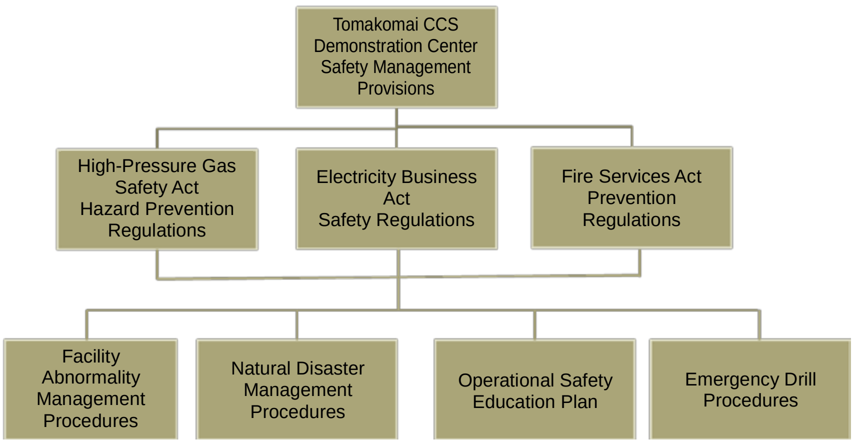


Figure 8: Safety Control Regulations System of Demonstration Project Center

On the other hand, we had not made provisions that addressed long-term power outage or loss of internet connection, and consequently, we incurred an interruption of data acquisition at the injection wells, observation wells and OBC (Ocean Bottom Cable), and inability of data verification (confirmation of data transmission to general monitoring system and situation from maintenance sites) caused by the disconnection of data transmission lines from the observation wells and the onshore seismometer. Accordingly, the issues were analyzed and remedies were proposed as follows:

- ❑ Issues to be avoided
  1. Power outage in Demonstration Project Center
     - Operation-related equipment, office equipment, and communication equipment become unusable.
     - Data acquisition of temperature and pressure sensors in the injection wells is no

longer possible.

- Data acquisition of the seismic sensors of the OBC is no longer possible.
- Data acquisition of the seismic sensor of the OBS (wired type) is no longer possible.

2. Power outage at observation wells
    - Data acquisition of the temperature and pressure sensors and seismometers (monitoring) of the observation wells is no longer possible.
3. Disconnection of communication lines from the observation wells and onshore seismometer
    - Real-time confirmation of the measurement records of the observation wells and onshore seismometer is no longer possible.

- ❑ Measures for improvement (introduction of new equipment)
    1. Demonstration Project Center: Emergency power supply (80 kVA)
    2. Injection wells: Battery (12V, 130 Ah) for the data logger
- ❑ Estimated cost/rental cost: Approx. 8.1 million yen/year (Items 1&2 of above measures for improvement)
- ❑ Remaining issues when the improvement measures are implemented
    1. Observation wells: Possibility that interruption of data acquisition occurs
    2. Observation wells/onshore seismometer: Possibility that the measurement records cannot be confirmed real time when the lines are disconnected

JCCS proposed the implementation of the above measures for improvement, and no objection from the committee members was expressed.

4.4. Risk management of CO_2 reservoir and present status

With regard to the CO_2 reservoirs, the provisions of the Reservoir Management Criteria during CO_2 Injection prepared by JCCS are applied, and the judgment of abnormalities and actions are stipulated therein.

4.5. Relationship to Act for the Prevention of Marine Pollution and Maritime Disasters

The Marine Environment Monitoring program of the Act for the Prevention of Marine Pollution and Maritime Disasters stipulates that “When an earthquake with maximum acceleration of 150 gal or greater occurs and the CO_2 separation/capture and injection equipment are subjected to an emergency stop, pressure/temperature data of the formations shall be confirmed, and water sampling survey shall be implemented.”

With regard to this Earthquake, although acceleration of 158 gal was measured at the capture/injection facilities, the situation does not fall under the above-stated requirement of the Marine Environment Monitoring program because the facilities and the CO_2 injection were in stop mode due to conditions of the CO_2 source since September 1 (Confirmation by METI with the Ministry of the Environment on September 6).

5. Relationship of CO_2 Injection and Earthquake

Regarding this Earthquake, although evaluations and investigations have already been made by experts in the national Earthquake Research Committee of the government, the relationship between the CO_2 injection of the Demonstration Project and the Earthquake has not been discussed. Therefore, by way of this review meeting, deliberations on the relationship between the CO_2 injection and the Earthquake were implemented by examining the monitoring data that were actually acquired in the Demonstration Project and simulations of CO_2 behavior, and the committee members reached a common understanding that the existence of a causal connection between the two was inconceivable.

5.1. Mechanism of earthquake induction

In 2011, prior to the startup of the project, an examination was conducted on the possibility that, when the underground storage of CO_2 was implemented, the friction force on the crack surface would be reduced by pressure rise of the fluids existing in the cracks of bedrock including faults, and accumulated strain would be released, thereby inducing earthquakes. We reviewed the 2011 evaluation, and also examined the impact of the CO_2 injection of the Demonstration Project on the earthquake source fault of the Earthquake.

5.1.1. Examination of earthquake induction in the reservoir and cap rock by CO_2 injection

In 2011, the "Evaluation of the possibility for inducing earthquakes by CO_2 injection" was implemented by the National Institute of Advanced Industrial Science and Technology (AIST). In the evaluation, examinations and evaluations of the possibility that crack surfaces in the bedrock would slip due to the assumed total CO_2 injection of 750,000 tonnes (250,000-ton injection per year for three years) were conducted through simulations of stress changes.

In the examinations, time-dependent changes in the spatial distribution of the pressure rise of formation water and slip-tendency coefficients (a slip occurs when the shear stress/slip strength on slip surface exceeds 1) were estimated, and it was extrapolated when and where the possibility that earthquakes would be induced increased.

The calculation results of the spatial distribution of slip-tendency coefficients in the Moebetsu and Takinoue Formations revealed that the reservoir pressure increased up to about 2 MPa, but locations at which the slip-tendency coefficient rises to 1 were not detected; thus, it was believed that there was no possibility that fault slips would be caused (micro earthquakes would occur) by the CO_2 injection of the Demonstration Project.

5.1.2. Examination of the impact of CO_2 injection on the earthquake source fault

In order to examine the impact of the CO_2 injection on the earthquake source fault, we conducted simulations of CO_2 behavior at the end of the CO_2 injection with the assumed cumulative injection amounts (300,000 tonnes into the Moebetsu Formation, and 750 tonnes into the Takinoue Formation) using reservoir models updated by the actual injection record (as of July 2018), and we estimated anew the CO_2 distributions (Figure 9) and pressure rise (Figure 10) in the reservoirs. Regarding the Takinoue Formation, in which the rise in reservoir pressure would be largest, it was found that even when the pressure in the injection well was increased by about 5 MPa (considering the upper limit of the injection pressure), the pressure rise in the 50m area surrounding the injection interval reaches 2 MPa, reducing to approx. 0.25 MPa or less 1 km away. As for the Moebetsu Formation, the upper limit of the injection pressure of the injection well results in an increase by about 0.7 MPa, based on past injection records.

In addition, the stress change caused by the CO_2 injection near the epicenter located over 30 km away from the injection site was calculated to be about 1 Pa (equivalent to applying a pressure of about 0.01g/cm^2).[*2] In other words, the impact caused by the CO_2 injection was about 1/1,000 of stress changes exerted on the earth's crust by earth tides (several kPa), meaning that the impact is negligible when compared to that of the earth's tide.

Therefore, it is inconceivable that there is any relationship between CO_2 injection and the Hokkaido Eastern Iburi Earthquake. [*2] This result was obtained by an additional examination proposed by the committee members in the review meeting and commissioned to AIST following the meeting.

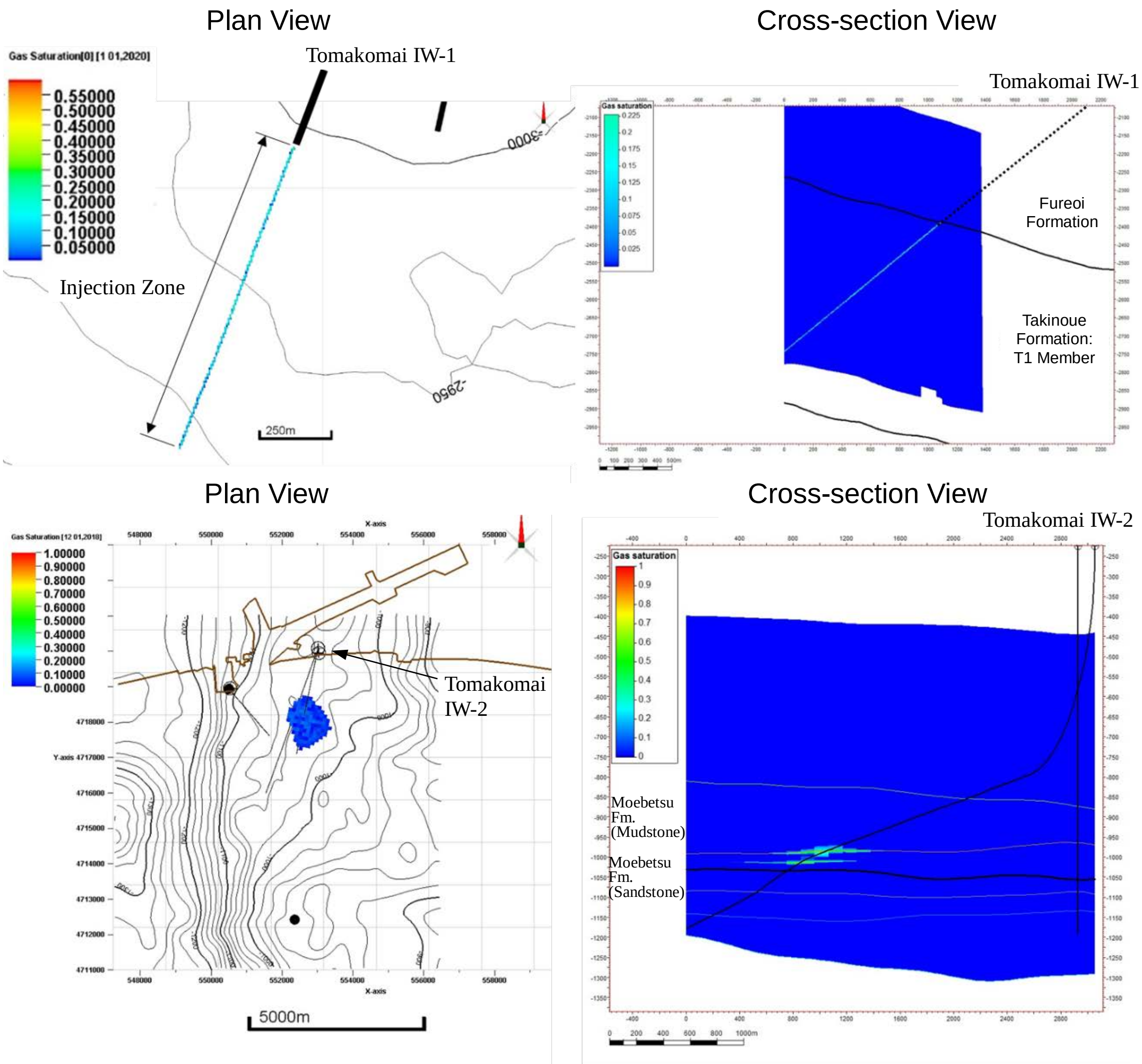


Figure 9: Prediction of behavior of stored CO_2: Degree of CO_2 saturation (at the end of injection); Takinoue Formation (Top), Moebetsu Formation (Bottom)

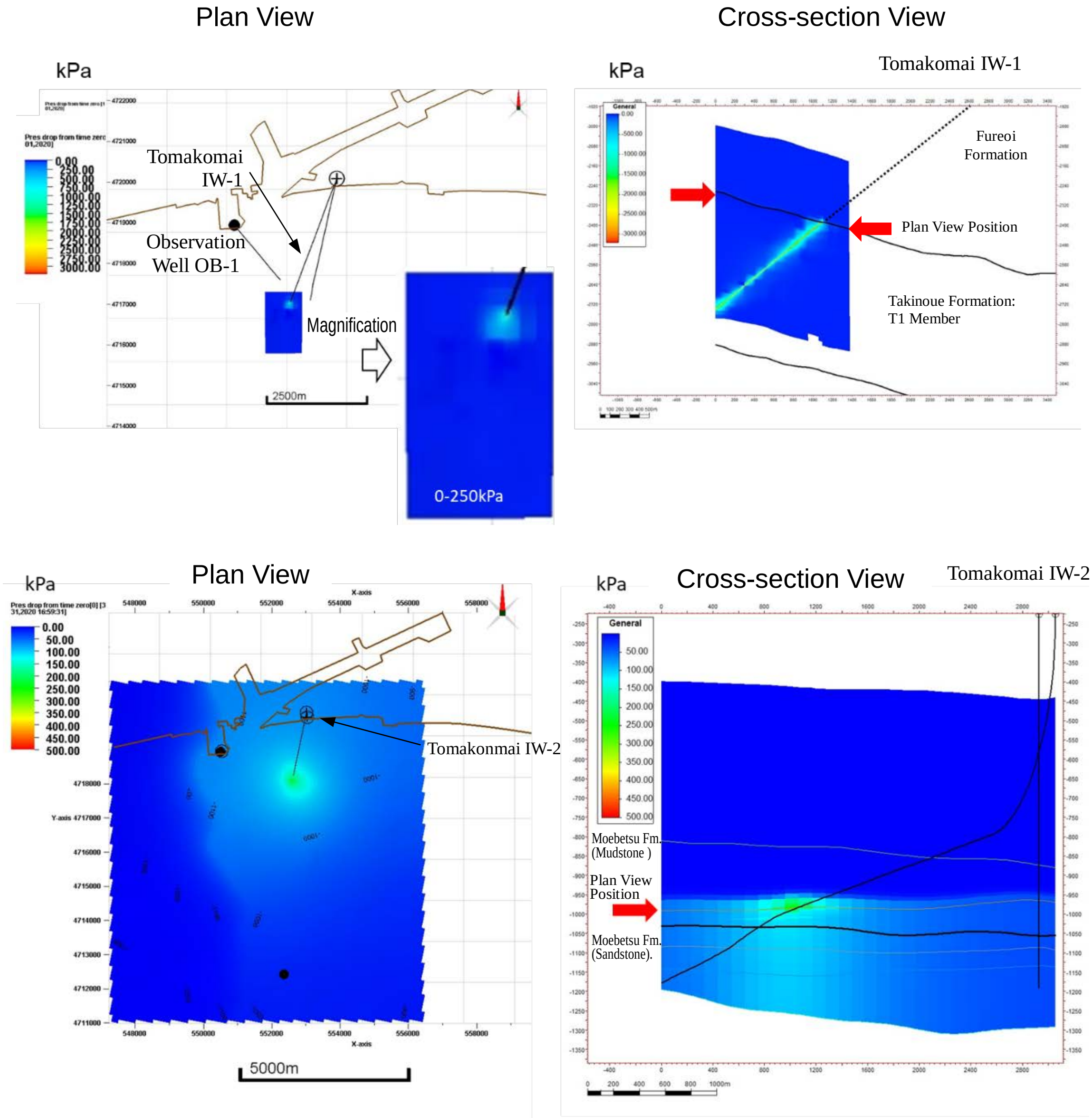


Figure 10: Prediction of behavior of stored CO_2: Pressure change (at the end of injection); Takinoue Formation (Top), Moebetsu Formation (Bottom)

5.2. Impacts on reservoir

5.2.1. Monitoring results of micro-seismicity/natural earthquakes

In this project, as shown in Figure 11, earthquake observation is being implemented by downhole seismometers installed in observation wells at three locations - two locations near the injection point and one location about 10 km to the east, an OBC (Ocean Bottom Cable : receiver line length of 3.6 km) permanently buried 2m below the seabed on a line crossing directly above the injection points, OBSs (Ocean Bottom Seismometers) installed at four points above and surrounding the injection points, and an onshore seismometer installed at a location about 6 km to the northwest of the injection points.

The above data is combined with four Hi-net government observation station data to monitor natural earthquakes covering ~~a~~ 50 km east-west, 38 km north-south and 50 km deep area shown in Figure 11.

In addition, within this area, a 6 km east-west, 6 km north-south and about 15 km deep area surrounding the injection point is defined as the Micro-Seismicity Monitoring Area ("monitoring area"), and focuses on the observation of micro-seismicity that could occur in association with the injection. In this observation system, seismic events[*3] having a magnitude of -0.5 or greater can be detected. [*3] Vibrations are to be called as events in the stage where the features of detected vibrations are not identified.

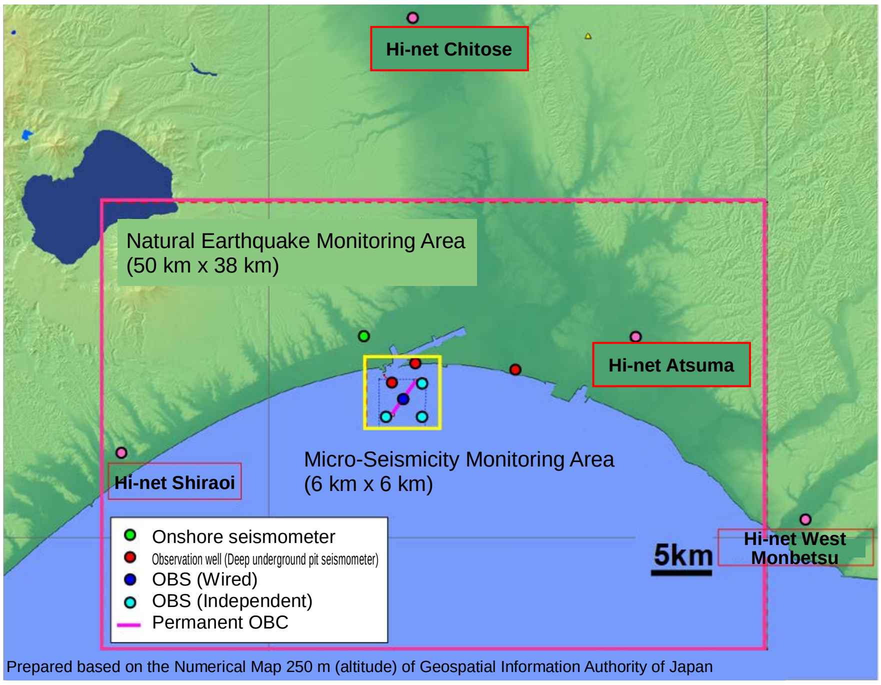
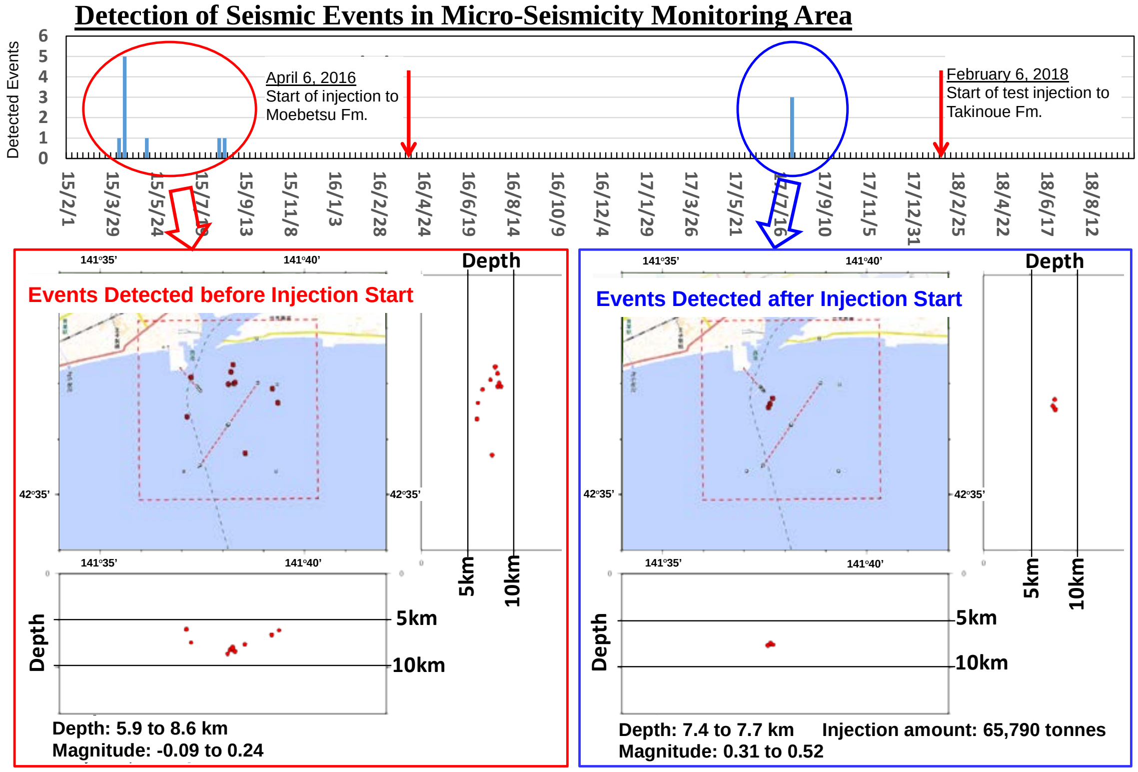


Figure 11: Allocation of Earthquake Observation Points and Monitoring Area

Figure 12 shows the number of micro-seismic events and estimated epicenter locations detected in the monitoring area during the period from February 2015 to the end of September 2018. Prior to startup of injection, nine micro-seismic events between April to August 2015 were detected in the monitoring area, and three events in August 2017 after the implementation of injection. These micro-seismic vents all occurred at a depth of about 6 km or greater, which meant that vibrations associated with the minimal scale natural earthquakes that could normally occur in the area were captured. After the three micro-seismic events in August 2017, no such events have been detected in the monitoring area, including the period before and after the 2018 Hokkaido Eastern Iburi Earthquake.



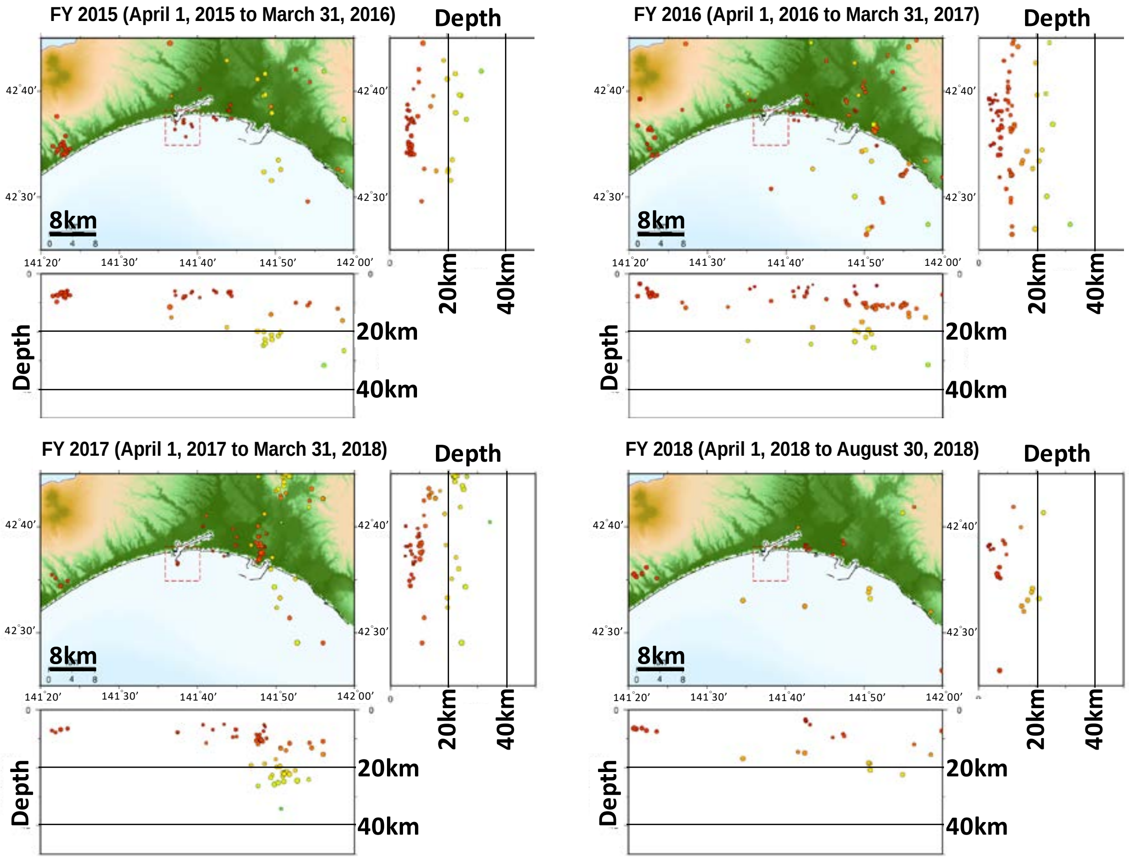
[Map source: Electronic Map (GSI Map) issued by Geospatial Information Authority of Japan; additions made by JCCS]

Figure 12: Event Detection Status in Micro-Seismicity Monitoring Area

Figure 13 shows the results of natural earthquake monitoring in the Natural Earthquake Monitoring Area for each fiscal year from 2015 to 2018 (results until the end of August for FY 2018). In each year, salient seismic activities are noted around the area south of Mt. Tarumae and the peripheral area of the southern part of the Eastern Boundary Fault Zone of the Ishikari Lowland and its extension. Although the seismic activity of FY 2017 is characterized by a concentration of small and micro-seismicity in the vicinity of the eastern division of Tomakomai Port, many small and micro-seismic events were detected in each fiscal year, and no salient time-oriented fluctuation was noted before and after startup of injection. In addition, no salient change was noted immediately before the occurrence of the Earthquake either.

After the occurrence of the Earthquake, though there is a gap in the data of the monitoring results of natural earthquakes until the end of September 2018 due to a power outage immediately after the main shock of the Earthquake and a periodic inspection, as a vast number of aftershocks are occurring in the vicinity of the hypocentral area, the aftershocks occurring near the hypocenter are being excluded from the monitoring as a temporary measure.

After the main shock, in accordance with the activation of the overall seismic activity around the hypocentral area, many small and micro-seismic events were detected near the eastern division of Tomakomai Port. As previously mentioned, because many small and micro-seismic events have been observed in this area since before the earthquake, these events are believed to be a part of the after-shock activities occurring after the main shock. In addition, though there is a salient increase in the number of occurrences, the hypocenter locations do not fall outside the hypocenter distribution prior to the Earthquake. Furthermore, no change in the seismic activity area corresponding to the Earthquake is observed in the vicinity of the storage location (Micro-seismicity Monitoring Area).



[Source: Made by JCCS based on GSI Digital Map. 250 m mesh (Altitude) and "Japan Oceanographic Data Center" 500 m mesh Depth Data of Japan Coast Guard]

Figure 13: Observation Results of Natural Earthquakes in 2015 to 2018 (Results til the end of August for FY 2018)

5.2.2. Monitoring results of temperature and pressure

In this project, temperature/pressure observation is being implemented in the injection wells with high-precision sensors using silicon oscillation devices. Figure 14 shows the observation results of temperature/pressure in the injection wells for the three months from July 1 to September 30, 2018. In the Takinoue Injection Well (IW-1), test injection was resumed on July 30, 2018, and in the Moebetsu Formation Injection Well (IW-2), full-fledged injection was resumed on July 25, 2018. However, the injection had been stopped due to the stoppage of CO_2-containing gas supply from the source on September 1, 2018, prior to the occurrence of the Earthquake, and the pressures in both injection wells were on a downtrend as a result of the injection stoppage. The downhole temperature when the earthquake occurred was on an upward trend in IW-1 because the injection CO_2 temperature was lower than the formation temperature. On the other hand, in IW-2, the downhole temperature was on a downward trend because the injection CO_2 temperature was higher than the formation temperature. As shown in Figure 14, although there is a gap in the data due to an island wide blackout, there is no change in the trends before and after the earthquake.

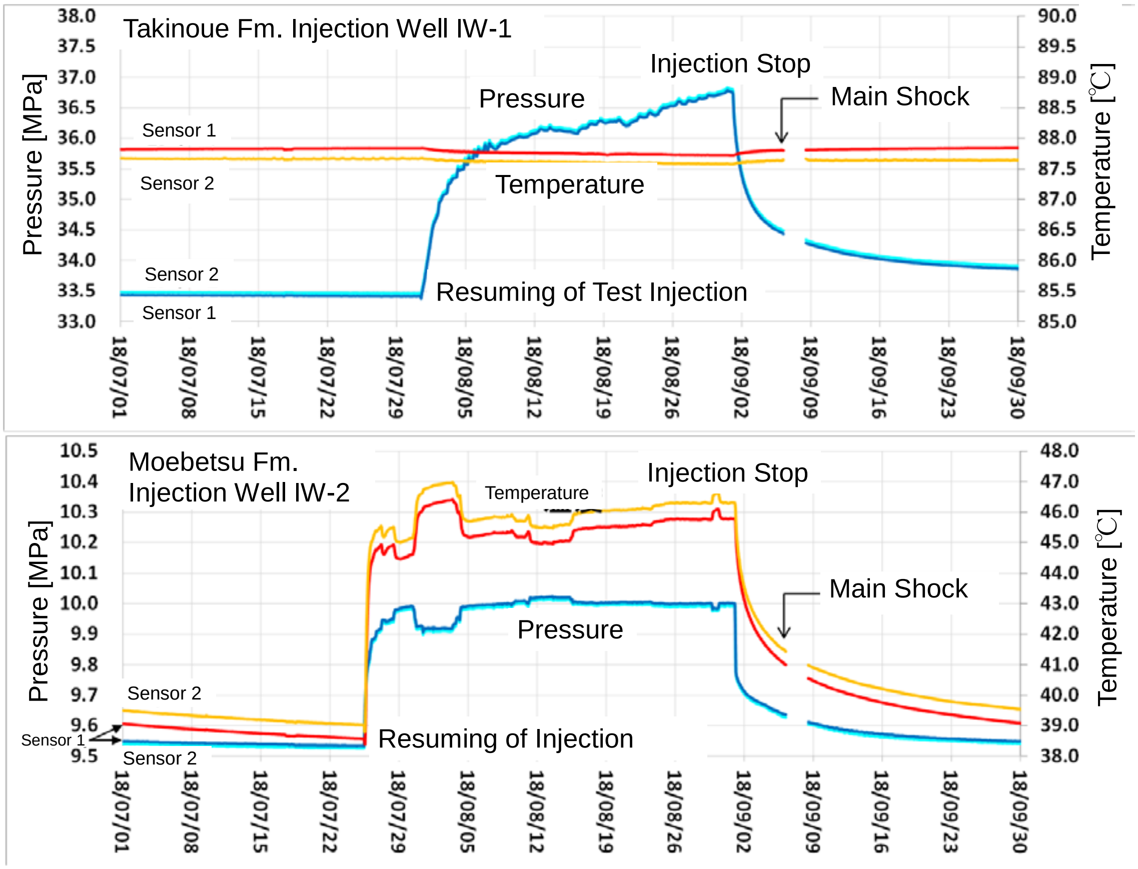


Figure 14: Observation Results of Temperature/Pressure in Injection Wells before and after Hokkaido Eastern Iburi Earthquake of 2018

It should be noted that, the pressure rise during injection in IW-1 reflects an injection test to investigate the relationship between the injection amount and pressure, wherein the pressure had been increased to 37 MPa, which was lower than the upper pressure limit (38 MPa).

From a broad perspective, though no change in temperature and pressure behavior attributable to the earthquakes was found, a very slight rise in the downhole pressure in IW-1 was noted just after the main shock, as shown in Figure 15. The downhole pressure rose abruptly by about 1.8 kPa[*4] just after recording the main shock, decreasing as time elapsed and approaching asymptotically the trend of pressure drop before the main shock. The rate of pressure drop during the three hours before the earthquake was about 3.8 kPa/h. Although the complete situation is unknown because data recording stopped 95 minutes after the occurrence of the earthquake due to a power outage, it can be inferred from the asymptotic trend that the downhole pressure returned to the original downward trend within several hours. [*4] The pressure right before the main shock is about 34.49 MPa, and 1.8 kPa is about 1/20,000th thereof.

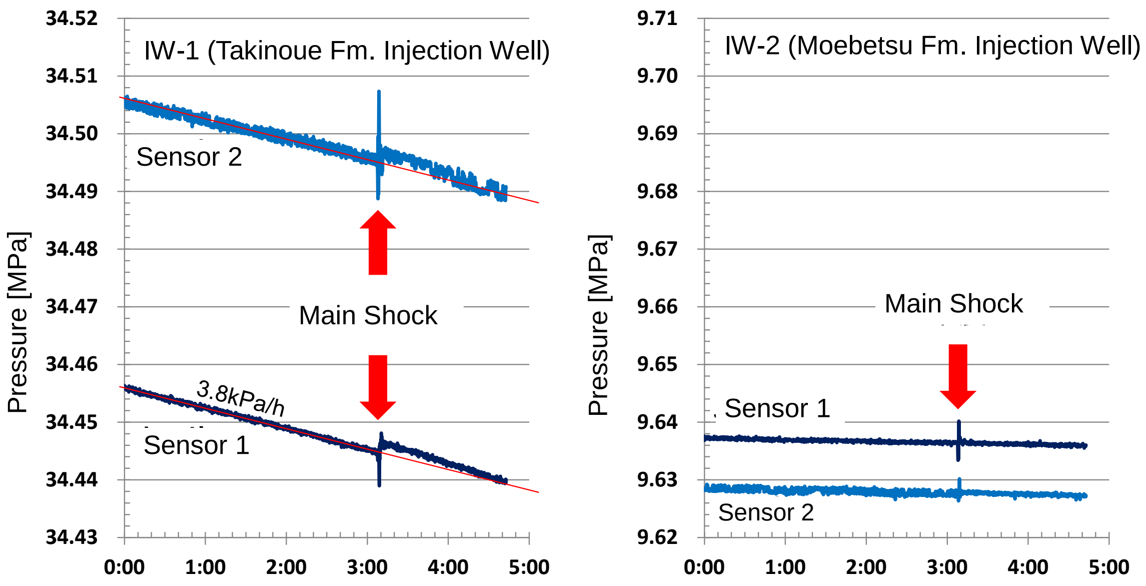


Figure 15: Micro Variations in downhole Pressure right after Hokkaido Eastern Iburi Earthquake of 2018 (Vertical scale is unified to 0.01 MPa.)

It is possible that the pressure rise observed here can be deemed a certain type of co-seismic variation*5, and the causes of co-seismic pressure variations include variations in bulk strain caused by static crustal deformation associated with fault displacement at the epicenter of the Earthquake.

Regarding this static crustal deformation, JCCS asked Professor Toda of the International Research Institute of Disaster Science, Tohoku University, to prepare a model of the earthquake source fault, taking into consideration the distribution of initial aftershocks of the earthquake, and to calculate an estimate of pressure variations at the observation point. Figure 16 shows a model of the earthquake source fault, and Figure 17 shows the distribution of bulk strains calculated by this model. According to this calculation, the injection point is located in a compressional field, and the formation fluid pressure will rise after the earthquake. Figure 18 shows the normal stress variations*6 calculated by assuming the strike and dip of the reservoir of N45°W/10°NE to the bulk strain distribution obtained here. At the injection point of the Takinoue Formation, the formation fluid pressure is calculated to rise by about 1.9 kPa.

The calculation result using the model matches the observation result (rise by about 1.8 kPa), and it is possible to explain the observed pressure rise as a static crustal deformation associated with fault displacement at the epicenter.

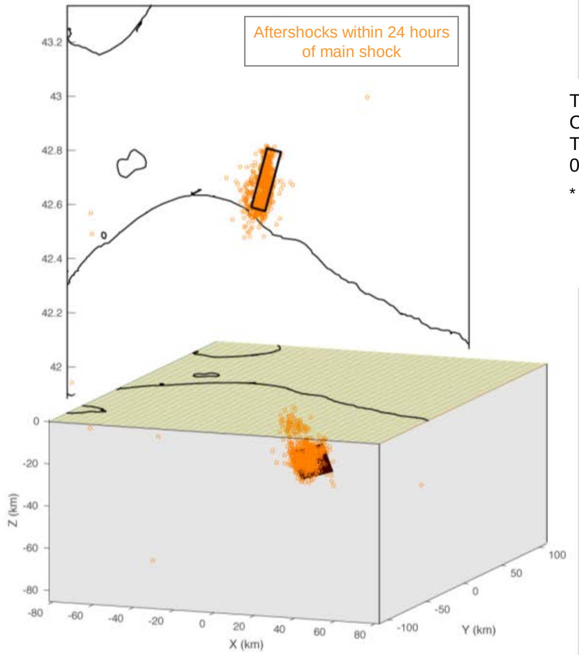
Therefore, as the model calculation result can explain the observed result in a rational way, and because the variation of 1.8 kPa is extremely small, the pressure variation observed does not indicate any abnormality in the reservoir (rupture of the geological formation resulting in leakage of CO_2, etc.).

As a result of the discussions above, the committee members reached the common understanding that no CO_2 leakage caused by the earthquake occurred.

*5 Phenomena of changes (co-seismic) when an earthquake occurs, which include fluctuation in groundwater level.

*6 Stress change that work perpendicularly on the fault surface.

Fault Model	Longitude [°]	Latitude [°]	Depth of Upper Margin [km]	Length [km]	Width [km]	Strike [°]	Dip [°]	Rake [°]	Slip Amount [m]	Mw
Aftershocks Distribution Model	141.920	42.591	30.0	25.0	13.9	15	65	90	0.9	6.6



The homogeneous, isotropic and semi-infinite elastic body of Okada (BSSA, 1992) was used.
The assumed Young's modulus is 80 GPa*; Poisson's ratio is 0.25.

* When the modulus of rigidity of 32 GPa which is generally used in earthquake seismology is adopted, where the modulus of rigidity is E and Young's modulus is PR, the Young's modulus G can be expressed as follows:
G = E/(2(1+PR)) = 80 GPa

Model where the initial aftershock distribution is taken into consideration (Earthquake Source Fault Model)

Figure 16: Model of Earthquake Source Fault

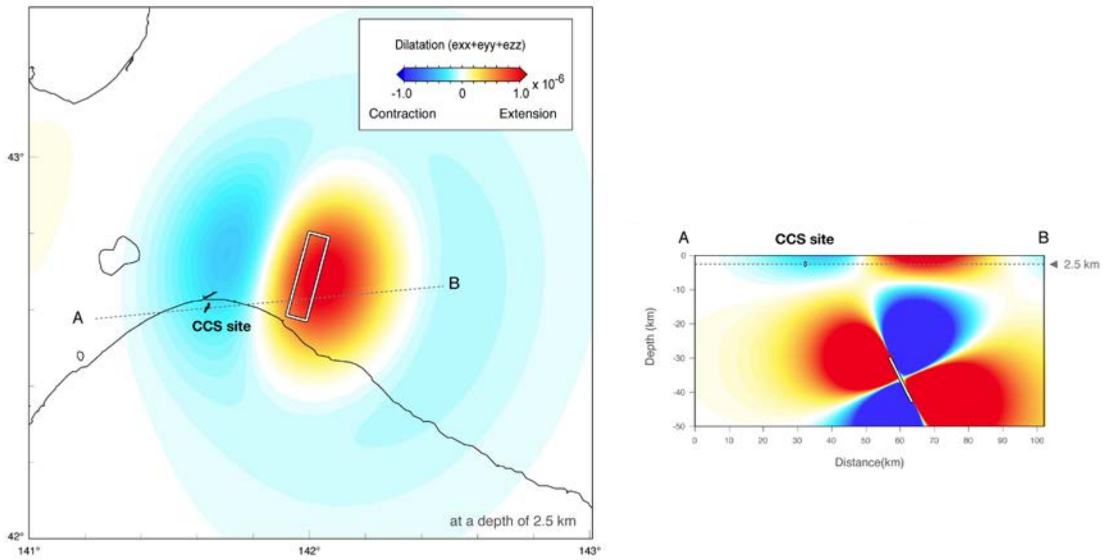


Figure 17: Calculation Result of Bulk Strain

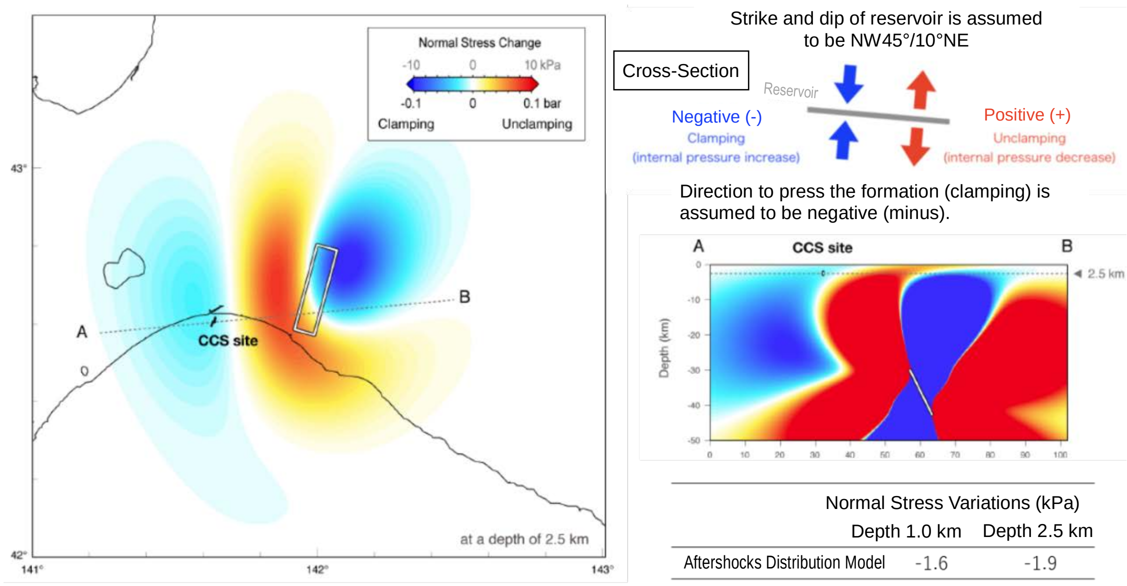


Figure 18: Calculation Result of Normal Stress

6. Future Plan

Regarding the implementation of the Tomakomai CCS Demonstration Project, JCCS takes actions based on the "Guidelines for Safe Implementation of a CCS Demonstration Project" (METI, August 2009). The document includes "Measures to be taken for settling abnormalities" in anticipation of cases such as the occurrence of large-scale earthquakes. Though on this occasion, there was no abnormal situation as there was no damage caused by the earthquake to the facilities and no emergency shutdown was executed, we used the document as a reference for actions to be taken after the occurrence of the Earthquake.

Specific actions in light of the guidelines include the following:

(1) Discussions by persons concerned for taking actions

A "Review Meeting on the Tomakomai CCS Demonstration Project"[*7] was held on October 19, 2018. [*7] A JCCS internal committee consisting of external advisers

(2) Survey of impacts of the earthquake

- Grasping of trends of aftershocks
- Confirmation of restoration operations including separation/capture/injection facilities
- Inspection of the monitoring facilities (Normal activation of facilities)
- Confirmation of integrity of injection wells (Observation of downhole temperature/pressure)
- Grasping of situation of the reservoirs (Occurrence of micro-seismicity, downhole temperature/pressure of each observation well)
- Review of monitoring data (Calculation of stress change attributable to the Earthquake in injection wells)
- Seismic exploration (Confirmation of CO_2 storage state)
- Marine environment survey (Summer survey completed; autumn survey to be implemented in November)
- CO_2 containing gas supply status (Grasping of situation of gas source; confirmation of

supply commencing time)

- Review of countermeasures, etc. taken
- Securement of electric power during power outage

(3) Explanation to local stakeholders[*8]

JCCS will make efforts to conduct reporting/explanations of the results of the review meeting (explanations will be commenced by the end of October) for obtaining understanding of stakeholders. [*8] Tomakomai City Government, Tomakomai Fisheries Cooperative Association, Hokkaido Federation of Fisheries Cooperative Associations, etc.

In the future, actions to be taken will be done so based on the contents of the “Guidelines for Safe Implementation of a CCS Demonstration Project”. JCCS explained that, if the operation of the facilities of the CO_2 containing gas source resumes, the CO_2 containing gas will be supplied; therefore, regarding the restart of injection, we will make efforts to first obtain the understanding of local stakeholders as we investigate the integrity of the capture/injection facilities and the injection wells and the trend of aftershocks, and obtained the understanding of the committee members.

Furthermore, regarding the content of the review meeting, JCCS explained its policy to prepare the report immediately and include the contents in the annual progress report to be submitted to NEDO at the end of the current fiscal year, and obtained the approval of the committee members.

Ends

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Research Report on Impacts of Hokkaido Eastern Iburi Earthquake on CO_2 Reservoir

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