Strategy for carbon dioxide emissions reduction and CCS policy in Japan

*Sadayuki Kamada[1], Takeshi Nagasawa[2]

1.Tomakomai City, 2.Ministry of Economy, Trade and Industry(METI)

Widespread adoption of CCS technology could be key to limiting global average temperature increase. Supporters of carbon capture and storage technology say CCS needs to be brought to scale to limit global warming. This presentation covers an introduction on current status of research and development on CCS technology and CCS policy in Japan. Main topics are listed below.
1) overview of the Tomakomai large scale demonstration project
2) potential storage site survey
3) R&D of CO2 capture and storage technology
4) international collaborations
5) Japanese goverment's policy on CCS

Keywords: CCS, policy, CO2

Incentives for operational CCS projects in the World

*Ryozo Tanaka[1]

1.Research Institute of Innovative Technology for the Earth

CCS is recognized as a promising technology to fulfill an ambitious target of CO2 emission reductions. But the advancement of its deployment has been very slow than expected and acute growth in deployment cannot be anticipated at least for a short term. One of the reasons behind is the lack of economic incentives to compensate costs of CCS deployment. Then what are driving forces for existing large-scale CCS projects? There are currently 15 operational and 7 under-construction large-scale CCS projects in the world. The half of these projects have inherent CO2 separation in the production process and sell the captured CO2 to enhanced oil recovery (EOR) operation. This combination generally requires no additional investment for the installation of CO2 separation and can generate revenue by selling CO2. The remaining half has an additional CO2 capture facility and/ or use a saline formation as a CO2 reservoir. To fill a financial gap, these projects receive public funding and/ or enjoy other forms of financial incentives such as carbon credit, tax credit and avoidance of carbon tax. This presentation analyses factors making existing projects financially feasible and financial incentives implemented for future projects in major countries.

Development of geological model using core-well-seismic integration technique at the Nagaoka CO_2 storage site, Japan

*Takuma Ito[1], Takahiro Nakajima[1], Ziqiu Xue[1]

1.Research Institute of Innovative Technology for the Earth

When utilizing saline aquifers as a geological storage site, available dataset is limited due to their sparse geological information. Under such conditions, however, development of geological model is essential for site characterization. To overcome this condition, applying core-well-seismic integration technique appears to be one of the feasible solutions in addition to use of existing available dataset. Here we propose a geological modeling procedure using saline aquifer for geological storage of CO_2. The proposes are (1) to identify the depositional environments and the sequence boundaries used as a stratigraphic framework of a geological model, (2) to make the voxel model using the sequence boundaries, and (3) to show the spatial gamma-ray, porosity and permeability distributions using core-log-seismic integration technique as a case study of the Nagoaka site.
In the Nagaoka project, total of about 10,000 tons of CO_2 was injected into the saline aquifer, which situates about 1,000m depth below the Niigata Plain. The target saline aquifer is correlated to the early Pleistocene Haizume formation. During the project, one injection well (IW-1) and three observation wells (OB-2, -3 and -4) were drilled. Sediment core of the target reservoir rock was taken from the IW-1, and well log data was obtained from all of the wells. During CO_2 injection to date, detailed monitoring has been made by well logs to monitor CO_2 behavior in the underground.
Firstly, we carried out facies analysis and grain size measurements using the sediment core materials to identify depositional environment of the reservoir rock. Detailed sedimentological features indicate that the reservoir rock has fining-upward to coarsening-upward successions that developed on ravinement surface. The reservoir rock is attributed to a part of prodelta and deltafront deposits. Prodelta and deltafront deposits can be divided by mud content of about 40% as a threshold value at the Nagaoka site.
Secondly, we used geophysical logs at each well for stratigraphic correlation of the reservoir rock. Comparison between core and geophysical logs at the IW-1, profile of natural gamma-ray show similar pattern with that of mud content. Thus, prodelta and deltafront deposits can be divided by natural gamma-ray value of about 75 API. This fact indicates that natural gamma-ray value can be used as identification tool for depositional environments at the Nagaoka site. We defined the sequence boundary and correlated it at each wells. Moreover, we confirmed that positive correlation exists between natural gamma-ray intensity, porosity and permeability. The above information is used when constructing geological models.
Lastly, we used 3D seismic data for defining a stratigraphic framework. For making a stratigraphic framework, we defined the two sequence boundaries above and below the reservoir rock. The sequence boundaries were traced spatially by Petrel (Schlumberger software) using multiple 3D seismic slices, and then a grid model of the reservoir rock was developed. Spatial natural gamma-ray and permeability models were constructed using GDI (Geological Driven Integration)-based spatial porosity model as a guide by Sequential Gaussian simulation with collocated cokriging.
A given spatial distribution of natural gamma-ray and permeability shows the eastern part of the reservoir has fine-grained and low permeability. This trend is similar with the paleogeography that the sediments were supplied generally from west to east based on the previous geological survey around the Nagaoka site. Moreover, the result of CO_2 monitoring suggests that the CO_2 migration is not uniform that its breakthrough has not been observed at the OB-3, where is located at the most

east side. This fact is also supported that a given geological model is reasonable.

Keywords: Geological storage of CO2, Nagaoka site, Sedimentology, Geological modeling, core-log-seismic integration

Construction of an integrated geological model characterized by a seismic survey data and calibrated by log-based monitoring data: A case study at Nagaoka CO_2 injection site

*Takahiro Nakajima[1], Takuma Ito[1], Ziqiu Xue[1], Shun Chiyonobu[2]

1.Research Institute of Innovative Technology for the Earth, 2.Faculty of International Resource Sciences, Akita University

This paper discusses a methodology for the site characterization of deep saline reservoirs evaluated through dynamic flow simulations. Not only the traditional site characterization techniques, but also the injection and monitoring data can be used for the geological modeling. In this study we carried out flow simulations using a geological model based on a seismic survey data and monitoring data after the CO_2 injection at Nagaoka site.
Nagaoka project was undertaken in order to verify an ability of CO_2 injection into Japanese formation. The target reservoir consists of marine strata at a depth of 1100m. Between 20 and 40 tons of CO_2 were injected and a total of 10.4 k-tones of CO_2 was injected into a thin permeable zone. Bottom-hole pressure measurement, time-lapse well loggings and cross-well seismic tomography were conducted using three observation wells drilled between 40m and 120m from the injection point.
For the modeling of the reservoir with heterogeneity, the method presented by Ito et al. (2016) was used; determined the sequence boundaries of the formation from the analysis of depositional environments, constructed a 3D reservoir framework by horizon picking of seismic trace, and developed a 3D distribution of reservoir parameter after the integration of lithologic records, well logging data, and 3D seismic attributes. It is worth to note that the heterogeneous feature from NNE to SSW direction can be seen in the revised interpretation model. For the hydrological properties we referred measured results as reported in Nakajima et al. (2015).
For the simulation of multiphase flow, we used TOUGH2/ECON2 simulator. The model was calibrated through the process of history matching to the bottom-hole pressure and CO_2 saturation. Several absolute permeability models were tested manually and good matches were achieved between monitoring data and simulated CO_2 behaviour. The results of CO_2 distribution were also consistent with the observed velocity anomalies from the cross-well tomography. The numerical results revealed the migration of CO_2 plume to up-dip direction along the most permeable zone during the post-injection period.
Sensitivity studies were conducted to investigate the effect of poorly constrained model parameters. We tested alternative parameters on absolute permeability, ratio of horizontal to vertical permeabilities, and pore compressibilities. We found that the effect of the ratio between horizontal and vertical permeabilities was relatively large, and pore compressibility had effects on pressure response. A small anisotropy in horizontal direction could also explain a better matching. These anisotropies could be created during the depositional process of the reservoir.
We will report the long-term fate of CO_2 in the reservoir to evaluate the contribution of the trapping mechanisms.

Keywords: CO2 geological storage, Nagaoka site, multiphase flow, trapping mechanism

Simulation study on trapping processes of CO_2 at Nagaoka pilot project

*Hajime Yamamoto[1], Takahiro Nakajima[2], Ziqiu Xue[2]

1.Technology Center, Taisei Corporation, 2.Research Institute of Innovative Technology for the Earth

Long term stability of CO_2 stored in reservoir is of intrinsic importance for ensuring the viability of geologic sequestration of carbon dioxide. Demonstrating the permanence of storage is an important task of pilot projects. In the Nagaoka project, Japan’s first pilot-test of geological CO_2 sequestration that injected about 10,400 tonnes of CO_2 from 2003 to 2005, a stable containment of CO_2 in a reservoir has been successfully demonstrated by kept monitoring the CO_2 behavior even after the end of injection during about 10 years. Systematic and continuous data acquisition of time-lapse well loggings (e.g., resistivity, neutron, and sonic velocity) successfully illustrated the detailed nature of CO_2 migration at intra-reservoir resolution.
In this study, a three-dimensional reservoir model with sub-meter spatial resolution has been developed with comprehensively involving coupled process of two-phase fluid flow and geochemical transport. The model was history-matched against a set of monitoring data acquired during the post-injection period including pressure, well loggings, and fluid samplings. The calibration of a large model is computationally demanding, hence we newly developed a parallel version of coupled fluid flow and geochemistry TOUGHREACT V2.0/ECO2N with MPI parallelism, in-house. The new code also features hysteretic effect in relative permeability and capillarity which was not implemented in the original TOUGHREACT V2.0.
The detailed 3D history matching study reproduced the observed distribution of CO_2 saturation at sub-meter scale over time. From the lessons learnt through the history matching study, the following insights into the trapping processes of CO_2 at the project have been obtained.
- During the injection, free CO_2 migrated preferentially through higher permeable layers. The uneven arrival times of CO_2 to the well-depths are well explained by, and consistent with the non-uniform permeability distribution measured at wells.
- Pressure-driven-flow during the injection squeezed the formation water out of the reservoir, and consequently resulted in hydrodynamic dispersion of dissolved CO_2 into over- and under-lying lower permeable layers. This behavior is highly consistent with the resistivity changes observed by well loggings.
- In the post-injection period, negligible vertical migration of free CO_2 suggests that even a thin, intra-reservoir muddy-layer behaves like an impermeable flow barrier to trap CO_2, by a combined effect of lower vertical permeability and high capillarity to prevent the invasion of CO_2.

Keywords: Reservoir Simulation, CO2 trapping, Nagaoka, Parallel Computation, TOUGH2

Subsurface monitoring using seismic interferometry for the large-scale CCS Demonstration Project at the Tomakomai Area

*Ryuji Niiro[1], Motonori Higashinaka[1], Susumu Abe[1], Makoto Tsuchiya[2], Hideo Saito[2], Ziqiu Xue[3], Tetsuma Toshioka[3]

1.JGI, inc., 2.Japan CCS Co., Ltd., 3.RITE

JCCS, commissioned from METI, deployed the permanent OBC (Ocean Bottom Cable), and seismic signal has been continuously recorded since July, 2014. The cable length of the OBC is 3.6km and the receiver interval is 50m, respectively.
The main purposes of this observation are the earthquake monitoring and the time-lapse seismic survey, what is more, subsurface imaging by seismic interferometry can be implemented by using the continuously observed data in the arbitrary spans of the 6 years monitoring period.
As the baseline survey, 3D seismic survey was already conducted in 2009 and 2D in 2013. Furthermore, periodic monitoring seismic surveys will be conducted after the start of CO_2 injection. Seismic surveys in which active sources are used provide reliable subsurface images, but those expensive costs make it difficult to conduct monitoring surveys frequently. As an alternative approach, passive seismic survey methods have a potential to delineate the temporal change of CO_2 plume distributions in the reservoir in a shorter period, because the seismic interferometry can be applied to any period of the continuous observation data.
In this study, we applied the seismic interferometry to local earthquake seismograms recorded by the permanent OBC. We begin with synthesizing the pseudo shot gathers by applying seismic interferometry to the P-wave and P-coda of 158 earthquakes which have occurred from January 1, 2015 to November 21, 2015. Note that the selected earthquakes are larger than magnitude of 2.0 and those hypocentral distances are longer than 48 km. Processing the pseudo shot gathers, we obtained the seismic images through the CMP stacking method. As a result, we can clearly image the reflector at the depth of the reservoir.
It is necessary to examine the repeatability, the relation between the number of seismic events and S/N of the passive seismic section to confirm its applicability in CO_2 monitoring.

Keywords: Seismic Interferometry, CO2, CCS, monitoring

Time-lapse observation and its interpretation in Al Wasse field in Saudi Arabia using ultra-stable seismic source

*Junzo Kasahara[1,2,4], Khaled Al Damegh[3], Ghunaim Al-Anezi[3], Kei Murase[4], Aya Kamimura[4], Osamu Fujimoto[4], Hiroshi Ohnuma[4], Yoko Hasada[5]

1.University of Shizuoka, Faculty of Earth Scieces, 2.Tokyo University of Marine Science and Technology, 3.KACST, 4.Kawasaki Geological Engineering Co. Ltd., 5.Daiwa Exploration and Consulting Co. Ltd.

1. Introduction

The Carbon Capture and Storage (CCS) is one of ways to reduce the CO2 radiation to the air. In CCS, CO2 is injected to the subsurface and is stored in the subsurface. Technologies of monitoring (time-lapse) of CO2 leakage from the storage zone have been studied in many institutions. We have used the ACROSS seismic source for the time-lapse and have tested the technology in Al Wasee field, Saudi Arabia after the air injection study in Japan (Kasahara *et al*., 2013). The same technology can be used in EOR (Enhanced Oil Recovery) and PRM (Permanent Reservoir Monitoring) cases.

2. Time-lapse observation in Saudi Arabia and data processing

The test site is a national water pumping field. Water is pumped up from aquifers around 400 m depth. The geology of this area comprises limestone, sandstone and unconsolidated sand. There is no seismic survey in this area before our study.

We used the ACROSS unit as an ultra-stable seismic source and 32 seismographs at 500 m spacing grids with distances between 500 m to 1.76 km. The source transmitted chirp signal from 10 to 40 Hz and the seismic waves were recorded by data-loggers. Because of so frequent power downs during the observation, the obtained data were intermittent. The transfer functions between the source and receivers were obtained by division of observed records by source signatures in spectral domain by the similar way as before (*e.g.*, Kasahara *et al*., 2013, 2015). By processing, we obtained the transfer functions corresponding to vertical and horizontal forces. As the interpretation of one-day stacked data, we used the refraction survey in 2015 (Kasahara *et al*., 2016; in this session).

3. Results

We obtained the transfer functions from April to December, 2015 for 30 stations, but the data are not continuous for whole period due to frequent power downs. The first arrivals disappear at the distance further than 1 km and large amplitude phase is dominant at the stations further than 1.5 km. The temporal variation in the arrivals later than 1.0 seconds is extremely large as same as that in April to June, 2015 (Kasahara *et al*, 2015). The first arrivals closer than 1 km do not give large temporal changes, which is similar to the previous results in April to June 2015

Using the refraction data obtained in 2015 we interpreted the phases. The first arrivals at the distance less than 1 km are refracted wave with 3.5 km/s travelling the upper limestone layer. The phase with large amplitude at the distance further than 1 km is estimated as refracted wave with 4.5 km/s travelling in the basement. This phase shows some temporal variation. The Raleigh wave could have large amplitude and this is dominated after refracted waves. The temporal changes in surface waves do not show coherent characteristics from one to another.

4. Discussion and conclusions

The presence of low velocity zone just below the 3.5 km/s layer makes difficult to interpret the temporal change. The first arrivals quickly decay at the distance further than 1 km by the low-velocity layer. At the distance further than 1 km, large amplitude phase refracted at the layer deeper than 800 m is dominant. The upper limestone layer does not show large temporal changes and the refracted arrivals show some temporal changes due to the migration of aquifer. The surface waves seem travel in the low velocity layer, and the temporal change of surface wave is so large and shows roughly week period. This may be caused by pumping of water from aquifer.

Acknowledgements
This survey was supported by JCCP (Japan Cooperative Center for Petroleum) in Japan and KACST in Saudi Arabia. We express our great thanks to members of JCCP and KACST for their aggressive support of this project.

Keywords: Time-lapse, ACROSS, shadow zone, refracted wave, low-velocity layer, aquifer

Geomechanical monitoring of caprock and wellbore integrity using fiber optic cable

*Ziqiu Xue[1], Tsutomu Hashimoto[1]

1.Research Institute of Innovative Tech for the Earth

We have been developing a new technology to monitor the caprock and wellbore integrity at CO_2 injection sites by utilizing the Distributed Fiber Optic Sensing (DFOS). DFOS has an advantage to measure temperature and strain at any point in an unprocessed optical fiber, contrary to the conventional Fiber Bragg Grating (FBG) sensing which measures temperature and strain at a limited number of discrete points along the processed fiber cable. To put the DFOS technique into the practical use at the CCS sites, we measured the frequency shifts of the Rayleigh and Brillouin scattering in an optical fiber attached to sandstone samples under hydrostatic pressure, and also measured strain of the samples by conventional strain gages simultaneously. Strains measured by optical fiber are estimated based on the frequency shifts and those strains agreed well with the strains by conventional strain gages. The experimental results demonstrated the potential use of DFOS as a promising technology for monitoring the geomechanical deformation of geological formation at the CO_2 injection site.

Keywords: CO2 geological storage, optic fiber sensing , integrity monitoring

Self-potential Monitoring Study for Geological Storage of CO_2 in AIST

*Yuji Nishi[1], Tsuneo Ishido[1]

1.National Institute of Advanced Industrial Science and Technology (AIST), Geological Survey of Japan, Institute for Geo-Resources and Environment

An appropriate monitoring program is important for an CO_2 geological storage project to detecting subsurface changes within the reservoir, to provide for potential risk, and to improve the predictive capability of reservoir simulation. AIST have studied passive geophysical monitoring method to reduce the repetition of the expensive seismic sounding, especially in post-injection period (Nishi et al., 2015).
The self-potential (SP) method is mainly used in volcanic or geothermal field to delineate thermal anomaly from streaming potential generated by subsurface fluid flow. In CO_2 geological storage site, SP changes due to stream-potential might be a promising geophysical tool to monitor pressure changes in shallower levels (Ishido et al., 2009).
SP anomaly just around a well could be another important target for SP monitoring. As subsurface changes in geochemical condition might change the well-casing SP due to geo-battery effect (Ishido et al., 2013), simple surface SP monitoring could be an early warning alarm for CO_2 plume arrival to the well bottom.
In the presentation, some of our recent advances in SP monitoring & modeling will be summarized.

Keywords: monitoring, self-potential, geo-battery

A Study on seismic stability safety evaluation of the cap rock for geological CO_2 storage using non-linear dynamic response analysis

*Shigeo Horikawa[1], Takeshi Sasaki[1], Naohide Takada[1], Tsutomu Hashimoto[1], Takahiro Nakajima[2], Ziqiu Xue[2]

1.Suncoh Consultants Co., Ltd., 2.Research Institute of Innovative Technology for the Earth (RITE)

Authors studied non-linear dynamic response analysis at the geological CO_2 storage site, and tried the seismic stability evaluation of the cap rock and the reservoir. The test site is the Nagaoka CCS site. The input earthquake motion used the wave of the 'Mid Niigata Prefecture Earthquake in 2004' recorded by the surface-type seismograph installed in this site. The engineering characteristic values of the foundation used for analysis inputted the numerical value acquired at this site.
In advance of dynamic response analysis, the earthquake motion recorded on the earth surface assumed the horizontally layer model, and set up the input wave from a basement layer (We assumed Shiiya Formation distributed from the depth of 1,370m) by SHAKE (= One-Dimensional Seismic Response Analysis). This wave was inputted into the analysis model and the equation of motion was solved using the direct integral calculus by Newmark Beta Method. In Seismic Response Analysis, authors have used Multiple Yield Model (=MYM, Two-Dimensional Finite-Element Method), which can respond also to complicated geological structure.
The intensity deformation property of the foundation added the offloading characteristic to the composition rule of Duncan-Chang model in consideration of confining stress dependency, and used for and carried out the non-linear repetition model. The deformation characteristic which made it depend on confining stress with the cyclic loadings and un-loadings, and combined Mohr-Coulomb's law as a strength characteristic. Analysis ranges are about 1.2km * 1.4km focusing on an injection well.
The maximum dynamic shearing strain of the cap rock was generated about 1.1E-04 after the end of an earthquake. Although the dynamic safety factor was 1.925 on the beginning, after the end of an earthquake fell 0.05 point. This result is equivalent to having fallen about 2.5% from the beginning, the influence on safety is slight.
As a result of CO_2 migration monitoring by the seismic cross-hole tomography, CO_2 has stopped in the reservoir through two earthquakes till the present after injection, and the leak is not accepted till the present. By the result of non-linear dynamic response analysis, we obtained a result in support of them. That is, it turned out that the stability of the foundation is not spoiled after the earthquake. By carrying out performance simulation using this non-linear dynamic response analysis by MYM, the prediction of the safety assessment in rock masses at the deep depth accompanying the occurrence of a massive earthquake is possible also at geological CO_2 storage site planned from now on.
Acknowledgements : The 5th and 6th authors were funded by the Ministry of Economy, Trade and Industry (METI), Japan under the contract research of ''Development of Safety Assessment Technology for Carbon Dioxide Capture and Storage''.

Keywords: Carbon Dioxide Capture and Storage, non-linear dynamic response analysis, seismic stability evaluation

Numerical study mitigation of pressure build-up mitigation by production of formation water during CO_2 injection

*CLAUDIA FUJITA[1], Yusuke Hiratsuka[1], Hajime Yamamoto[1], Takahiro Nakajima[2], Ziqiu Xue[2]

1.Taisei Corporation , 2.Research Institute of Innovative Technology for the Earth

Due to injection of supercritical CO_2 into the deep underground, the pressure in the geologic formation increases, first locally around the injection point, later spreads radially throughout the capture formation. The range of pressure increase depends on the injection rate, injectivity and reservoir volume. The increase of pressure in the reservoir may cause several problems, including fault reactivation.
In this study, numerical simulation was applied in order to investigate the effect of production of formation water to mitigate pressure build-up during CO_2 injection into the storage aquifer. The hypothesis, that it will be possible to reduce the pressure buildup in the reservoir during injection by applying pre-injection formation water (brine) production as proposed by Buscheck et al. in 2014 (dual-mode wells), or by production of brine at the same time during injection of CO_2 will be explored in this paper. Numerical simulations were conducted, using the TOUGH2/ECO2N code for non-isothermal, multi-dimensional coupled fluid and heat flow, developed at the Lawrence Berkeley National Laboratory (LBNL).
We employed a simple reservoir model based on available data of the large-scale CCS demonstration project at the Tomakomai area in Hokkaido, Japan. The efficiency and influence of different production/injection rates, reservoir volumes, and the appropriate arrangement of production / injection well on pressure build-up in the storage formation were tested. Three models (15 km x 8 km x 100 m, 24 km x 24 km x 100 m, and 5 km x 5 km x 100 m) with different volumes were employed, and two production / injection rates (200 kt/yr and 1 Mt/yr) were applied for generally three different cases. The first case was only injection of CO_2 for 100 years without previous production. The second case included previous production for 3 and 5 years with subsequent injection for 100 years. The last (third) case considered production of brine while injection of CO_2 by using a separate installed production well. Furthermore, for the third case, appropriate installation and management methods for the wells also were investigated.
In the case of pre-injection brine production, we found that due to production, pressure can be lowered in the storage formation effectively, but due to the recovery effect of pressure, after starting injection of CO_2, the pressure increases rapidly and reaches almost the same value after a view years comparing to the base case without initially production of brine, thus the pre-injection pressure lowering is only effectively for a short time. Regarding to the three different sizes, the results have shown that with smaller reservoir volume the pressure lowering effect increases in efficiency. The most promising result brought up the system of a separate production well and production of brine at the same time during injection. Here, the recovery effect is neglected during the injection, thus the pressure can be kept almost constant during injection.
Judging by the results, the conclusion that can be drawn is that pre-injection, or especially production and injection at the same time can be very effective in order to lower the reservoir pressure and avoid too much pressure build-up and harmful effects on the hydrogeological conditions due to high pressure rise in the storage formation. Even regarding the capacity of injectable CO_2, these methods can be applied to make CCS technology much more sufficient.
For these results, it has to be emphasized, that the effectiveness of the production strategies may highly depend on site conditions. Therefore, the results obtained in this study should be regarded as a preliminary evaluation for the Tomakomai site specifications. Further investigations would be

necessary, when more data becomes available through the site investigation and even operations.

Keywords: Carbon Capture and Storage, pressure build-up, production of formation water

An Experiment study on dynamic displacement and non-equilibrium dissolution for CO_2 in porous media

*LANLAN JIANG[1,2], Ziqiu Xue[1], Hyuck Park[1], Yongchen Song[2]

1.Research Institute of Innovative Technology for the Earth, 2.Dalian University of Technology

A clear understanding of the displacement and dissolution processes in porous media is of importance for CO_2 trapping mechanism during geological storage. The porous media were filled with quartz glass beads. CO_2 and water injection with different flow rates in porous media were investigated using MRI. The intensity of MRI images decreased with CO_2 injection and increased with water injection in the longitudinal sections at various times. Flow patterns in the drainage, changed with different flow rates. However, water imbibition proceeded as the uniform displacement front even with the fast flow rates. The residual CO_2 saturation after imbibition was sensitive to the capillary number and initial CO_2 saturation. As capillary numbers increased, viscous forces dominated the flow resulting in a decreasing in CO_2 phase trapping. At high initial saturation range, the residual saturation decreased with initial CO_2 saturation. For post imbibition, CO_2 dissolution dominated the mass transfer reflecting the transition from capillary trapping to solubility trapping. The concentration of supercritical CO_2 (ScCO2) decreased sharply during imbibition and slightly during post imbibition. In contrast, lots of gaseous CO_2 dissolved into water during post imbibition. The dissolution rate for $ScCO_2$ was around the order of magnitudes 10^{-6} - 10^{-7} $Kg/m^3.s$.And the CO_2 saturation during post imbibition decreased. The study visualization measured dynamic drainage and imbibition processes and investigated the influence of dissolution to trapping characteristics which is useful for CO_2 geological storage.

Keywords: capillary trapping, dissolution, CO2 saturation, geological storage, flow pattern

Effects of stress relaxation and clay mineral contents on permeability changes of mudstones during fracturing processes

*Takashi Fujii[1], Masao Sorai[1], Xinglin Lei[1]

1.National Institute of Advanced Industrial Science and Technology

An understanding of fluid transport within aquifers plays an important role for geological CO_2 storage (GCS). During CO_2 injection into the reservoirs, a change in stress induced by increasing pore pressure might lead to deformation of surrounding reservoir rocks including caprocks, and this might also result in occurrence of seismic or aseismic slip along fractures/faults because of decreasing rock matrix and fault strengths. Thus, the presence of fractures and faults into caprocks such as mudstones and shales should provide an impact on the relationship between hydraulic properties (i.e., permeability and capillary pressure) and rock deformation. A few studies on measurement of permeability during shear fracturing in mudstones have been reported so far, but evolution of permeability throughout fracturing, slipping, stress-relaxing and variations of effective pressure levels processes has rarely been investigated. The objective of this study is to measure experimentally a change in permeability in a series of complex processes from fracturing to effective pressure dependency for mudstones. Particularly, we investigate impacts of stress relaxation and clay mineral contents on permeability evolution in response to variations of effective pressure levels which assume change in stress within targeted reservoirs resulting from the occurrence of overpressure. In this study, permeability tests were performed by employing the four steps: (i) fracturing, (ii) slipping, (iii) stress-relaxing, and (iv) effective pressure dependency at temperature of 40°C and effective pressure ranging from 2 to 15 MPa (confining pressures: 12-25 MPa and pore pressure: 10 MPa at constant) for two mudstones. The two samples tested were taken from GCS demonstration site of Tomakomai in Hokkaido (DS) and lower formation of Tentokuji in Akita associated with screening of all GCS sites in Japan (SS). Based on mode analysis of mineral compositions, it was shown that majority of mineral compositions for the SS sample was about 70 vol.% smectite-rich matrix. On the other hand, for the DS sample, little clay minerals was observed. Our results demonstrated that the rock samples tested exhibited brittle failure behaviours in stress-strain curves. As for the process (iii), it was apparent that permeability values measured after the long relaxation time (almost 7 days) were a significantly more susceptible to change in effective stress than that after the short time within 1 day. A comparison result showed that for the DS sample, magnitude of change in permeability values with decreasing effective pressure for the DS was almost two times larger than that for the SS sample relative to permeability values in the stress-relaxation state. This result showed that in the case of lower contents of clay minerals such as smectite and kaolinite, if the pre-existing fractures/faults into such mudstones had several events of tectonic movement over a long period, it might possibly lead to slipping behaviour easily due to the decrease of effective pressure induced by CO_2 injection. Also, it is further shown that its degree of slipping and magnitude of change in permeability could be depending strongly on the types of mudstones such as clay mineral contents.
The present results should be pointed out that time of stress relaxation and clay mineral contents could provide a significant impact on change in permeability against effective pressure levels depending on the types of caprocks.

Keywords: Stess relaxation, clay mineral contents, change in permeability, mudstones

Influence of flow pattern of two-phase fluid flow on deformation of mudstones

*Hiroki Goto[1,2], Tomochika Tokunaga[2], Masaatsu Aichi[2]

1.JSPS Research Fellow, 2.University of Tokyo

Injection of carbon dioxide into geological formations may result in ground surface deformation. In order to control the ground surface deformation, understanding deformation of rock mass caused by infiltration of carbon dioxide is required. In this study, laboratory experiments were conducted to understand deformation of mudstones caused by infiltration of non-wetting phase fluid. In the experiment, air was injected into a water-saturated cylindrical mudstone sample, which belongs to the Umegase Formation of the Kazusa Group, under hydrostatic external stress condition. During the experiment, both axial and circumferential strains at half the height of the sample were monitored. Numerical simulation of the experiment was tried by using a simulator which can solve coupled two-phase fluid flow and deformation of porous media (Aichi, 2010). Calculated strains were larger than the measured ones. Considering the pore size distribution of the mudstone and the pressure condition set in the experiment, air was thought to flow through preferential flow paths in the sample. Since preferential paths of air were not formed in the numerical simulation due to two-phase fluid flow based on Darcy’s law, flow pattern of two-phase fluid flow is suggested to affect deformation of mudstones.

Reference:

Aichi, M. (2010), Thermodynamically consistent multiphase poroelasticity and its application to water-dissolved gas reservoir simulation, PhD Thesis, Dep. of Geosys. Eng., Univ. of Tokyo.

Keywords: Geological sequestration of carbon dioxide, Mudstone, Deformation, Two-phase fluid flow, Laboratory experiment

In-situ observation of water, oil and coal under high CO_2 pressure for CO_2-EOR and ECBMR

*Yuichi Sugai[1]

1.Kyushu University

In geologic CO_2 sequestration, the pH of formation water may be reduced due to CO_2 dissolution, which may cause the change of porosity and permeability of reservoir rock. The pH changes of formation water are widely varied depending on CO_2 pressure and the content of substances having pH buffering action, therefore, it is important to determine the wide range of pH change of various types of formation water under the various CO_2 pressure conditions. We considered a determination method of pH change of various types of formation water under the various CO_2 pressure conditions based on the spectrophotometry using a windowed high-pressure cell and a mixed pH indicator consisting of 4 single pH indicators. The well-defined absorption peaks were found at the wavelength of 614 nm or 444 nm when the pH of the solution was ≥5.6 or <5.6 respectively, therefore, two different calibration curves were derived from the absorbance of standard pH buffer solutions at each wavelength. The validity of this method was confirmed by an experimental result that the pH change of deionized water under 0.1 MPa CO_2 pressure had been determined accurately by this method. We carried out experiments on this method using the real formation water samples which contained bicarbonate ion having pH buffering action with different concentration under various CO_2 pressure. The results of the experiments demonstrated that this method is capable of determining the pH change of various types of formation water under various CO_2 pressure conditions.
Oil swelling is an important phenomenon in CO_2-EOR. According to various studies in the past, the degree of oil swelling depends on the partial pressure of CO_2, temperature, and oil composition. However, we expect that other factors, such as oil saturation, capillary pressure, and grain size of reservoir rock must be also considered in evaluating oil swelling because they may influence the interfacial area between oil and CO_2, which affects the dissolubility of CO_2 in oil. Therefore, we had made clear the effect of the interfacial area on oil swelling in this study. Oil and CO_2 were injected into a small see-through windowed high-pressure cell and oil swelling was observed under a microscope. The swelling factor increased with the increase of the specific interfacial area between oil and CO_2. Moreover, oil swelling in porous media was observed by using micro-models which had been made of 2 different diameter glass beads. Swelling factor in fine beads micro-model became larger than that in coarse beads micro-model whose interfacial area between oil and CO_2 was smaller than that of fine beads micro-model. Therefore, the swelling factor is expected to be larger with an increase in the interfacial area in porous media. These results suggest that the oil swelling should be expressed as a function of oil saturation, capillary pressure, and grain size of reservoir rock which are related to the interfacial area as well as the partial pressure of CO_2, temperature, and oil composition.
Coal swelling is also an important phenomenon in CO_2-ECBMR. The reduction of permeability of coal seam will be caused by the swelling phenomenon. The coal swelling should be controlled by a certain method in order to prevent the permeability reduction. Coal and CO_2 were injected into a small see-through windowed high-pressure cell and coal swelling was observed under a microscope. The coal swelling became smaller as the temperature was higher. This result suggest that the coal swelling can be controlled by heating the coal seam around the injection well.

Keywords: CO2, water, oil, coal, pH, swelling

Field experiment of carbonate reactions in the CO_2-injected hot spring waters

*Masao Sorai[1], Munetake Sasaki[1]

1.Research Institute for Geo-Resources and Environment, National Institute of Advanced Industrial Science and Technology

On geological CO_2 storage (GCS), the evaluation of the injected CO_2 behavior over a long time requires the numerical simulation considering geochemical processes. Among such geochemical processes, both precipitation and dissolution of carbonate minerals are important from each perspective of storage potentials and leakage risks. However, there have remained many uncertainties on their kinetics under conditions of GCS.
In this regard, to obtain reliable dataset on carbonate kinetics, we have performed reaction experiments of carbonate minerals at bicarbonated springs, which can be regarded as a natural analogue of GCS. Specifically, an input of CO_2 gas and Mg ions into spring waters allowed to highlight the effects of these chemical species on the reaction rate and precipitating phase of carbonate minerals under natural conditions. Previous experiment injected CO_2 at an atmospheric pressure. Under this condition, the solubility of CO_2 was too low (i.e., the pH was too high) to dissolve carbonate minerals. This time, we tried to change the pH lower by injecting high pressure CO_2 using a stainless-steel tube.
The experiment was performed at the Utoro hot spring in Hokkaido, Japan. In this site, the spring water from a well was stored once in a tank, and then it was flew down through a pipe 50 meters long. We created the bypass system, where the spring water pumped up from the tank was flowed through a stainless-steel tube. After passing through the tube, the water was thrown down the existing pipe. Three sample holders were arranged in series within a tube; each holder set cleaved crystals of major carbonate species, calcite and aragonite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$), and magnesite ($MgCO_3$). These samples were dipped into the flowing water over a period up to 24 hours. Then, the holder was taken out one by one at predetermined time. Present experiments included reactions injecting the CO_2 gas at 0.3 MPa with and without addition of magnesium chloride (i.e., Mg/Ca = 0.5, and 3, respectively), along with reactions in the untouched spring water.
Reaction rate was estimated from measurements of the height level difference between original and reacted surfaces by using a phase-shift interferometer and a laser microscope. The CO_2 injection tests resulted in the dissolution of calcite and aragonite. Although both dissolution rates were almost equal, addition of Mg ions induced an opposite trend: calcite dissolution rate was reduced by nearly half, whereas aragonite dissolution rate was slightly increased. On the other hand, the optical microscopic observation showed no obvious changes on dolomite and magnesite surfaces. These results suggest that the dissolution rate of carbonate minerals depends on both water compositions near a CO_2 injection well and mineral species of carbonates, and that the kinetics for carbonate reactions associated with GCS cannot be uniformly defined.

Keywords: Geological CO2 storage, Bicarbonated spring, Dissolution rate, Reaction kinetics, Carbonate minerals

A numerical model for calculating the behavior of leaked CO_2 in the sea for assessing the potential impacts on the marine environment

*Keisuke Uchimoto[1], Yoshimasa Matsumura[2], Jun Kita[1]

1.Research Institute of Innovative Technology for the Earth, 2.Institute of Low Temperature Science, Hokkaido University

To mitigate global warming, the reduction of carbon dioxide (CO_2) in the atmosphere is indispensable. We should make every endeavor to do it. Among options for it, CO_2 capture and storage (CCS) is thought to be one of the most important ones. Captured CO_2 in major CO_2 emission sources, such as power plants, is transported into deep geological formations and stored there. In Japan, mainly off shore areas will be selected as the storage sites. There is still concern that stored CO_2 may leak out into the sea and that leaked CO_2 may impact the marine organisms. To diminish the risk of CO_2 leakage, it goes without saying that it is necessary to select the storage sites and the formations where CO_2 will be stored stably and safely. In addition, we should enhance scientific knowledge and develop methods to assess the potential marine environmental impacts in case the stored CO_2 should leak out. How much the marine environment or organisms will be impacted depends on the rise in the CO_2 concentration in seawater consequent on the leakage.
Aiming at calculating dispersion of leaked CO_2 in the sea, we are developing a numerical model. In JpGU 2015 meeting, we presented a model where the leaked CO_2 dissolved into seawater (ΔDIC) is represented as a passive tracer. In the model, CO_2 bubbles were not calculated. However, it is considered that CO_2 would leak out from the seafloor mainly as bubbles. CO_2 bubbles from the seabed rise in the water column, dissolving into seawater. These processes may affect the distribution of ΔDIC because the dissolution rate and the movement of CO_2 bubbles depend on the size of the bubbles, and temperature and salinity of ambient water. Therefore, we have incorporated CO_2 bubbles into the model. The model is based on a non-hydrostatic ocean model, named kinaco, which has a Lagrangian particle tracking scheme. To represent CO_2 bubbles in the model, we apply properties of CO_2 bubbles, such as the mass and volume, to the particles. Based on the size of bubbles, and temperature and salinity of the cells that the bubbles exist in, the buoyancy and the dissolution rates are calculated. According to them, the movements and the sizes of CO_2 bubbles are computed. CO_2 dissolved into seawater is dispersed as ΔDIC, which is calculated as a passive tracer in the model. In our presentation, details of the model and examples of the calculation with the model will be presented.

Keywords: potential marine environmental impacts, carbon dioxide capture and storage, numerical model

The cost of CO2 capture and storage

*Yasuhide Nakagami[1], Jyunichi Shimizu[1], Ichiro Saito[1], Masato Takagi[1]

1.Research institute of innovative technology for the earth

Carbon capture and storage (CCS) has been widely recognized as a key technology for mitigating global climate change, but the relatively high cost of current CCS systems remains a major barrier to its widespread deployment at power plants and other industrial facilities. The objective of my presentation is to assess the current costs of CO2 capture and storage (CCS) for new fossil fuel power plants.

Keywords: CCS, cost, CO2 storage

Compilation of Best Practice Manuals toward CCS commercialization

*HIRONOBU KOMAKI[1], Michimasa Magi[1], Atsusi Ibusuki[1], Osamu Takano[1], Ziqiu Xue[1]

1.Research Institute of Innovative Technology for the Earth

The first CO_2 aquifer storage project was started at Sleipner, Norway in 1996. Following after Sleipner, many CO_2 geological storage projects were started in the world. Various Best Practice Manuals or Guidelines are made to summarize the knowledge and experience obtained from the existence projects.
For example, the European Commission provided Guidance Document published in four. These Guidance Documents "CCS directive" present rules related to CCS implementation to the EU member countries. On the other hand, the United States EPA (Environmental Protection Agency) provided many "UIC Class Ⅵ Well Guidance". DOE (The United States Department of Energy) was promoting preparation of a BPM (Best Practice Manuals) based on the knowledge experience of the CCS projects. As described above, accumulated experience and knowledge of pilot-scale tests involving CCS projects are analyzed and reviewed and adopted, and preparations are being made overseas for full-scale implementation of CO_2 storage subsurface.

Foreseeing domestic and global CCS deployment in future, RITE has been compiling “CCS Best Practice Manuals” as a technical reference for Japanese companies to carry out CCS projects. As best practices in Japan, we have been summarizing mainly various technical aspects of the CO_2 injection test carried out in Nagaoka from 2003 to 2005. We have also been collecting and sorting out best practices in the USA RCSP (Regional Carbon Sequestration Partnership) and Europe.

Standard process flow of the CCS project is shown below. We classify the whole CCS process flow it takes into 8 phases. It consists of 8 phases, i.e. basic planning, site screening & selection, site characterization, master planning, design & construction, operation, injection cessation & well plug and abandon, post injection monitoring, post closure monitoring, and post closure liability transfer. Each phase correspond to individual chapter. Chapter 1, first step design relevant information is collected from within Japan and overseas, sorted and analyzed, and key aspects and major data of the Nagaoka CO_2 Pilot-Scale Injection Test are sorted out and summarized in parallel. Then, based on results from research and development conducted by RITE, a RITE version of the CCS best practice manual is compiled, and as a final step, a Japanese version of the CCS best practices manual is to be developed, incorporating the large-scale demonstration project in Japan.

Keywords: CCS, CO2 geological storage, Best Practice Manual

Refraction study using ACROSS seismic source to interpret the time-lapse data in Al Wasse field, Saudi Arabia

*Junzo Kasahara[1,2,3], Ghunaim Al-Anenezi[5], Khaled Al Damegh[5], Kei Murase[3], Hiroshi Ohnuma[3], Osamu Fujimoto[3], Aya Kamimura[3], Yoko Hasada[4]

1.University of Shizuoka, Faculty of Earth Scieces, 2.Tokyo University of Marine Science and Technology, 3.Kawasaki Geological Engineering Co. Ltd., 4.Daiwa Exploration and Consulting Co. Ltd., 5.KACST

Introduction

To understand the physical change of subsurface by injection of CO2 or vapor into the ground, we are proposing the time-lapse method using the very stable ACROSS (Accurately and Routinely Operated Signal System) seismic source and an array of seismometers for our studies.

In 2011, we carried out the time lapse study in Awaji Island by the injection of air into the ground and showed the clear migration of air just after the air injection (Kasahara *et al.*, 2013). In 2012, we moved the whole system to the water pumping site in Al Wasse, Saudi Arabia. In the test site, there are no seismic structural surveys in past. By our study in this field, we observed very rapid and large temporal changes during several months (Kasahara *et al*., 2015). No structural data and sparse seismic stations in 500 m grids make difficult to explain the cause of temporal change seen in observed data. To solve this problem, we carried out refraction and reflection studies. In this paper, we report the first part.

Survey and processing:

Water is pumped up by more than 64 wells from aquifers at ~400m depth. The geological information is very poor. The surface of ground is partly covered by loose-sand and limestone pebbles.

The total length of survey line was 3 km. We used the ACROSS as the seismic source and placed 60 data loggers on the surface with 50 m spacing. The each sweep was 10 to 40 Hz during 200 seconds and an hour data contain 16 sweeps. The direction of rotation of ACROSS was switched every hour. One day data were recorded by data loggers with 200 Hz sampling and 24 bit A/D.

Recorded data were processed by similar way to the previous one (*e.g.*, Kasahara *et al*., 2013 and 2015). We compared observed and synthetic waveforms. The synthetic waveform was calculated by FDM. We used vertical single force with 20Hz Ricker wavelet as the source.

Results

The records show that the first arrival has approximately 3.5km/s and tend to disappear around 700 m in offset distance. Later phases of 3.5km/s phase show weak amplitudes, but they disappear for further distance than 1.7km. The strong later arrivals with 4.5 km/s appear and become dominant at further than 1.5km/s.

The comparison of observed and synthetics suggests the presence of low velocity layer just about of 3.5km/s layer. The 4.5km/s phase seems the refracted phase from the deeper basement layer with velocity of 4.5-5km/s. The layer between 3.5km/s and 4.5km/s is thought to be inter-bedding of sand stone and limestone with velocity lower than 2.5km/s. The negative gradient of inter-bedding layer could explain the decay of amplitudes of 3.5km/s phase with distance.

Discussion and conclusions

The observed data show very weak first arrivals even if the offset distance of 1km. As shown in our results in Kasahara *et al.* (2015), the temporal change of the first arrivals is as much as 1-1.5ms during two months at the largest case. On the other hand, the most of large amplitude later phase show slower arrivals and seems Rayleigh waves in the present study. The rapid change of waveforms with time suggests the rapid migration of water in aquifers due to the pumping. The continuous monitoring stations are located at the grids of 500m distance and it is still difficult to explain the magnitude of migration. The refracted arrivals from 4.5km/s layer is only identified a few grid stations and it is also difficult to find this phase.

Acknowledgements
This survey was supported by JCCP (Japan Cooperative Center for Petroleum) in Japan and KACST (King Abdulaziz City for Science and Technology) in Saudi Arabia. We express our great thanks to members of JCCP and KACST for their aggressive support of this project. We also express our great thanks to staffs in KACST for the hard works during the survey.

Keywords: Time-lapse, ACROSS, crustal structure, shadow zone, aquifer, water pumping

Application of Sequentially Discounting AR Learning (SDAR) Algorithm to Real-time Event Detection

*Makiko Takagishi[1], Tetsuma Toshioka[1], Akira Narita[2], Nobuhiro Furuse[2], Ziqiu Xue[1]

1.Research Institute of Innovative Technology for the Earth, 2.MITSUBISHI SPACE SOFTWARE CO., LTD.

Microseismic monitoring is one of the most variable monitoring techniques at the CO_2 injection site to demonstrate safe CO_2 injection operation to stakeholders. Microseismic monitoring has been conducted at major CO_2 injection sites. Real-time and accurate detection of seismic events from huge recorded data enables reliable event locations. The seismic events include microseismicity induced by CO_2 injection and natural earthquakes.

Real-time signal detection methods have been studied with the development of the seismic monitoring. For example, the detection method using thresholds of amplitudes, STA/LTA method (Coppens, 1985), the detection method by combination use of AR model and Akaike Information Criterion (Yokota et al., 1981) have commonly used to detect seismic events. These methods are very effective for seismic events with good S/N ratios and are used to detect natural earthquakes. On the other hand, microseismic events induced by CO_2 injection usually have small magnitudes around M0 or less than M0. At offshore CO_2 injection sites, the data recorded by the seismometers deployed on the seabed usually have high noise levels, therefore the event detection method which are robust to noise are highly required.

Recently, we have been developing a new event detection method using Sequentially Discounting AR Learning (SDAR) algorithm, which can eliminate unwanted noise properly and can detect seismic events with small magnitudes in a real-time basis. The SDAR algorithm expresses non-stationary time-series data with AR model in a short period of time. The algorithm renews the short-term AR model corresponding to the new data over discounting the old data. Therefore, this method can detect rapid changes of time-series data in a real-time basis without giving information in advance. The algorithm was originally developed in information and communication fields and have been used to detect unauthorized or break-in access (Takeuchi and Yamagishi, 2006).

At the meeting, we will introduce our real-time seismic event detection method using SDAR algorithm.

[References]

Coppens, F., (1985) : First arrival picking on common-offset trace collections for automatic estimation of static correction: Geophysical Prospecting 33, 1212-1231.

Takeuchi, J., and Yamanishi, K.(2006) : A Unifying Framework for Detecting Outliers and Change Points from Non-Stationary Time Series Data, IEEE Trans. on Knowledge and Data Engineering, 18(4), 482-492.

Yokota, T., Zhou S., Mizoue, M., Nakamura, I. (1981): An Automatic Measurement of Arrival Time of Seismic Eaves and Its Application to an On-line Processing System, Bulletin of Earthquake Research Institute, 55, 449-484. (In Japanese with English abstract)

[Acknowledgement]

This work was funded by the Ministry of Economy, Trade and Industry (METI), Japan under the contract research of ''Development of Safety Assessment Technology for Carbon Dioxide Capture and Storage''.

Keywords: CO2 Geological Storage, Sequentially Discounting AR Learning (SDAR), Real-time Event Detection, Microseismic Monitoring

Estimation of supercritical CO_2 threshold pressure by the mercury intrusion method and direct method

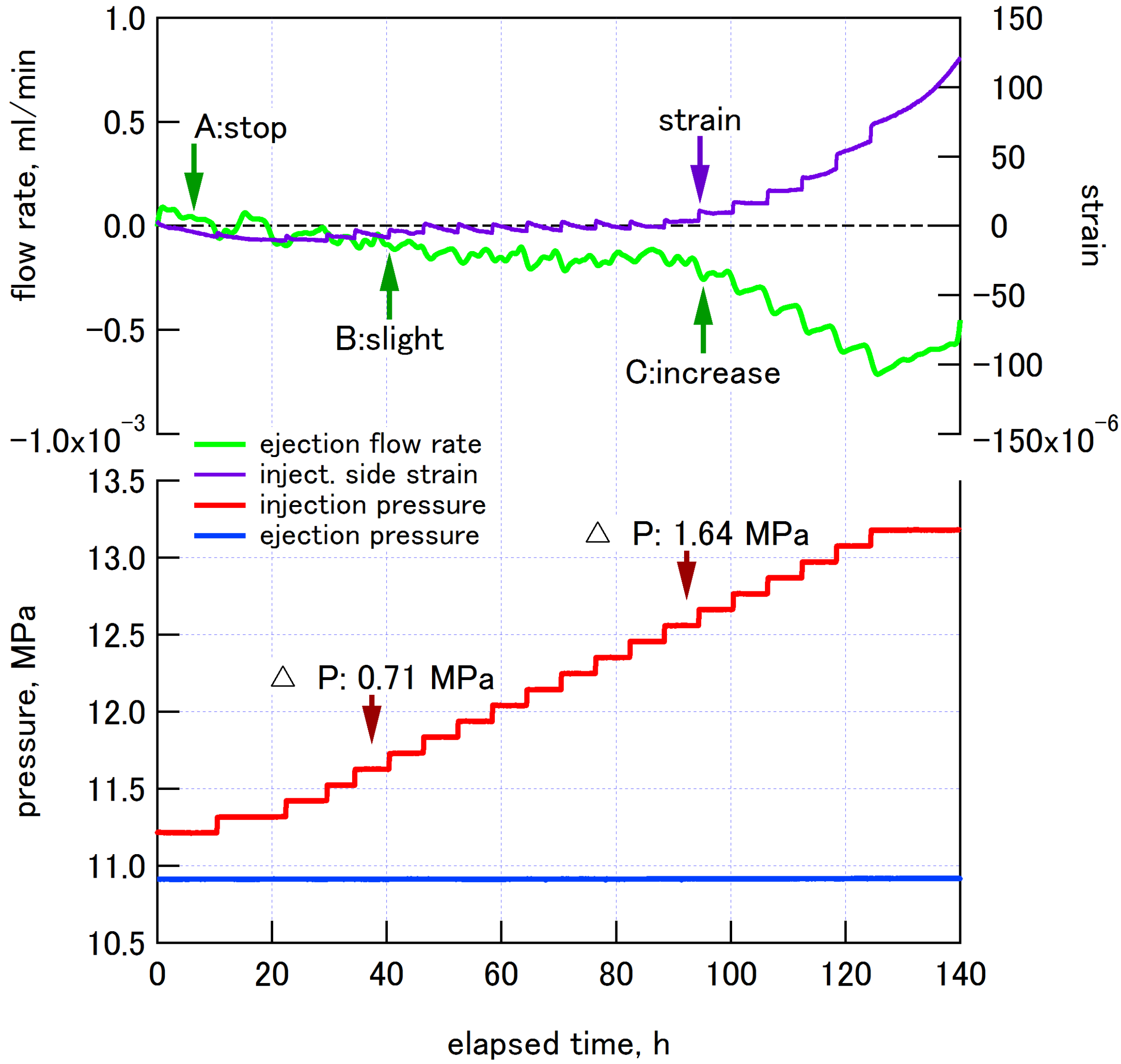
*TAMOTSU KIYAMA[1], Ziqiu Xue[1]

1.Research Institute of Innovative Technology for the Earth

In order to perform safety and economical design of CO_2 geological storage, the precise estimate of the threshold pressure of the cap rock to determine the CO_2 storage capacity of the reservoir is important in the CCS. Threshold pressure caused by capillary pressure at which to penetrate supercritical CO_2 into the porous rocks saturated with brine, is governed by pore size distribution, interfacial tension and contact angle. At first, the pore size distribution of Tertiary mudstone was analyzed by mercury intrusion method. Capillary pressures were estimated with contact angle, interfacial tension and pore throat diameter. Then using a core sample, threshold pressure was measured by the direct method such as step by step method and residual pressure method. In the experiment, pore pressure was 10MPa, temperature was 40 ℃, the diameter of specimen was 50mm, length 50mm, and was attached to the strain gauge in the circumferential direction at the position of 10mm from the both end faces.
Before the step by step method, the residual-pressure method was applied, and then flushed water sufficiently in order to return to the initial state. Threshold pressure was estimated to 0.60MPa by the residual pressure method. Flow rate is stopped at point A in the figure of the step by step experiment; it suggests that supercritical CO_2 has reached to the face of the specimen. A slight increase of flow rate was confirmed at point B. Threshold pressure was estimated to 0.71MPa by the step by step method. However, Flow rate did not increase although the differential pressure was increased. Then obvious increase of flow rate was observed at point C, flow rate also increased with the subsequent differential pressure increases. Here, the threshold pressure is estimated to 1.64MPa. A slight inflatable strain was observed at point B, significant inflatable strain was observed at point C the flow rate was increased obviously.
Results of the mercury intrusion method, pore size distribution showed bimodal characteristic with a peak at 0.09μm and 0.16μm. Capillary pressure Pc, is expressed as pore size D, interfacial tension γand contact angle θ.
$Pc = 4\gamma\cos\theta / D$
where γis the interfacial tension of brine and supercritical CO_2: 28.5 mN / m, θis the contact angle: 0 °at 40 ℃ and 10MPa, the capillary pressures were estimated 1.27MPa and 0.71MPa respectively corresponding to the two mode diameters.
The 0.71MPa estimated by step by step method and the 0.6MPa estimated by residual pressure method were consistent with the 0.71MPa calculated by the pore size of 0.16μm with the equation described above. Also the 1.65MPa estimated by step by step method at which the flow rate increased obviously was consistent with the 1.27MPa calculated by the pore size of 0.09μm.
The reason for the flow rate followed by a slight flow did not increase is related to volume, distribution and continuity of the pore. Such information are not be obtained by the mercury intrusion method because of hydrostatic condition.
Residual pressure method is reported easily under estimation of threshold pressure as compared to step by step method. The capillary pressure corresponding to the mode diameter of 0.16μm in this case coincides with the result of the residual pressure method. As the equilibrium of pressure is observed after stopping flow in the residual pressure method, it is conceivable that asymptotically approaches the capillary pressure so that the pressure propagates in the displacement of a small fluid.

Pore distribution characteristics that are analyzed by the mercury intrusion method are to provide a lot of useful information in estimating the threshold pressure. On the other hand, It is not possible to correspond to the anisotropy, it is impossible to omit the direct method using a core such as step by step method.

Keywords: Mercury intrusion method, supercritical CO2, Threshold pressure, Step by step method, Residual pressure method, Bimodal



Visualization and measurement of CO_2 flooding in heterogeneous sedimentary rock

*Hyuck Park[1], Lanlan Jiang[1], Tamotsu Kiyama[1], Osamu Nishizawa[1], Yi Zhang[1], Ryo Ueda[2], Masanori Nakano [2], Ziqiu Xue[1]

1.Research Institute of Innovative Technology for the Earth (RITE), 2.Japan Petroleum Exploration Co., Ltd. (JAPEX)

To investigate CO_2 flow mechanisms and fluid recovery processes in heterogeneous rock, we designed a laboratory experimental system which visualizes CO_2 movements during flooding experiments by using X-ray CT. We carried out laboratory experiments of CO_2 flooding in heterogeneous sandstone, together with porosity calculation, fluid saturation monitoring based on CT images, and mass flow measurements for ejected fluids. Based on the experimental results, we try to understand the flooding characteristics of CO_2 in heterogeneous rocks having complex sedimentary structures, which will contribute to CO_2 geological sequestration and oil recovery. Sarukawa sandstone (diameter: 34.80mm, length: 79.85mm, north central Japan) was used in this study. Porosity of the specimen determined by X-ray CT imaging was 31.2%. As shown in figure1a, the specimen has a heterogeneous structure. Especially, upper part of the specimen is more complex than the lower part. The experiment was conducted under the pressure and temperature conditions that simulate underground environments; pore pressure: 10MPa, temperature: 40 degrees Celsius. The confining pressure selected in this study was 12MPa. Fluid pressure and its injection rate were controlled by high-precision syringe pumps. A high-pressure vessel having high transparency for X-ray was utilized in this study. The specimen was first saturated with KI aqueous solution (12.5%), and then oil was injected to change the specimens into oil-water mixed state. Totally, ten steps of CO_2 flooding were performed for this experiment. For each step, KI aqueous solution and oil were carefully recovered from the syringe pump which plays a role of back pressure. The CO_2 flooding test was carried out until the CO_2 injection reaches 3.03PV (pore volume). Figure 1b shows the differential CT images when the CO_2 injection reaches 0.26PV. In the figure, almost all of the CO_2 preferentially moves through the upper part of specimen. This represents that the sedimentation heterogeneity is the main factor that affects the CO_2 flooding pattern. The oil recovery was identified as 48.9% when injected CO_2 reached 1.0PV in the specimen. We increased the differential pressure to examine the influence of differential pressure on oil recovery in heterogeneous media. The oil recovery was 69.7% when injected CO_2 reached 2.0PV. The increment of oil recovery from 1.0PV-step to 2.0PV-step, 20.8% corresponds to more CO_2 flooding into the non-recovering zone (low porosity and/or low permeability) due to increasing of capillary pressure.

Keywords: CO2 flooding, heterogeneity, X-ray CT, visualization, CO2-EOR

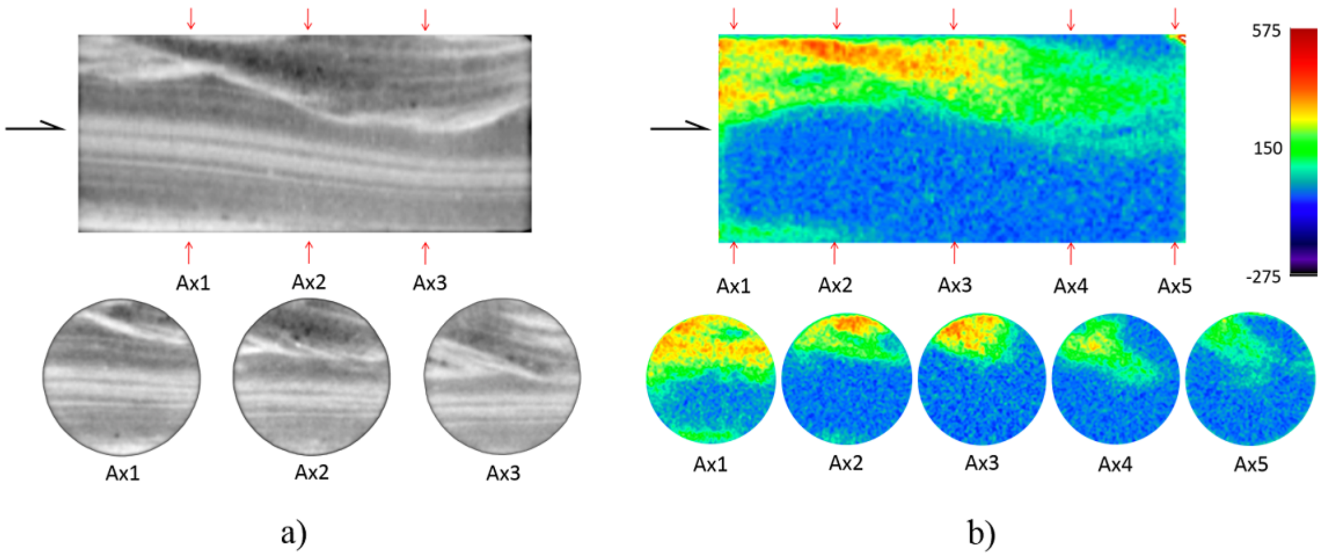


Figure 1: X-ray CT images of CO_2 flooding experiment.
a) core in dry condition, b) differential CT images at 0.26PV(pore volume) CO_2 injected

Development of acoustic methods for detection of CO_2 leakage from sub-seabed storage site

*Takamichi Nakamura[1], Makoto Nishimura[1], Keisuke Uchimoto[1]

1.RITE, CO2 storage research group

Carbon dioxide capture and storage (CCS) is the primary technological option for reducing CO_2 emissions into the atmosphere and is expected to be an effective climate change mitigation technology. Because storage sites are selected deliberately to minimize the risk of leakage, CO_2 is assumed to be stable in the reservoirs. However, in a worst-case scenario, CO_2 could leak out from the ground surface into the atmosphere or from the seabed into the adjacent sea. Leakage could be caused by various factors, such as an increase in subsurface pressure due to CO_2 injection. CO_2 leakage may lead to significant damaging effects on the local environment. Therefore, concerns are emerging from the public about the risk of *in situ* leakage and ecological impacts. In Japan, operators of offshore CCS are required to plan monitoring programs, as stated in the Act for the Prevention of Marine Pollution and Maritime Disasters. In the monitoring plan, an operator has to be able to determine the location and extent of any CO_2 leakage. Consequently, it is necessary to develop detection methods of CO_2 leakage in the sea.
This study focuses specifically on active acoustic methods. Active acoustic methods, which are a type of bathymetry imaging, are examined for use in the detection of CO_2 leakage in shallow seawater columns. Side scan sonar (SSS) and multibeam sonar (MBS) were tested for use in detecting gas bubble streams in shallow coastal waters. In addition, image data was acquired with a sonar video camera. Gas bubbles were released from the seabed in a controlled manner using compressed air while scanning the seabed and water column using acoustic methods. All sonar technologies were able to detect gas bubbles and visualize gas streams in a water column (Fig.1). Both MBS and SSS data had a lower detection limit of bubbles at 100 mL/min of flow rate. MBS produced high precision localization, but detection sensitivities were affected by vessel speed. MBS is therefore most suitable for narrow area monitoring. SSS could scan wide views, and detection sensitivities were not affected by vessel speed, making SSS suitable for broad area monitoring. Additionally, there is some possibility of quantifying gas bubble concentrations from SSS scan data, which is the topic of ongoing research. Using the sonar video camera, gas streams could be visualized in the water column as dark areas in the video image. Sonar video cameras are only suitable for fixed-point observations. The data gathered indicate that acoustic methods are useful for the detection of CO_2 leakage, and may eventually be able to determine concentrations. In order to apply practical monitoring techniques, further experimental study in deep seas is required.

Keywords: sub-seabed CCS, leakage detection, acoustic methods

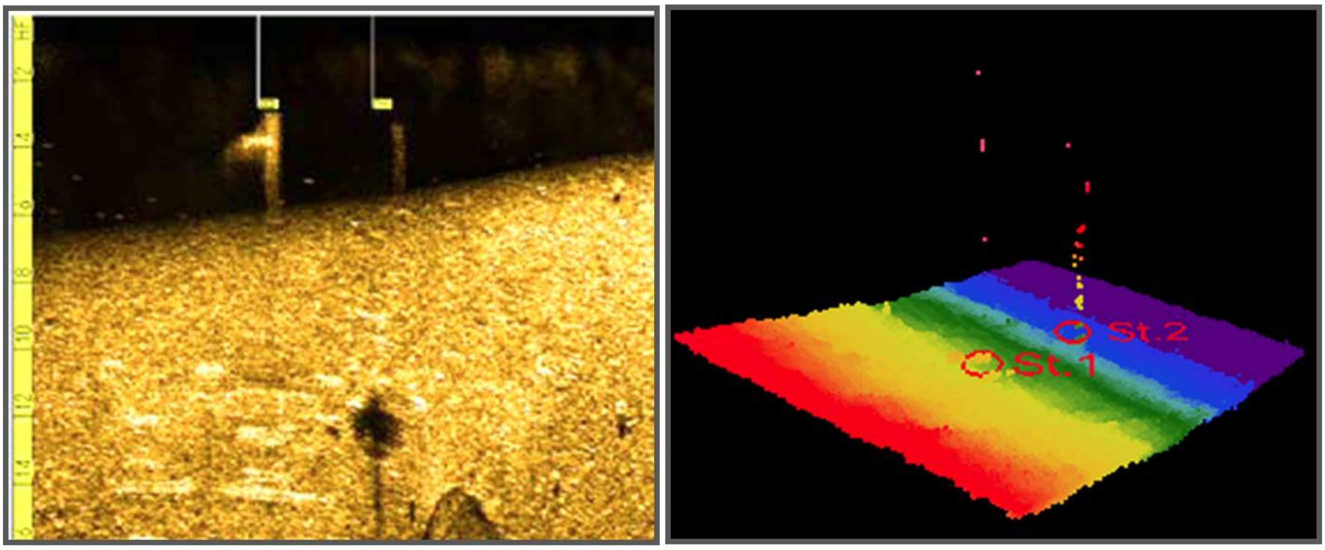


Fig. 1. Water column bubbles imaged on the data of SSS (left) and MBS (right)