Analysis of long-term CO2 emission reduction scenario and the role of CCS

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As significant CO2 emission reduction is required on the long-term at international level, this presentation will introduce various assessments based on RITE models on the following topics:
・The global CO2 emission pathways for achieving the 2℃ and 1.5℃ target
・The marginal abatement costs for CO2 emission reductions
・The evaluations of Nationally Determined Contributions (NDCs) under the Paris Agreement
・The role of CCS

Keywords: CO2, Climate Change, Model Analysis, Environment, CCS

Automatic optimization for well placement for large-scale geologic CO2 storage

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Carbon dioxides capture and storage (CCS) is a viable technique for reducing amount of CO2 emitted to the atmosphere by injecting captured CO2 into underground reservoirs. When we consider a large scale CCS with more than 1Mt/y injection rate, the injection has to be processed efficiently and safely keeping reservoir pressure at an allowable level. One of the promising solutions is to employ pressure relief wells to reduce reservoir pressure by producing formation water. However, a huge number of reservoir simulations would be required to determine an optimum placement of the relief wells such as the number of wells and location. Therefore, automatic and efficient optimization methods that can reduce number of reservoir simulations and obtain beneficial solution will be essential. In this study, we developed a tool for efficient and automatic optimization by combining a commercial general-purpose optimizer HEEDS with a multiphase fluid flow simulator TOUGH2/TOUGHREACT. Users can select a variety of optimizers and will be benefited from massively parallel computation that can largely reduce computational time of each simulation. The tool was applied to well placement problems on reservoir models having homogeneous and heterogeneous permeability. The performance of a couple of optimizers (i.e. generic algorithm, particle swarm optimization, simulated annealing) were investigated and demonstrated through the applications

Keywords: Carbon dioxide capture and storage, Optimisation, Reservoir Simulation, TOUGH2

Numerical simulation study on mitigation of the pressure build-up in the geological formation during injection of CO_2

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The injection of supercritical CO_2 into the deep underground increases the pore pressure in the geologic formation, 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, changes in the groundwater flow direction, changes in hydrogeological conditions and changes in the neighboring pressure regimes.
We investigated how effective pressure build-up can be reduced by applying pre-injection formation water (brine) production as proposed by Buscheck et al. in 2014 (dual-mode wells), or production of brine in parallel to CO_2 injection. Numerical simulations were conducted, using the TOUGH2/ECO2N code, 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 two reservoir volumes, and a hypothetical placed production well, on pressure build-up in the storage formation were tested. Two models with different volumes, and an injection rate of 1 Mt/yr were applied and three cases were simulated for each model. The first case only considered injection of CO_2 for 100 years without previous production. The second case examined the dual-mode well, which included previous production for 5 years prior CO_2 injection for 100 years. The last (third) case considered production of brine while injection of CO_2 by using a separate installed production well. Judging from the results, the following conclusion can be drawn: 1) The dual-mode well with short duration of water production (5 years) was not so effective to maintain the reservoir pressure in the large reservoir volume considered here. The method would be better suited for smaller reservoir, otherwise a very long-term production would be necessary. 2) Water production in parallel with injection was very effective in order to maintain the reservoir pressure and to avoid harmful effects on the overlying seal layers and other hydrogeological conditions. The methods can be applied to make CCS technology much more sufficient through increasing the effective capacity of injectable CO2. It may also lead to more opportunities related to site selection. However, it has to be emphasized, that the effectiveness of the production strategies investigated here 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 become available through the site investigation and even operations.

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

An automatic seismic event identification method by sequential discounting autoregressive (SDAR) change point detecting

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In recent years, more and more reservoir evaluation studies, including CO2 sequestration, hydraulic fracturing and fracture mapping, focus on seismicity monitoring. The primary task for monitoring is the identification of seismic events in a long-term sustained time series record. Unfortunately, the time-varying characteristics of SNR (signal to noise ratio) and seismic event waveforms increase the difficulty in the automatic detection of seismic events. First, The uneven data energy distribution due to uneven data energy distribution influences the outlier identification of the targeted event, especially for weak energy earthquakes. Second, different seismic events contain different waveform properties. A fixed detecting model is inappropriate for long-term observation. Events in close propinquity of a time series also lead to a complex automatic detecting model.
The STA/LTA (short term averaging / long term averaging) method is a widely used seismic first arrival identification algorithm. This method is simple and suitable for real-time processing. It contains 2 steps: 1. set a short time window included in a long time window and calculate the time window signal amplitude (or energy) average, respectively. 2. slide the windows in the time series and calculate the two average ratios. The outlier of the ratio refers to the appearance of a seismic event. The STA/LTA method can be employed for real-time processing. However, for low SNR or related signal noise situation, STA/LTA detecting effect will be impaired. Besides, for long-term series, it is difficult to estimate an appropriate time window size for the ratio calculation. Considering seismic observed record as a stochastic time series, AR (autoregressive) process can be applied for seismic event detecting. For the event phase arrival, AR method assumes that the segments before and after the event phase is stationary as different AR models. The change point between these two models refers to the seismic event on time series. Since the AR method avoids the amplitude or energy calculation, it produces better results for low SNR signals. However, AR method needs the signal stationarity assumption, so it is not suitable for time-varying long-term records.
In this work, an improved AR method for automatic seismic event detecting is applied. This algorithm, called SDAR (sequential discounting AR learning), is widely used to represent a statistical behavior of a time series. There are 2 advantages of SDAR: 1. Real-time estimation. When new data appears in the record, the SDAR model parameters can be updated. 2. Discounting property. Comparing with AR method, the SDAR introduces the discounting parameter to decrease the statistic value on future data. Therefore, the SDAR method can handle the unstable time-varying long-term series. Comparing SDAR and STA/LTA method, the Tomakomai OBC observation test shows that SDAR can increase the seismic event detecting rate.

Keywords: seismic event detecting, SDAR, change point

Acoustic sonar detectability of gas bubbles from seafloor for environmental monitoring at offshore CO_2 storage sites

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Geological CO_2 storage is proposed in sedimentary formations. Because storage sites are selected deliberately to minimize the risk of leakage, CO_2 is assumed to be stable in the reservoirs. CO_2 leakages from geological storage systems are unlikely, but still possible. At offshore CO2 storage site, CO_2 could leak out from the seafloor into the seawater. CO_2 leakage may lead to significant effects on the local environment. From the public and stakeholders, concerns about the risk of in situ leakage and ecological impacts are emerging. Therefore, it is the most important verification for geological CO_2 storage project that there is no detectable leakage or migration of CO_2 by environmental monitoring. Appropriate environmental monitoring methods and public communications are lead to secure social license and also needed to progress of safety geological CO_2 storage project. Further, 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.

For offshore environmental monitoring, acoustic methods were expected that could direct detection of CO_2 bubbles in the seawater. It was described that effectiveness of acoustic methods for seafloor and water column monitoring in IEAGHG special report (IEAGHG, 2012). In practice, it was used in seafloor survey of several offshore geological CO_2 storage projects. For example, in Sleipner, side scan sonar (SSS) and multibeam echo sounder systems (MBES) were used for seafloor observations on storage site (www.eco2-project.eu). In QICS project (Blackford et al., 2014) that CO_2 controlled release experiment from shallow seafloor, clearly images of both gas plume within the water column and pockmarks on the seafloor obtained using MBES (Cevatoglu et al., 2015). Furthermore, gas flux quantification using hydrophone, passive acoustic method was shown (Bergès et al., 2015). However, there were no data about flow rates of released CO_2 and MBES image data was used as check the location of releasing point. Detectability of acoustic methods was unclear.

This paper focuses specifically on the detectability of active acoustic method. Controlled compressed air release experiments were carried out in shallow inner bay at the depth of 5 to 6 m. Observations using active acoustic instruments such as multibeam sonar (MBS) and SSS were deployed to assess its detectability for gas bubbles stream.Analysis of the image acquired by active acoustic instruments led to the following conclusions:

·Images of MBS data could detect gas bubbles stream. The survey using MBS have the potential to be effective method for localization of leakage point in narrow area.

·Images of SSS data could detect gas bubbles stream. Images of SSS data showed high detectability of gas bubbles stream The survey using SSS have the potential to be effective method for detection of CO_2 leakage and localization of leakage point.

·Image processing and analyzing of SSS data, the quantification data of gas bubbles stream were obtained. Flow rates from any image data could estimate within order of magnitude, with relative high quantification accuracy.

·The survey using SSS have the potential to be effective method for not only leakage detection but also leakage scale grasp. The broad seafloor survey using active acoustic instruments such as SSS is crucial point of efficient leakage detection and localization.

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Keywords: offshore environmental monitoring, offshore CO2 geological storage, acoustic sonar, leakage detection

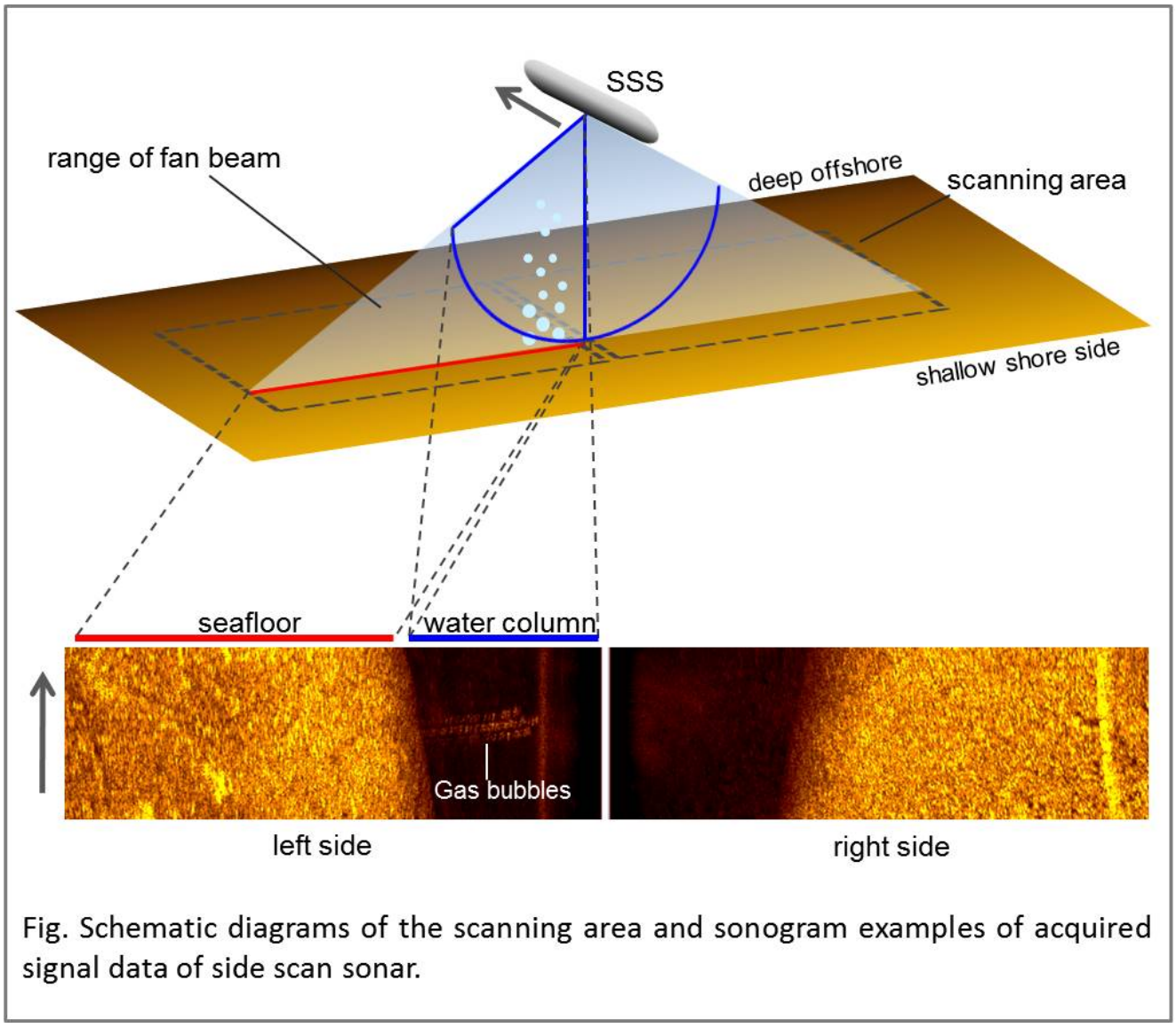

Fig. Schematic diagrams of the scanning area and sonogram examples of acquired signal data of side scan sonar.

Scientific response to successive changes of next Earth and human society and CO_2 capture system

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Any sustainable future oriented idea on active Earth is indispensable for the active human society from the mini Earth type system where we would like to report briefly on the future of human society located in planet Earth as follows.

1. Descriptive present research on the later stages of the Earth have been overlooked to be studied precisely carbon dioxides change during resource burning.

2. Carbon dioxides gas capture immediately after burning before cool atmosphere because of difficult collection at global distribution.

3. The sources of action of the inorganic planet Earth and the organic matter are different with formation conditions.

4. Earth atmosphere ocean water and solid rocks show different activities with remnants of changed signature.

5. Our Earth and human society show different system in duplicated circulated system. Earth's natural resources with CO_2 gas formation should be applied to circulated processes developed in human society.

6. Material changes of our Earth are reconfirmed as evidence of its activity by remained rocks reacting with atmospheric gases and seawater solutions. Author has been confirmed and reported the remained traces of the three states changes naturally and artificially by the recent high technical observation method.

In short in the case of using active Earth resource substances in our human society any effective scientific and technical developments of recycling of disposal waste is definitely indispensable for future human energy by using the Earth resources with carbon dioxides gas waste.

We would like to present scientific ideas and proposals at the meeting. This is main essence of our Earth and human society with related scientific and technical development of continuous reformation process of active Earth resources where we should apply to human life society by duplicated process of Earth and life systems.

Keywords: Carbon dioxides capture system, Earth system, Human life system

Evaluation of shale volume using a combination of the gamma-ray logs and core analysis in terms of sedimentology and geochemistry: a case study of the Nagaoka site, Japan

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Evaluation of spatial distribution of shales is important for selecting of reservoir rocks suitable for geological storage of CO_2. Shale volume from well logs is useful as deterministic data for evaluation of spatial distribution of shales in the strata. Gamma-ray log can be used to evaluate shale volume in the reservoir. Gamma-ray logging is a method of measuring naturally occurring gamma radiation from ^{238}U, ^{232}Th, and ^{40}K in the strata. Mudstone generally has higher total GR value than sandstone. However, it is difficult to evaluate reliable shale volume if the mineralogical composition significantly changes during deposition of the strata. This means that understanding the minerals which have an effect on the total GR value is essential for evaluation of shale volume, but few studies have focused on that. Herein we present the results of reservoir characterization in terms of sedimentology and geochemistry, and comparison among core analysis and gamma-ray logging as a case study of the Nagaoka geological storage site, Japan. Furthermore, we show the importance of sedimentological interpretations of the strata for reliable evaluation of shale volume.

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. Standard GR logging was carried out at all the wells, and spectral gamma-ray logging, which can measure ^{238}U, ^{232}Th, and ^{40}K contents, was performed at all observation wells.

We carried out the interpretation of depositional environments, measurements of major and minor elements by XRF analysis, and identification of minerals by XRD analysis in the target strata. The target reservoir comprises two depositional sequences characterized by fining-upward to coarsening-upward succession that developed on the erosional contact. According to core description, the deposits can be interpreted as prodelta to deltafront deposits. Total GR value has high sensitivity to depositional environments. Profile of total GR value is basically consistent with that of mud content (<1/16mm), and this suggests that main source of total GR value is mainly attributed to minerals in mud fraction. Comparison between total GR value and spectral GR logging shows that distribution range of K content against total GR value show low contrast between prodelta and deltafront deposits, and this trend suggests that K content is not carrier of radioactivity. On the other hand, distribution range of U and Th contents against total GR value show basically high contrast between two deposits and have positive correlation. This result indicates U and Th-bearing minerals are main carrier of radioactivity. Comparison between total GR value and major and minor elements shows that minerals including MgO, TiO_2, Th, and Zr are likely to be main source of total GR value. The XRD analysis using samples of mud fraction shows that those minerals can be attributed to zircon grains, smectite and chlorite, because it is known that these minerals contain or adsorb the Th andor U ions.

As stated earlier, stratigraphic profiles of GR logging show two depositional sequences at all wells. The scatter diagrams of radioactive elements by spectral GR logging against total GR value shows similar trend basically in two depositional sequences, implying that no significant changes of mineralogical composition during deposition. However, maximum of total GR value is significantly different between two

sequences. The result indicates that the endmembers of total GR value for evaluating shale volume by gamma-ray logging should be selected in each depositional sequence. Detailed studies in terms of sedimentology are essential for reliable evaluation of shale volume.

Keywords: Nagaoka site, Sedimentology, Geochemistry, Natural gamma-ray logging, Spectral gamma-ray logging, Shale volume

Reservoir heterogeneity based on sediment sorting associated with GR and permeability in turbidity sandstone sequence, Kitaura Formation, Akita, Japan

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Outcrop and core data from the interbedded with turbidity sandstone and siltstone, Kitaura Formation of Akita basin show that realistic reservoir characterization can be based on stratiogaraphic architecture. This deposit represents turbidity sandstone reservoirs that developed from cyclic turbidity currents within hemipelagic basin. Kitaura Foramtion outcrop are good analogs to CO_2 reservoir characterization and modeling in off Akita area. Analysis and modeling of the turbidity sandstone based on outcrop measurements provide detection and identification of ranging data for sandstone reservoir characterization.
Ourcrop displays of differential weathering, coloration, cementation, and seepage reflect stratigraphic and sedimentary control of fluid flow within the turbidity sandstone. The first step of this study is observations of sedimentary facies that characterized by sedimentary structures, grain-size distribution, thickness of sandstone and siltstone, and cyclicity and lateral variations of sandstones. Measurements of permeability using a field permeameter and conventional soil analysis (e.g. Talsma and Hallam, 1980) yield some of magnitude range of values between distinct populations as follows; a part, b part, and c part of Bouma sequence and low density current deposit composed very fine sandstones. These differences within turbidity sandstones depend on grain size distribution, which indicate sediment sorting. The lateral variations of the sorting of a sandstone layer reveal that various values of reservoir property depend on depositional mechanisms. Natural gamma ray (GR) measured for ratio between clay and sand contents in sandstone layers can regards as a physical property of reservoir heterogeneity. Recognition of physical levels of reservoir heterogeneity can be identified GR and permeability within turbidity sandstone layer even though factor and distribution of physical properties are sampling scale dependent. Outcrop analogs for flow within turbidity sandstones can be generated spatial distribution of reservoir heterogeneity based on sedimentary systems.

Keywords: Reservoir heterogeneity, turbidity sandstone, sediment sorting

Impact of the injection speed on CO_2 saturation and pore pressure

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It is an essential issue to understand the behavior of injecting CO2 in reservoirs. Injected CO2 forms two-phase flow with brine and arises CO2 saturation (SCO2) and pore fluid pressure(Pp). The estimation of SCO2 in the reservoir is one of important task in CCS projects. Fluid pressure (Pp) is also important to estimate the integrity of CO2 reservoir and overlying cap rocks. Generally, elastic waves are used to monitor the changes of SCO2. Previous experimental and theoretical studies indicated that SCO2 and Pp are controlled by the fluid velocity of invaded phase. In this study, we conducted the CO2 injection test for Berea sandstone (Φ=18.1%) under deep CO2 reservoir conditions. We try to estimate the changes of SCO2 and Pp with changing CO2 injection rate (FR) from 10 to 5000 ml/min for Berea sandstone. P-wave velocities (Vp) are also measured during CO2 injection test and used to investigate the relationships between SCO2 and Vp and Pp. We set 3 Vp-measurement channels (ch.1, ch2 and ch.3) to monitor the CO2 behavior. The result shows step-wise SCO2 changes with increasing FR from 9 to 25% in low-FR condition (10-500 ml/min). Vp also shows step wise change from ch1 to ch.3. Ch.1 indicates that Vp-reduction stops around 4% at 10ml/min condition. However, ch.3 changes slightly from 4% at 10 ml/min to 5% at 100 ml/min. On the other hand, differential Pp (DP) dose not shows obvious changes from 10 to 30kPa. Over 1000 ml/min, SCO2 increases from 35 to 47 %. Vp show slight reductions and Vp-reductions reach constant values as 8%, 6% and 8%, respectively at 5000 ml/min. Then, DP shows rapid increasing from 50 to 500 kPa. It suggests a drastic change of CO2 behavior with injection rate. CO2 flows gently and enlarges SCO2 up to 25 % under low FR conditions without arisen DP (<500 ml/min). Over 1000 ml/min, CO2-flow causes rapid increment of SCO2 and DP. These results clearly indicate that SCO2 and DP are strongly controlled by CO2 injection rate.

Keywords: CO2 saturation, differential pressure, injection speed, two-phase flow

Numerical Study on the Effects of Change of Contact Angle on Sealing Capacity

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For geological storage of CO_2 in Japan, general aquifer storage site often have geological characteristics favorable for geochemical reactions. When pH-lowered pore water due to CO_2 dissolution causes geochemical reactions in such formations, some kind of mineral may envelop the surface of rock, change the wettability (contact angle), and result in change of the capillary pressure. In this study, we will present the results of the numerical analysis of the effects of change of contact angle on seal capacity and the long-term behavior of injected CO_2.

We constructed a two-dimensional radial model with 20 km width and 0.5 km depth for the simulation. Subsurface conditions of 31 ˚C and 9.0 MPa are assumed for the top boundary. Reservoir is located at 1,000 m depth with 100-m or 200-m thickness. A 100-m thick seal layer overlies it. Basement underlies the reservoir, and second aquifer overlies the seal layer. CO_2 is injected into the reservoir at a rate of 1 Mt/year. The injection interval is 50 years. We conducted numerical simulations on the long-term behavior of CO_2 for the injection period and 450 years of shut-in. Simulations are carried out using the "STAR" reservoir simulation code with the "SQSCO2" equation of state.

Reservoir and seal layer have vertical/horizontal permeabilities of 10/100 mD and 0.1/1 mD, respectively. Models of relative permeability for water and CO_2 were assumed to be common to all formations. They are represented by functions of van Genuchten type and Corey type, respectively. Irreducible water saturation and residual CO_2 saturation are 0.2 and 0.05, respectively. Hysteresis model is adopted for the relative permeability. Capillary pressure was represented by van Genuchten type, and the threshold pressure (P_{th}) was given as the capillary pressure at the residual CO_2 saturation. P_{th} of reservoir is set to be 0.1 MPa, and that of seal layer is 0.5 MPa or 1.0 MPa. In this study, the initial contact angle of water-CO_2-rock system is assumed to be water-wet 0˚. We assume the contact angle θ changes at some point, to be 15˚, 30˚, 60˚, and 75˚. According to the change of contact angle, threshold pressure P_{th} will change following Laplace's equation: $P_{th} = 4\sigma\cos\theta/d$, being proportional to $\cos\theta$ at all CO_2 saturation. Interfacial tension σ and throat diameter d remain unchanged in this study. For case study, P_{th} is i) unchanged all over simulated time, changed at ii) 25 years, iii) 50 years, and iv) 100 years later from the start of the injection.

Simulated results showed that i) for unchanged case, part of CO_2 intrudes into the seal layer during the injection period, however, it almost stops in shut-in period. ii) CO_2 remains with in the reservoir and seal layer, and do not reach the second aquifer after 450 years later from the stop of the injection in the all cases of this study. Low permeability of the seal layer and residual gas trapping are presumed to contribute it. iii) When capillary pressure is lowered due to change of contact angle, CO_2 intrusion into the seal layer continues during shut-in period in some cases. iv) This effects are pronounced especially in the cases where the initial capillary pressure is low, and/or buoyancy is large due to thick reservoir. These results indicate that change of contact angle due to geochemical reaction can affect long-term seal capacity at CO_2 storage site.

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Keywords: Geological storage of CO2, contact angle, capillary pressure, numerical simulation

Micro-bubble Injection Enhanced dissolution during CO_2 Sequestration in saline

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CO_2 micro-bubble injection is available for storing CO_2 in aquifers with non-anticline (monotonic) structure in a low-cost concept. In this study, the dynamic displacement and dissolution during CO_2 flushing was investigated by using medical X-ray CT scanner. CO_2 was injected into brine saturated sandstone with 0.05 mL/min under reservoir condition (10MPa/40°C).Two sets experiments with micro-bubble and normal bubble CO_2 were conducted to quantify compare the enhanced dissolution efficiency. Larger interfacial area between CO_2 and brine during the injection enhanced the mass transfer and delayed CO_2 breakthrough. The breakthrough time for micro bubble was nearly 120 min corresponding to 180 min for normal bubble under the same injection rate. By image analysis, the high sweep efficiency during micro-bubbles injection was obtained. Micro-bubble CO_2 preferred to trap into tiny pores since the small size bubble and micro-bubbles injection accelerated gas trapping because of the fully dissolution. CO_2 micro-bubble sequestration is also a novel technology to store CO_2 from the small- to middle-scale emission sources by enhanced dissolution and effective use of pore space suggested by our experimental results.

Keywords: micro bubble, CO2 saturation, high sweep efficiency, dissolution

Study of advanced CO_2 dissolution technology for improvement of CO_2 storage efficiency

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Reducing cost of CO_2 injection and storage is important challenge for applying to commercialization. Establishing the advanced CO_2 dissolution technology which controls the reservoir pressure during CO_2 injection is very important to inject and store CO_2 in reservoir efficiently and we focused the technology of CO_2 injection as the microbubble (MB). In this study, we proceeded the unraveling the efficiency of increase of CO_2 storage and the mechanism by MB-CO_2 from experiment and flow simulation.
MB is formed by CO_2 passed through the porous filter. In past study, it was seen that CO_2 saturation which is ratio of CO_2 volume divided by pore volume increase by MB-CO_2 injection more than normal injection and now it is the key point to applying this technology to field scale to study for the behavior and the efficiency of MB in the well and the reservoir and the mechanism of them.
As one of the studies, we targeted the “Effective area of MB-CO_2” and estimated the relation between the effective area of MB-CO_2 and CO_2 storage by conducting core flooding test with the long berea sand core (length : 30cm). Core flooding test was conducted at the reservoir condition (40℃, 10MPa) at which it is supercritical CO_2 and CO_2 saturation was increased 7.4% and CO_2 Storage is also increased 30.4% in core by MB-CO_2 injection as relative increase against normal injection. It was considered that these results show the effect of advance of CO_2 dissolution to water by MB-CO_2 injection technology. In addition, the behavior, which breakthrough time of CO_2 in MB-CO_2 injection was later than that in normal injection, was observed.

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reference
Akai, T., Xue, Z., Yamashita, Y., Yoshizawa, M. Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, 2015 SPE-177672-MS

Keywords: Geological CO2 Storage, advanced dissolution, microbubble, core flooding

Trapping mechanisms in field scale observed by time-lapse well logging at the Nagaoka site

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This paper discusses CO_2 trapping in field scale observed at the Nagaoka pilot-scale injection site. IPCC (2005) illustrated the contributions of various trapping mechanisms over time, and pointed out the importance of capillary and solubility trapping at the early stage of geological CO_2 storage. Capillary trapping is caused by interfacial forces at the pore of rock and prevents migration of CO_2 bubble. Solubility trapping means that gaseous CO_2 dissolves into formation water. After the report of IPCC, many laboratory experiments related to these trapping mechanisms have been conducted. Meanwhile, field observations were limited. In this paper, we study trapping mechanisms observed at the Nagaoka site.

Nagaoka project was undertaken in order to verify an ability of CO_2 injection into Japanese formation. The target reservoir is consists of a limb of anticline structure and have 15 degree dipping. About 10 k-tones of CO_2 were injected into a thin permeable zone from July 2003 to January 2005. Time-lapse well loggings have been carried out for more than 12 years, and the number of monitoring logging is 44 times so far. CO_2 breakthrough was detected at a down-dip well (OB-2) located 40m away from the injection well, and at a up-dip well (OB-4) located 60m from the injection point. From the neutron logging data, CO_2 saturation in super-critical phase was evaluated, and from the induction logging the existence of super-critical and dissolved CO_2 is deduced. At OB-2, CO_2 saturation peaked at 63% around 22 months after the start of injection, decreased gradually, and stabilized at around 20%. At OB-4, CO_2 saturation peaked at 69% around 15 months and remained relatively high value (40%).

We considered that the maximum saturation at each depth was corresponding to the initial saturation of drainage process and the latest observation could be assumed as the residual state. The relationship between the initial and residual saturation is called IR curve and represents the fundamental flow properties in drainage process. The results at OB-2 showed that most of the data can be explained by single Land’ s model. Exception came from relatively silty layer, which means pore distribution is different from other layers. At OB-4, IR relationship was scattered and indicated that the latest state is far from the residual condition. The difference between down- and up-dip direction is thought to exhibit migration effects in the reservoir.

Concerning the dissolved CO_2, the thickness of the low resistivity anomaly became larger. This showed that the solubility trapping was progressing. The rate of thickening was the same order as the dissipation of bicarbonate ion. This was consistent with the expectation from the linear instability theory for density convection of CO_2 dissolved water.

These results showed capillary and solubility trapping mechanisms in the field scale observation. The drainage process in field scale could be explained by Land’ s model as laboratory experiments, and the fitted model was depend on rock type. Solubility trapping in several mD formations was confirmed that dissipation process was dominant during the first decade of CO_2 storage. These results could be used for simulation tasks to build a better flow model.

Keywords: CO2 geological storage, multiphase flow, residual trapping, solubility trapping, Land model, Nagaoka site

Visualization and measurement of CO_2 microbubble flooding in heterogeneous sedimentary rock

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We carried out laboratory experiments of CO_2 microbubble and normal bubble flooding in porous sandstone to confirm the difference in dissolution and sweeping effect. During the experiments, we obtained the specimen porosity and monitored fluid saturation process by using CT image analysis. Sarukawa sandstone (diameter: 34.80mm, length: 79.85mm, north central Japan) was used in this study. Porosity of specimen determined by X-ray CT imaging is 30.94%. The specimen has heterogeneous structure. The experiments were 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 is 12MPa. The specimen was first saturated with KI aqueous solution (12.5%), and then oil was injected to make oil-water mixed state. Totally, ten steps of flooding were performed for each experiment. For each step, KI aqueous solution and oil were carefully recovered from the syringe pump (back pressure pump). We increased the differential pressure to examine the influence of differential pressure on oil recovery in heterogeneous media. The microbubble and normal bubble flooding tests were carried out until the total fluid injections reach about 3PV (pore volume). Figures a) and b) show the differential CT images when the CO_2 microbubble and normal bubble injections reach 2.95PV and 2.98PV, respectively. It is clear that the CO_2 microbubbles were able to sweep out more than the normal microbubbles. For example, the oil recoveries were identified as 56.04% and 45.12% after 1.0PV injection of CO_2 in the specimen. The case of microbubbles is about 10.92 % point higher than the case of normal bubble.

Keywords: X-ray CT, CO2 microbubble, CO2 normal bubble, heterogeneous rock

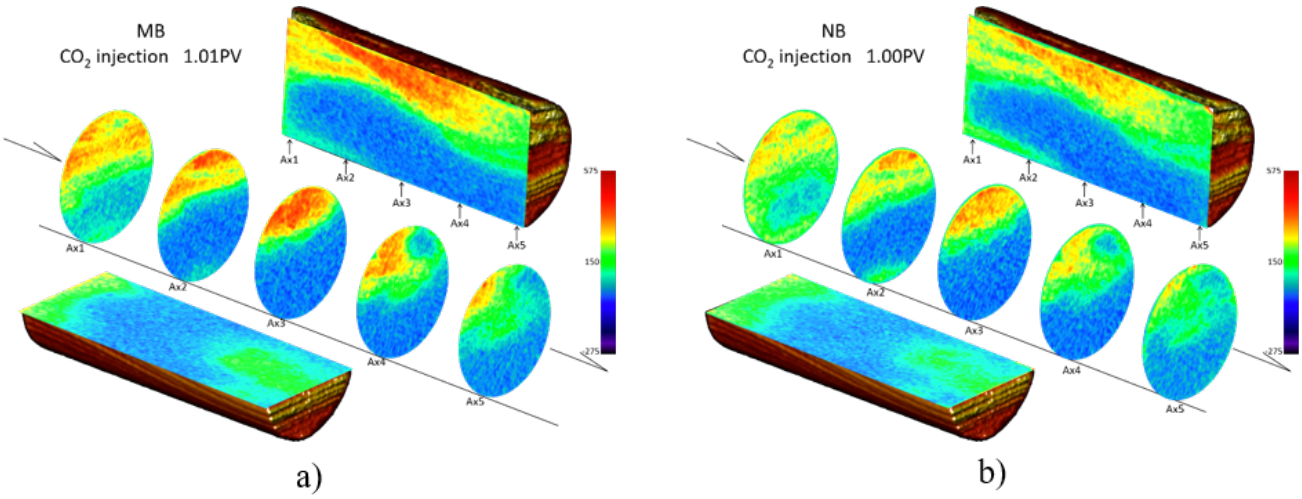

Figure. X-ray CT differential images of CO_2 microbubble and normal bubble flooding in the Sarukawa sandstone a) after 1.01PV(pore volume) injection of CO_2 microbubbles, b) after 1.00PV injection of CO_2 normal bubbles

Preliminary evaluation on geochemical impacts to rock's sealing performance

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Geologic CO_2 storage supposes that a caprock prevents the leakage of CO_2 to the ground surface. The sealing performance of caprocks is controlled by permeability *k* and threshold pressure P_c^{th}. Many efforts have been undertaken to measure these parameters for rocks obtained from actual storage sites. However, a caprock would be exposed to acidified circumstances over a long period of time. Our knowledge related to the sealing performance of such reacted rock is restricted. Therefore, this study aims to assess quantitatively the change of the sealing performance caused by geochemical reactions.

Six different kinds of rocks, i.e., three mudstones from Namihana Formation, Ohara Formation, and Ichishi Group, and the marlite from Itsukaichi-machi group, and two sandstones of Otomari foraminiferal sandstone and the coquinite from Haizume Formation, were collected from various outcrops located in Japan. These rocks were formed into a cylinder solid, with respective diameter and height of about 14 and 10 mm. Batch-type reaction experiments were done at 40˚C in deionized, distilled water using a supercritical CO_2-water reaction system. A constant CO_2 pressure of 10 MPa was maintained for four weeks at a maximum. After 1, 2, and 4 weeks, the system was opened to extract rock samples. Then, *k* and P_c^{th} of each sample were measured using a capillary pressure measurement system.

Results revealed that the degree of geochemical impacts strongly depends on rock types. Hydrological properties of Namihana and Ohara mudstones, and Haizume coquinite, were unchanged during 4 weeks. In contrast, other three rocks reduced their sealing performance by increasing permeability and decreasing threshold pressure. In fact, Ichishi mudstone and Itsukaichi-machi marlite produced numerous cracks after reactions. Therefore, their hydraulic changes were not caused by geochemical reactions. Consequently, geochemical reactions did damage solely to Otomari foraminiferal sandstone. Here, it is generally expected that rocks containing carbonate minerals would produce leakage paths of CO_2 because carbonates' dissolution rate is generally high. However, results showed no correlation between carbonate amount and hydrological changes. This means that mineral reaction is restricted by rock's internal structure on a microscale. In the presentation, the relationship between geochemical reactions and hydraulic properties will be discussed along with the information about chemical compositions of leached components and pore throat size distributions.

Keywords: Geologic CO2 storage, Sealing performance, Geochemical reaction, Carbonate minerals, Caprock, Threshold pressure

An option for marine monitoring at offshore CO_2 storage sites: observing pCO_2 in the sea

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Carbon dioxide (CO_2) capture and storage (CCS) is a promising option to reduce CO_2 emissions and consequently to mitigate global warming. Since reservoirs capable of storing CO_2 stably are selected, the risk of CO_2 leakage is extremely low. There is, however, concern that CO_2 might leak out. To verify that CO_2 is not leaking, as well as to detect CO_2 leakage if leakage occurs, monitoring is important. In offshore storage, since leaked CO_2 would go out into the sea out of the seabed, monitoring in the sea is necessary. However, there seems to be no monitoring method that is useful in all sea areas or for all situations. In the practical monitoring, it is necessary to combine a few methods according to the situation and the sea area. Partial pressure of CO_2 (pCO_2) in the sea is one of items to monitor since pCO_2 in the sea would increase by leaked CO_2. However, it is difficult to distinguish high pCO_2 values due to CO_2 leakage from those due to natural variability in some areas. In the present study, we discuss a method to assess anomalously high values of pCO_2 using not only pCO_2 but also dissolved oxygen. As an example, we analyzed data observed in Osaka Bay. We have shown that the method using both pCO_2 and DO is effective in the eastern (innermost) part, where stratification is relatively strong throughout the year. However, the method is less effective in the western part of Osaka Bay, where water is relatively well mixed vertically due to strong tidal currents. We have concluded that observing pCO_2 and assessing it based on both pCO_2 and DO is potentially a useful option for marine monitoring although this method is not effective in all sea areas.

Keywords: offshore storage, CCS, partial pressure of CO2, dissolved oxygen, marine monitoring

