Japan Geoscience Union Meeting 2014
(28 April - 02 May 2014 at Pacifico YOKOHAMA, Kanagawa, Japan)

HRE31-01 Room:419 Time:May 2 09:30-09:45

CCS-geoengineering: the only one reasonable climate geoengineering technology at present

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The climate geoengineering is already inevitable to avoid imminent global climate disasters. Even extreamly cautious approach is not enough for any grand-scale practices of climate geoengineering as we never understand the complex global climate system exactly. However, modern human beings have unintentionally done the global-scale climate geoengineering that increases the atmospheric CO2 level with the wide-spread massive burning of fossil fuels.

The CCS-geoengineering in the broad sense includes the CO2 capture and sequestration, CO2 capture and CO2-EOR/EGR, air capture and sequestration, air capture and CO2-EOR/EGR and also underground microbial CO2 recycling. The CCS-geoengineering only reduces the artificial emission of CO2 into the atmosphere or suck the excessive CO2 from the atmosphere. The CCS-geoengineering is a naturally safe geoengineering technology as the CCS-geoengineering restore the atmosphere only toward the natural CO2 level minimizing untoward effects.

Keywords: geoengineering, CCS, atmosphere, EOR, recycling, global warming

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The influence of measurement methods on evaluation of threshold pressures

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In site selection process for the geological sequestration of greenhouse gas, threshold pressures should be evaluated as sealing efficiency of a seal layer. Threshold pressure means the minimum gas injection pressure over which constant gas flow will occur through a sealing layer. For evaluating threshold pressure, strictly conditioned tests to reproduce in-situ stress, fluid pressure, temperature and type of injected gas will sometimes be planned. On the contrary, easy evaluation by simple method will sometimes be planned by estimating capillary pressure curves from pore size distributions and surface tensions. The former will provide more strict evaluations of threshold pressures but this process will be limited by using a particular test apparatus. So, researches for comparing the test results from some methods to verify the accuracy of each test have been studied. In the research on CO2 geological sequestration, three methods are usually used; i.e. (1) threshold pressure test using supercritical CO2, (2) threshold pressure test using N2 gas, (3) threshold pressure estimation from a mercury intrusion test result. In abroad, some researcher report that the results from different methods are consistent considering the surface tensions of relevant fluid system, but others say that the results are inconsistent because of the sample preparation process or anisotropy of samples. Also, there are only few studies in Japan. The authors conducted three kinds of tests using domestic and foreign sedimentary samples (mudstones and sandstones) and examined the consistencies of their results.

Comparing the results using supercritical CO2 and N2 gas, the threshold pressures might be consistent considering the surface tensions in relevant fluid systems. However, there are some inconsistencies with the anisotropic young sediments which could not be reused because of their low solidification. On the other hand, the threshold pressures from mercury intrusion tests with estimation are almost equal to or a little lower than those from N2 threshold pressure tests. This discrepancy may be caused by the anisotropy or shrinkage during drying process.

In Japan, the candidate of seal formation will be thought as not only massive mudstones but also alternated layers of mudstones and sandstones. In latter case, a limit number of strictly conditioned tests should be compensated by sufficient number of lower quality test results. So, the approach in this study will be important in future site selection process.

Keywords: threshold pressure, seal layer, sealing efficiency

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HRE31-03 Room:419 Time:May 2 10:00-10:15

Evaluation of permeabily fault related damage zone in sandstone from a viewpoint of microstructure

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It is known that strengthened fragmentation is often observed in damage zones along the fault planes. Studying permeability of faults and damage zones is important because they control fluid migration in subsurface environment (e.g. oil migration and reservoir development, carbon dioxide storage, methane hydrate development). Field and laboratory permeability test have shown that permeability within shear bands, fault gouge or cataclasite is lower than of wall rocks (Zhang and Tullis. 1998), and permeability of damage zones is higher than wall rocks (Fowles and Burley. 1994). The authors compared permeabilities of the wall rocks and damaged zones and their relation to the changes in porosity and pore-size distribution obtained by mercury porosimetry.

The sample was chosen from sandstones from the Nichinan Formation. We conducted shear test on cylindrical sample 90mm in diameter and 180mm long to develop damaged zones in the sample. Cylindrical sample of 50mm in diameter and 25mm long were then cored from the 90mm sample, that intersected the shear plane and damages zones at right angle. The permeability tests were conducted on the cored sample using transient pulse method (Brace et al. 1968) at effective confining pressures 5 and 10MPa. We calculated permeability by Hsieh method (Hsieh et al. 1981) that considered the specific storage value of sample and apparatus. Porosity and pore-size distribution were measured using mercury porosimetry on 10mm cube samples taken from 0 to 10mm, 10 to 20mm, 20 to 30mm, 30 to 40mm from the shear plane.

The permeability of the intact wall rock was 9.40x10^{-9}m/s at 5MPa effective confining pressure, and 2.52x10^{-9}m/s at 10MPa. Permeability of damaged zones were 1.41x10^{-8}m/s at 5MPa effective confining pressure, and 2.70x10^{-9}m/s at 10MPa. Porosity of the intact wall rock was 7.9% and the pore size was dominantly ~0.1 micro meter. Along the damaged zone, the frequency of 0.1 micro meter pore decreased and that of 0.5 to 10 micro meter pore increased with decreasing distance from the shear plane. On the other hand the porosity of the damaged zones was 5% in average and no clear correlation was observed between the distance from the shear plane and porosity. We suggest that pore structure was affected by micro-fractures or rearrangement of grains from the porosity reduction in the damaged zone samples; nevertheless permeability of the damaged zone samples is higher than that of wall rock samples.

Keywords: permeability, permeability test, mercury porosimetry, pore-size distribution, shear test

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HRE31-04 Room:419 Time:May 2 10:15-10:30

Injection-induced seismicity: insights gained from laboratory AE study using sedimentary rocks

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Injection-induced seismicity associated with applications, in which fluids are intensively pressed into deep formations such as Enhanced Geothermal System (EGS), fracking shale gas, geological sequence of CO2, have attracted growing attentions. Motivated by the desire to better understand the mechanism of damaging events so that they can be avoided or mitigated, we have started an integrated study on rock fracturing and fault reactivation in multiscales. In the present paper, we present some preliminary results of an ongoing experimental study utilizing acoustic emission technique in laboratory. Samples of typical sedimentary rocks collected from Sichuan basin, China, where a number of injection-induced seismic swarms with sizable earthquakes ranging up to M4˜5 have been observed in some gas/oil reservoirs. Since most injection-induced earthquakes are located in sedimentary formations of a wide range of lithology and depth, the fracturing behaviors of such rocks are thus important. In order to investigate the role of over pressured fluid in triggering fault instability, the authors carried out two rock fracture tests under tri-axial compression in laboratory. Detailed space-time distribution of acoustic emission due to microcracking was used to examine pre-failure damages and failure behaviors. Our experimental results demonstrate that dolomitic limestone, shale, and porous sandstone from the Sichuan basin show both brittle and ductile fracturing behaviors depending on a number of factors, including drainage condition and confining pressure.

Keywords: Acoustic emission (AE), Microfracture, Rock fracture, Injection-induced earthquake, Sedimentary rocks

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HRE31-05 Room:419 Time:May 2 10:30-10:45

Geochemical reproduction of deep water related to Matsushiro earthquake swarm for TOUGH-FLAC simulation

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A technique of fluid flow ? rock mechanics couple simulation is attracting attentions in the research on CO2 geological storage (CGS) as a promising tool to assess stress conditions in reservoir and caprock associated with CO2 injection. The assessment is important in CGS to set conditions for sustainable injection that does not cause dynamic responses of underground rock mass such as plastic deformation, minor fracturing, re-activation of small faults and so on. AIST is conducting a study using TOUGH-FLAC simulator developed by LBNL, USA, to numerically simulate the 1965-1967 Matsushiro earthquake swarm as a natural analogue of dynamic leakage of stored CO2 associated with fault re-activation. The study using natural data was chosen as the basic data on ground motions and recognizable seismicity would never be obtained in actual CGS demonstration sites because the dynamic responses of rock mass must not occur in the demonstration. The objective of this natural analogue study is to customize the simulator applicable to Japanese CGS sites having bedrocks composed of so-called ”soft rock”.

It is necessary for fluid flow ? rock mechanics coupled simulation to give salinity of formation water in a geologic model as an initial condition. In the case of Matsushiro simulation, the salinity of injected water is also necessary since the Matsushiro earthquake swarm is considered to be caused by a forcible intrusion of saline water beneath the Marsushiro area. The salinity of initial formation water is determined from water geochemistry on several deep wells obtained in the survey during 2010-2011. The salinity of input water is newly estimated based on the similar dataset combined with hydrogen and oxygen isotopic ratios. The hydrogen and oxygen isotopic ratios of well water fall on a line having a gentle slope as compared to the meteoric water line (MWL), a similar relation reported by Yoshida et al. (2002). The extension of this line presents a field of ”andesitic water” by Guggenheim (1992). Assuming that the deep water caused the earthquake swarm has isotopic characteristics of the minimum of ”andesitic water”, the ratio of dilution of the deepest well water was determined from the isotopic ratios of the ”andesitic water” and of the shallow ground water on the MWL. The geochemistry of the deep water caused the earthquake swarm was then determined by using the dilution ratio and the compositions of the deepest well water. The salinity of the deep water caused the earthquake swarm is found to be comparable to present sea water. The salinity is about 7 times higher than that assumed in the previous study of TOUGH-FLAC modeling of the Mtaushiro earthquake swam (Cappa et al., 2009). Similarly, the concentration of HCO3 is estimated by using well water data. The estimated amount of CO2-related soluble species indicates that the initial deep water was oversaturated with respect to CO2 at the postulated temperatures and pressures of Matsushiro simulation.

Keywords: CO2 geological storage, Matsushiro earthquake swarm, natural analogue, dynamic leakage, TOUGH-FLAC, salinity

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HRE31-06 Room:419 Time:May 2 11:00-11:15

Seismic monitoring at the commercial-scale CO2 geological storage site, Cranfield, U.S (Part 3)

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Public concerns about felt seismic events induced by fluid injection have been raised recently. These felt events have magnitudes of more than $M_L 3$ and occur in the area where seismicity not active. The induced seismic events were triggered due to the pressure changes at the reservoir. CO_2 geological storage, a kind of the fluid injection activities, is regarded as a key potential technology to mitigate greenhouse gas emission. Since this technology involves long-term and large amount of CO_2 injection, some researchers warm that CO_2 geological storage would trigger felt seismicities at the site. Passive seismic monitoring is conducted at CCS sites around the world since 2000's. A few of the sites reported occurrences of seismic events related to CO_2 injection and these events were unfelt with small magnitudes. To ensure the safety against induced seismicity and obtaining public acceptance, seismic monitoring is necessary for operating CCS project, especially for countries with high seismicity such as Japan.

RITE has performed a long-term seismic monitoring at the commercial-scale CO_2 injection site in the U.S. to elucidate the relation between CO_2 injection and occurrences of seismic events collaborating with Lawrence Berkeley National laboratory (LBNL) and Bureau of Economic Geology, University of Texas at Austin (BEG) since 2011. Seismic monitoring is conducted at the Cranfield oilfield, Mississippi. This oilfield is the CO_2-EOR field and a million tonnes of CO2 is annually injected into the Cretaceous sandstone reservoir (porosity 20 ˜30%, permeability for 10 ˜200mD) at the depth of about 3,100m. A total of more than four million tonnes of CO_2 have stored as of January 2013. We composed a circle seismic monitoring array deploying 6-3component of seismometers at the depth of 100m in a 3km radius.

We have monitored seismicities more than two years now, but we have recorded no seismic events at the Cranfield site. The recorded of vertical components of waveforms were examined by semi-automated processing and visual judgments for the entire monitoring of period, and the triggered signals were all identified as artificial noises, noises due to weather changes such as lighting or strong wind, and distant earthquakes.

In this presentation, we discuss why seismic events were not recorded at the Cranfield site. We estimated minimum detectable magnitudes of our monitoring array by means of theoretical calculations based on discrete wavenumber integration method which concerned geological properties from surface to the reservoir. We confirmed that the array could detect seismic events with more than Mw0.4 at the hypocentral distance of 3.2 km. We also discuss the question in terms of pressure changes at the reservoir and other studies conducted at the Cranfield site.

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Keywords: CO_2geological storage, Seismic monitoring, fluid injection

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HRE31-07 Room:419 Time:May 2 11:15-11:30

Risk Assessment Study of Bio-CCS (2)

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Among in-situ geo-microbes within depleted oil/gas reservoir, there are some species those generate methane gas from residual oil. Mayumi et.al (2013) identified some methanogens in depleted oil reservoir, those generate more methane gas when they are cultivated in higher CO2 partial pressure environment than in CO2 poor environment. CO2 acts as a catalyst in the reaction. If we maintain preferable conditions for methanogenesis archaea during geological CCS, we will be able to abate greenhouse gas emission and produce natural gas as natural energy resource at the same time. We named the technology concept as 'Bio-CCS'. Assuming Bio-CCS site, CO2 is injected from a well for to abate greenhouse gas emission and cultivate methanogenic geo-microbes, and CH4 is produced from another well. The procedure is similar to the Enhanced Oil/Gas Recovery (EOR/EGR) operation, but in Bio-CCS, the target is generation and production of methane out of depleted oil/gas reservoir during CO2 abatement. We are evaluating the basic practicability of Bio-CCS. In our project, while biologists are identifying the most effective cultivating conditions for methanogenic archaea, geologists, environmental scientists and system scientists are evaluating feasibilities of the technology concept. To evaluate total feasibility of Bio-CCS concept, we are estimating: CH4 generation volume, environmental impact along with life cycle of injection well, and risk-benefit balance of the Bio-CCS. For that purpose, we assumed two conceptual sites of Bio-CCS: One is depleted oil field and the other one is depleted gas field. In our presentation, we will introduce methodologies and interim results of our feasibility study on Bio-CCS.

Keywords: CO2 Geological Storage, CCS, Methanogenesis, Feasibility study, Risk assessment, Methane gas

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HRE31-08 Room:419 Time:May 2 11:30-11:45

Horizontal wells placement optimization for CO2 geological storage in confined aquifers subjected to brine recycling

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Geological storage of CO_2 has potential of mitigating CO_2 emissions into the atmosphere. CO_2 in geological formations can be trapped through solubility, residual, mineral, and structural trapping mechanisms. Of these trapping mechanisms structural trapping is likely to be the least secure because CO_2 accumulated at the cap-rock can potentially leak through pressure-induced fractures in the cap-rock.

In order to maximize the trapping of CO_2 and at the same time prevent the leakage of CO_2, placement of injection and production wells were optimized in a saline aquifer subjected to brine recycling under the constraint of a fixed maximum bottomhole pressure which corresponds to the breakthrough pressure of the cap-rock. Contrary to previous well placement optimization studies, in this study the target geological formation is a confined saline aquifer, permeability is heterogonous (10 - 100 md), and wells for CO_2 and brine injection are horizontal. TOUGH2-ECO2N and an iterative Latin hypercube sampling optimization method were employed for the multiphase flow and optimization calculations, respectively. Optimization variables included the locations of two CO_2 injection wells and one brine production well, as well as the injection rate of CO_2. The total volume of the geological model is 20 km $\times$ 20 km $\times$ 0.1 km which has 4 layers initially containing only brine at a temperature of 40 ℃ and pressure of 10 MPa at the top layer. Simulations were performed for 30 years of CO_2 injection at rates of 5 - 20 kg/s, and 10 years of brine production and/or recycling. The two injection wells for brine recycling were located above the two CO_2 injection wells.

Optimizations of wells placement were performed for two scenarios: 1) injection of CO_2 without brine recycling, and 2) injection of CO_2 with brine recycling. Our optimization results indicate that placing brine injection wells above CO_2 injection wells in conjunction with equal fractions of brine recycling and CO_2 injection to each well leads to highest amounts of dissolution and residual trapping of CO_2. The trapping of CO_2 was improved by 5.4% with brine recycling in comparison to the trapping of CO_2 obtained without recycling (13.26 Mt). Although CO_2 was confirmed to be produced along with brine from production wells located near the injection wells, placement of the production well has shown to have little to no affect on the trapping of CO_2 under the given conditions. With regard to the optimal placement of injection wells, 3 and 6 potential areas were clearly identified for scenario 1 and 2, respectively. It is theorized that heterogeneous permeability formations may have multiple local optima; however this is yet to be confirmed.

Keywords: CO2 geological storage, Well placement, Brine recycling, Optimization

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HRE31-09 Room:419 Time:May 2 11:45-12:00

Reservoir Rocks of CO2 Micro-Bubble Storage (CMS) and its Dissolution Characteristics

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Among many different portfolios in the CCS technology, CO2 micro-bubble storage (CMS) system that stores CO2 by injection in the gas phase and dissolution at shallower depths has been proposed. Basic concept of CMS is the replacement of underground water with CO2 dissolved water. CO2 is stored safely once it is dissolved and there is low leakage risk because of residual micro-bubbles having little buoyancy forces. CO2 dissolved in water is weakly acidic and can react with the minerals in the surrounding rocks. It is well-known that acidic solution is neutralized by rocks as it soaks into the ground, however the ability of neutralization is not completely estimated.

In this paper, in order to estimate the ability of rocks to neutralize CO2 micro-bubble dissolved water, two types of dissolution experiments of rocks were carried out using crashed and column specimens of sedimentary rock such as limestone, sandstone, and tuff. A batch type dissolution experiment in which rock samples were treated with the solution of CO2 dissolved in pure water using micro-bubble under CO2 partial pressure 0.0003 atm. And a flow-through type dissolution experiment was carried out using limestone samples for over 40 days in order to investigate the change of pore structure between before and after experiment. From these experimental results, the dissolution rate and the ability of neutralization of reservoir rocks were discussed.

HRE31-10 Room:419 Time:May 2 12:00-12:15

Dawsonite synthesis/dissolution experiment under the relevant condition of CO_2 underground storage

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Geochemical trapping is a mechanism for defining the longer-term security of CO_2 underground storage. Especially, mineral trapping improves the storage security by the transformation reaction of injected CO_2 (liquid or supercritical phase) to carbonate minerals.

Recently, several studies based on the computer simulation predicted the formations of dawsonite ($NaAlCO_3 (OH)_2$) as an initial phase of mineral trapping and that dawsonite may play important role for the storage security in the early stage of CO_2 storage. However, it has not been reported the formation of dawsonite in the experiments under the relevant condition of the CO_2 underground storage to date and the problem "whether dawsonite will be formed in the CO_2 reservoir and will contribute the improvement of the CO_2 storage security" is still remaining.

In this study, therefore, we conduct the synthesis/dissolution experiments of dawsonite under the CO_2 reservoir condition and discuss the formation/preservation condition of dawsonite. We further discuss the possibility of dawsonite formation in the CO_2 reservoir based on our experimental results.

Keywords: CO_2 underground storage, mineral trapping, dawsonite

HRE31-11 Room:419 Time:May 2 12:15-12:30

Liquid carbon dioxide storage beneath man-made hydrate-seal layers

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The findings by Sakai *et al.* (1990) that carbon dioxide (CO_2) hydrate occurs on the Okinawa Trough seafloor of 1,335m in depth and at a temperature of 3.8^{o}C stimulated the research on how to isolate the anthropogenic CO_2 from the atmosphere. Various offshore sites under the CO_2-hydrate stable conditions, *i.e.* above 4.4MPa and below 10^{o}C, are found in the Japan Archipelago. Above all, there are ten or more places where from the coastline the ERD well can make a direct access to the sub-seabed under the CO_2-hydrate stable conditions (Ohsumi, 2012). Sakai *et al.* postulated that CO_2 hydrate fills in the pore of the sediment right beneath the sea bottom, which can be explained by the fact that the density of $CO_2 \bullet nH_2O$ as calculated to be 1.07 ~ 1.04 g cm^{-3} corresponding to n = 7 ~ 8, is larger than that of the bottom seawater, and hence the even thin hydrate layer functions as a barrier for the underlain fluid (its estimated density is 0.92 g cm^{-3}) composed mainly of liquid CO_2 tending to leak to the bottom waters.

Koide *et al.* (1997) pointed out that the formation of CO_2 hydrate in pores and gaps, in rocks and sediments, could almost completely block the migration of fluid. CO_2 that is injected into a deep reservoir would migrate upward into cooler aquifers and eventually form a CO_2 hydrate cap. Numerous engineering studies thereafter were targeted at how such a sealing layer can be created in the CO_2 storage site. It should be noted that CO_2 hydrate exposed to the open bottom water will be dissolved easily even under the low-temperature, high-pressure stable conditions. Nevertheless, in his examination on how underwater pavement operation could realize the CO_2-hydrate storage beneath seabed, Ohsumi (2012) illustrated that a 1-m thick sediment layer would be enough to serve as an effective barrier. Since the solute CO_2 diffusion in sediment pores between the hydrate layer and the sea-bottom is rate-limiting, the seepage flux of CO_2 would be below 0.1 $kgCO_2$ m^{-2} per year.

There is an offshore steep slope to the Sagami Trough at the north-east coast of the Izu-Oshima Island. A 440-m isobath is near to the shoreline (the nearest point is 1.1 km offshore) and hence due to the fact that the sea bottom temperature will not exceed 10^{o}C throughout the year, the CO_2-hydrate stable conditions spread over the offshore bottom and its sub-seabed. The offshore geology consists of "old volcano" bodies, several hundred thousand years of age, of which volcanism is probably similar to the present volcano of the Izu-Oshima Island. Hence, we can suppose that it is composed of alternating layers of basalt lava and pyroclastic rocks. When the pores of horizontally permeable layers are filled with CO_2 hydrate, the underlain formations can hold the liquid CO_2 for storage. Ikegawa *et al.* (2012) proposed the injection method of CO_2-in-water emulsion applicable to the sedimentary layers for the purpose of enhanced recovery of methane hydrate. By their method, while avoiding hydrate blockage in the horizontal pore space flow, as shown in Figure we might be able to create the effective CO_2-hydrate seal layers with a large area coverage. A horizontal coverage of the supposed storage site could be 5$\times$1 km. When storage layers with 200-m effective thickness are selected, 10% of the effective pore volume ratio for liquid CO_2 storage gives 100 million tCO_2 as an attractive storage potential.

Ikegawa, Y *et al.* (2012) *CRIEPI Report* N11024 (in Japanese with English abstract); Koide *et al.* (1997) *Energy* **22**(2/3) 279-283; Ohsumi, T (2012) The 23rd Ocean Engineering Symposium (in Japanese with English abstract); Ohsumi,T (2013) *2013 Fall meeting Programme and Abstracts* (in Japanese) 152-154; Sakai *et al.* (1990) *Science* **248,** 1093-1096.

Keywords: man-made seal layer, CCS, hydrate seal, Izu-Oshima Island, Extended Reach Drilling, CO2-in-water emulsion

HRE31-11 Room:419 Time:May 2 12:15-12:30