CCSコスト
The cost of CO2 capture and storage

*中神 保秀[1]、清水 淳一[1]、斎藤　一郎[1]、高木 正人[1]
*Yasuhide Nakagami[1], Jyunichi Shimizu[1], Ichiro Saito[1], Masato Takagi[1]

1.地球環境産業技術研究機構
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.

キーワード：CCS、コスト、CO2貯留
Keywords: CCS, cost, CO2 storage

CCS実用化に向けた技術事例集の作成について
Compilation of Best Practice Manuals toward CCS commercialization

*小牧 博信[1]、間木 通政[1]、指宿 敦志[1]、高野 修[1]、薛 自求[1]
*HIRONOBU KOMAKI[1], Michimasa Magi[1], Atsusi Ibusuki[1], Osamu Takano[1], Ziqiu Xue[1]

1.公益財団法人 地球環境産業技術研究機構
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.

キーワード：CCS、CO2 地中貯留、技術事例集
Keywords: CCS, CO2 geological storage, Best Practice Manual

サウジアラビアAl Wasse地域におけるタイムラプスデータの解釈のためのアクロス屈折法調査
Refraction study using ACROSS seismic source to interpret the time-lapse data in Al Wasse field, Saudi Arabia

*笠原 順三[1,2,3]、Al-Aneezi Ghunaim[5]、Al Damegh Khaled[5]、村瀬 圭[3]、大沼 寛[3]、藤本 理[3]、上村 彩[3]、羽佐田 葉子[4]
*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.静岡大学防災総合センター、2.東京海洋大学産学地域連携機構、3.川崎地質（株）、4.大和探査技術（株）、5.KACST
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.

キーワード：タイムラプス、アクロス、地殻構造、シャドーゾーン、帯水層、揚水
Keywords: Time-lapse, ACROSS, crustal structure, shadow zone, aquifer, water pumping

リアルタイムイベント検出への忘却型学習アルゴリズム（SDAR）の適用について
Application of Sequentially Discounting AR Learning (SDAR) Algorithm to Real-time Event Detection

*高岸 万紀子[1]、利岡 徹馬[1]、成田 章[2]、古瀬 慶博[2]、薛 自求[1]
*Makiko Takagishi[1], Tetsuma Toshioka[1], Akira Narita[2], Nobuhiro Furuse[2], Ziqiu Xue[1]

1.公益財団法人 地球環境産業技術研究機構、2.三菱スペース・ソフトウエア株式会社
1.Research Institute of Innovative Technology for the Earth, 2.MITSUBISHI SPACE SOFTWARE CO., LTD.

CO_2圧入サイトにおける微小振動観測は、安全な貯留を示す上で重要なモニタリングの1つである。近年、多くのCO_2圧入サイトで微小振動観測が行われている。特に、観測された大量の波形記録から、リアルタイムでイベント（自然地震、微小振動）とノイズを正確に区別して到達時刻を読み取ることにより、信頼性の高い震源決定を行うが可能となる。
一般的なイベントのシグナルの検出方法として、波形振幅にしきい値を設定する方法、STA/LTA法（Coppens, 1985）、ARモデルとAICを組み合わせた手法（横田・他、1981）などが挙げられる。これらの手法はS/N比が良好な波形に対して非常に有効であり、自然地震などの波形処理に用いられている。一方、CO_2圧入に伴う微小振動はマグニチュードが小さく、多くはM0程度かそれ以下である。海域のCO_2貯留サイトの場合、海底面に設置された観測機器のデータはノイズレベルが高いため、ノイズに対してロバストなイベント検出手法が必要となる。
RITEではノイズを適切に処理できて、マグニチュードが小さいイベントをリアルタイムで検出する手法として、忘却型学習アルゴリズム（SDAR: Sequentially Discounting AR learning）を用いた波形処理手法に取り組んでいる。SDARは、非定常な時系列データを、局所的に定常性を仮定して自己回帰モデル（ARモデル）で表し、過去のデータを徐々に忘れながら新しいデータの性質に適応して統計モデルを更新するアルゴリズムである。つまり、先見情報を必要とせず、リアルタイムで時系列データにおける値の急激な変化を検出できる。もともと情報通信分野で開発された方法であり、不正アクセスの検知や侵入検知などに活用されていた（Takeuchi and Yamanishi, 2006）。
本報告では、このSDARを用いたリアルタイムイベント検出手法について紹介する。
[引用文献]
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.
横田崇・周勝奎・溝上恵・中村功(1981)：地震はデータの自動検測方式とオンライン処理システムにおける稼働実験、地震研究所彙報、55、449-484.
[謝辞]
本研究は経済産業省委託事業「二酸化炭素回収・貯蔵安全性評価技術開発事業」の一環として行われた。

キーワード：CO2地中貯留、忘却型学習アルゴリズム（SDAR)、リアルタイムイベント検出、微小振動観測
Keywords: CO2 Geological Storage, Sequentially Discounting AR Learning (SDAR), Real-time Event Detection, Microseismic Monitoring

水銀圧入法および直接法による超臨界CO_2スレッショルド圧力の評価

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

*木山 保[1]、薛 自求[1]
*TAMOTSU KIYAMA[1], Ziqiu Xue[1]

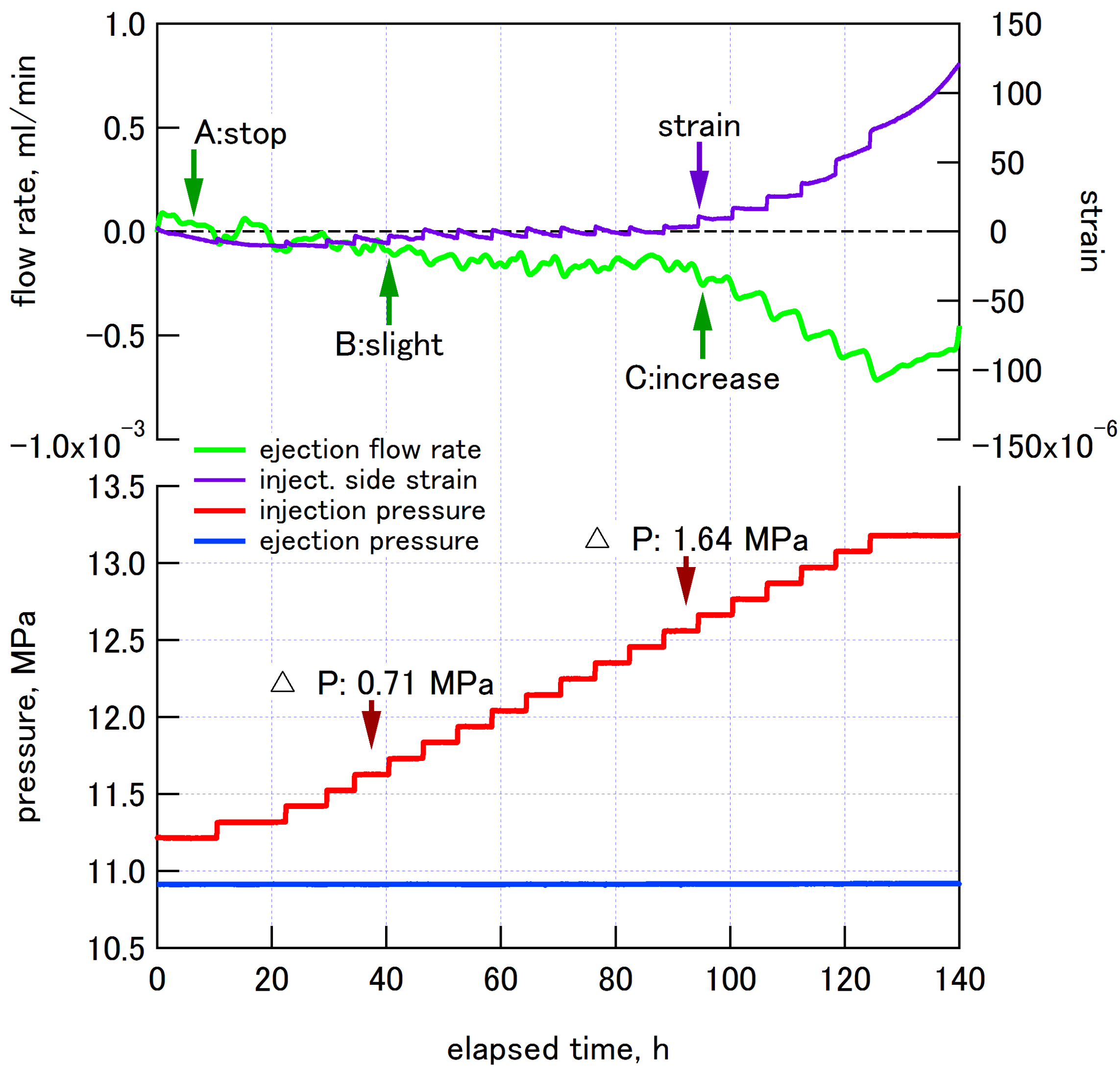
1.公益財団法人地球環境産業技術研究機構
1.Research Institute of Innovative Technology for the Earth

CCSにおいて遮蔽層のスレッショルド圧は貯留層のCO_2貯留能力を支配するので，スレッショルド圧の正しい評価はCO_2地中貯留を安全かつ経済的に設計し実施するために重要である。スレッショルド圧は，ブラインで飽和した多孔質岩石に超臨界CO_2が浸入する際の毛管圧に起因するので，細孔径分布，接触角および界面張力などに支配される。本論では新第三紀泥質岩を対象とし，まず細孔径分布を水銀圧入法で分析した。接触角および界面張力を設定し，特徴的な細孔径と毛管圧の関係を検討した。つぎにコア試料を用いて，段階昇圧法，残差圧力法などの直接法でスレッショルド圧を測定した。CCSの原位置条件を考慮して，間隙圧は10MPa，温度は40℃とした。試料は，直径50mm，長さ50mmで，両端面から10mmの位置に周方向にひずみゲージを貼付した。
段階昇圧法の事例を図示する。事前に残差圧力法で測定し，その後十分通水して初期状態に戻し，段階昇圧法に供した。残差圧力法で0.60MPaのスレッショルド圧が評価されたので，初期の差圧を0.3MPaから始め，その後0.1MPaずつ段階昇圧した。図中A点で排出流量が停止し，超臨界CO_2が試料の端面に到達したことを示唆する。B点でわずかな排出流量の増加が確認された。段階昇圧法の定義に従って1つ前のステップの差圧をスレッショルド圧とすると0.71MPaとなる。しかしその後差圧が増加しても流量の増加は認められない。つぎにC点において排出流量の明らかな増加が確認され，その後差圧が増加するのに伴って流量も増加した。ここでスレッショルド圧は1.64MPaと評価される。注入側のひずみ挙動を見ると，わずかな流量が発生したB点でわずかな膨張が認められ，流量が増大したC点で顕著な膨張が認められる。超臨界CO_2とブラインの境界では毛管圧が作用して超臨界CO_2側の圧力が高くなるので，超臨界CO_2が浸入した領域では間隙圧が高くなり，膨張変形をもたらす。
水銀圧入法の結果，細孔径分布は0.09μmと0.16μmにピークを持つバイモーダルな特性を示した。毛管圧Pcは，細孔径D，界面張力γおよび接触角θでつぎのように表される。
$Pc=4\gamma\cos\theta/D$
ここで，40℃，10MPaにおけるブラインと超臨界CO_2の界面張力γを28.5 mN/m，接触角θを0°と設定すると，上記の2つの細孔径に対応する毛管圧はそれぞれ1.27MPaおよび0.71MPaとなる。
残差圧力法による0.6MPaと段階昇圧法でわずかな流動が認められた0.71MPaは，0.16μmの細孔径に対応する毛管圧0.71MPaと良い一致を示した。また段階昇圧法で明らかに流量が増加した1.65MPaは，0.09μmの細孔径に対応する毛管圧1.27MPaに近い値を示した。
段階昇圧法におけるわずかな流動は径が0.16μmの細孔に超臨界CO_2が浸入するスレッショルド圧に，流量の明瞭な増加は径が0.09μmの細孔に超臨界CO_2が浸入するスレッショルド圧に対応すると考えると調和的である。一方，わずかな流動が発生してから，その後ほとんど流量が増加しなかったのは，細孔の容積，配向および連続性などの構造が関係していると考えられるが，これらの情報は等方的に水銀を圧入する水銀圧入法では得られない。たとえば，層構造を成す岩石の場合，コア試験では層に平行と直交でスレッショルド圧は一般に異なるが，水銀圧入法では同じ情報しか得られない。
残差圧力法は段階昇圧法などに比較してスレッショルド圧を過小評価しやすいといわれ，その一因として排水と浸潤過程で接触角が異なることなどが提案されている。本事例では0.16μmのモード径に対応する毛管圧が残差圧力法の結果に一致しているが，流動を停止して圧力の平衡を観測する残差圧力法ではわずかな流体の移動で圧力が伝播するので，段階昇圧法では流量が少なかった低い圧力でも，残差圧力法では毛管圧に漸近していくことが考えられる。
細孔径分布がバイモーダルを示さない岩石でも，淘汰が低い場合は大きい細孔径に対応する低い毛管圧で超臨界CO_2の浸入は開始し，残差圧力法では低いスレッショルド圧を示すが，段階昇圧法などではモード径に対応す

る比較的高い圧力で流量が増加すると考えられる。
水銀圧入法で分析される細孔分布特性はスレッショルド圧を評価する上で有益な情報を多く提供する。残差圧力法による結果の妥当性などに寄与することができる。一方，異方性などには対応できない。また，どの毛管圧で流量が増加するかは評価できないため，段階昇圧法などのコアを用いた直接法を省略することはできない。

謝辞：本研究は，経済産業省委託事業「二酸化炭素回収貯蔵安全性評価技術開発事業」の一環として行われた。

キーワード：水銀圧入法、超臨界CO2、スレッショルド圧力、段階昇圧法、残差圧力法、バイモーダル
Keywords: Mercury intrusion method, supercritical CO2, Threshold pressure, Step by step method, Residual pressure method, Bimodal



不均質堆積岩におけるCO_2流動の可視化と定量評価
Visualization and measurement of CO_2 flooding in heterogeneous sedimentary rock

*朴 赫[1]、蒋 蘭蘭[1]、木山 保[1]、西澤 修[1]、張 毅[1]、上田 良[2]、中野 正則[2]、薛 自求[1]
*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.公益財団法人 地球環境産業技術研究機構（RITE）、2.石油資源開発株式会社（JAPEX）
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.

キーワード：CO2流動、不均質性、X線CT、可視化、CO2-EOR
Keywords: CO2 flooding, heterogeneity, X-ray CT, visualization, CO2-EOR

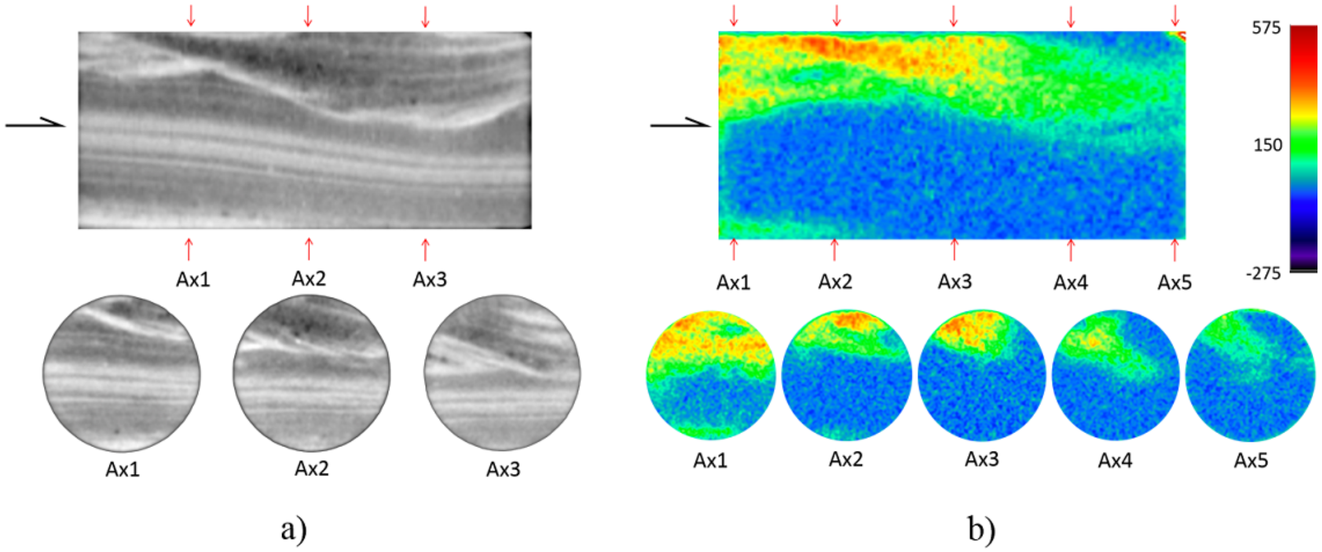


Figure 1: X-ray CT images of CO_2 flooding experiment.
a) core in dry condition, b) differential CT images at 0.26PV(pore volume) CO_2 injected

音響探査による海中の漏出CO_2気泡検知手法の開発

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

*中村 孝道[1]、西村 真[1]、内本 圭亮[1]
*Takamichi Nakamura[1], Makoto Nishimura[1], Keisuke Uchimoto[1]

1.地球環境産業技術研究機構, CO2貯留
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.

キーワード：二酸化炭素海底下貯留、漏出検知、音響技術
Keywords: sub-seabed CCS, leakage detection, acoustic methods

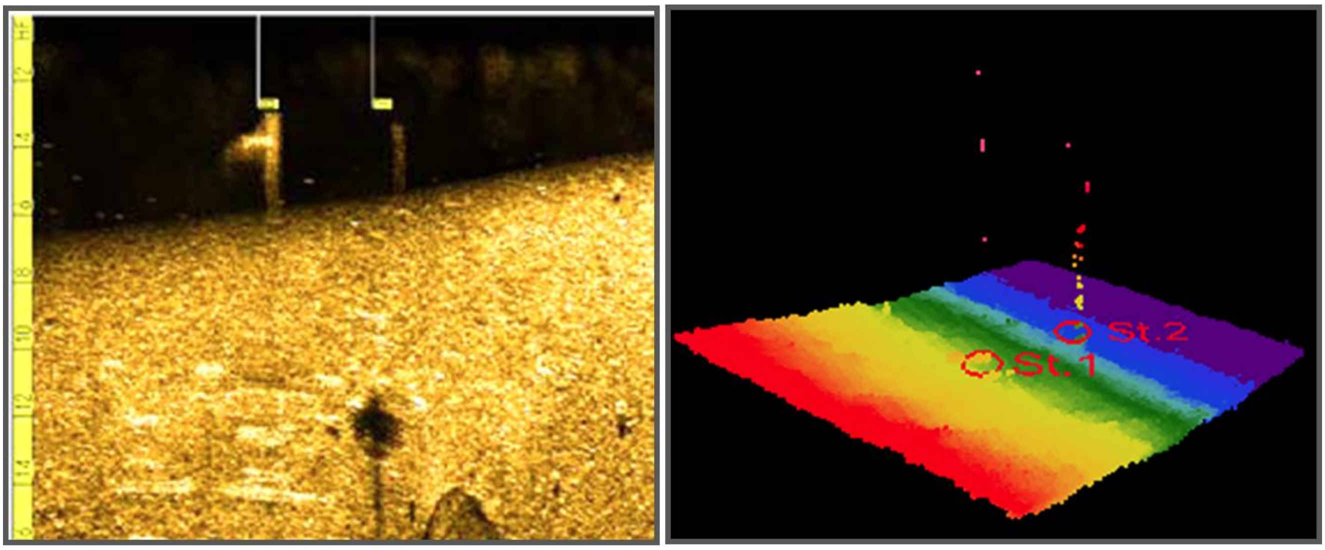


Fig. 1. Water column bubbles imaged on the data of SSS (left) and MBS (right)