The cost of CO2 capture and storage

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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

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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

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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

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

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

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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)

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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

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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.

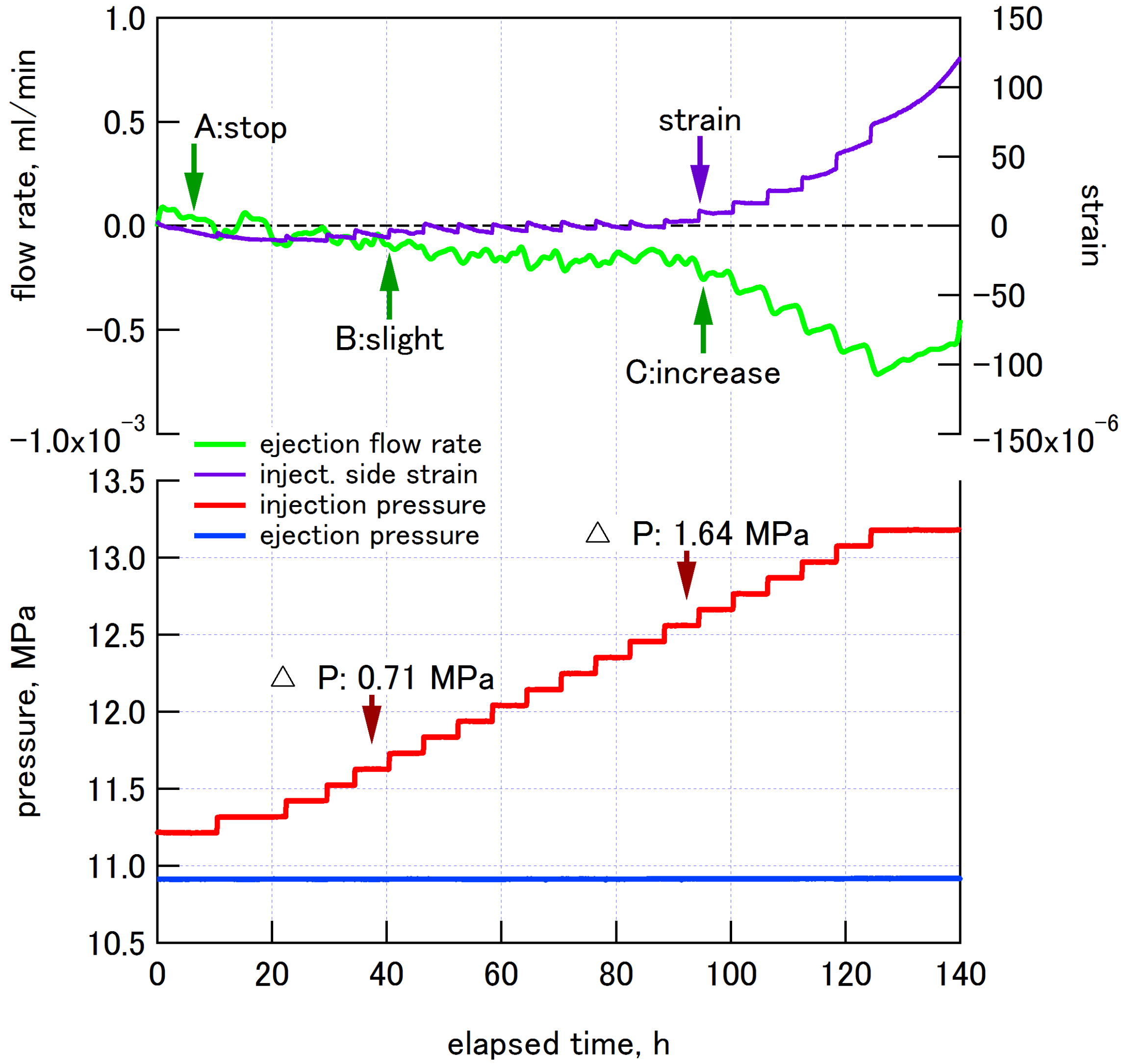
The 0.71MPa estimated by step by step method and the 0.6MPa estimated by residual pressure method were consistent with the 0.71MPa calculated by the pore size of 0.16μm with the equation described above. Also the 1.65MPa estimated by step by step method at which the flow rate increased obviously was 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

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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

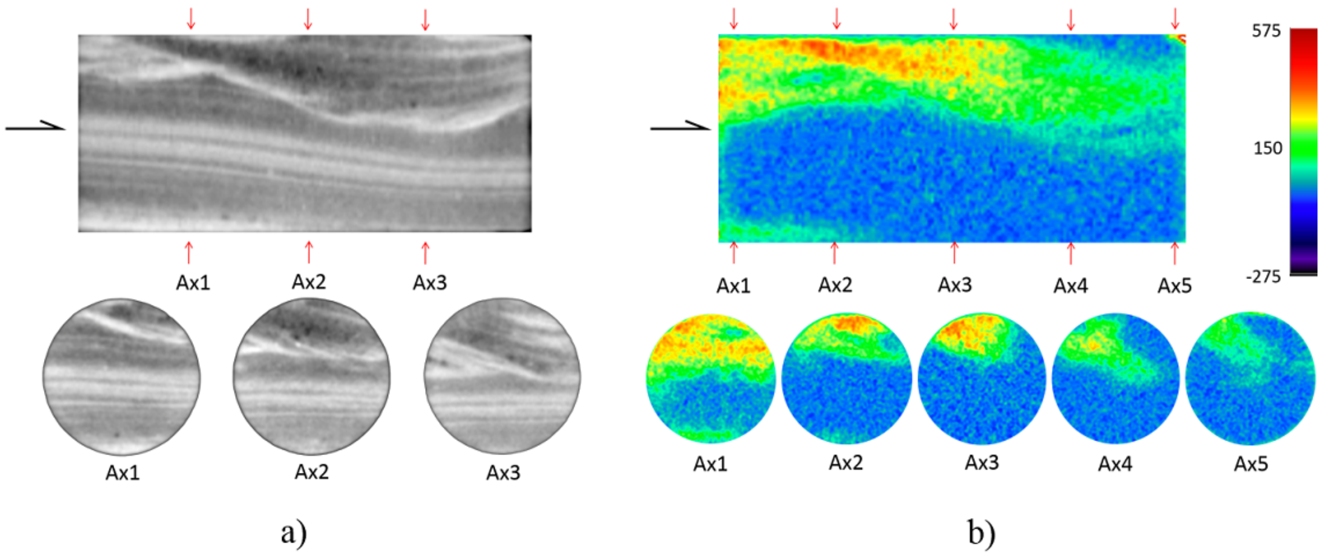

Figure 1: X-ray CT images of CO_2 flooding experiment.
a) core in dry condition, b) differential CT images at 0.26PV(pore volume) CO_2 injected

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

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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

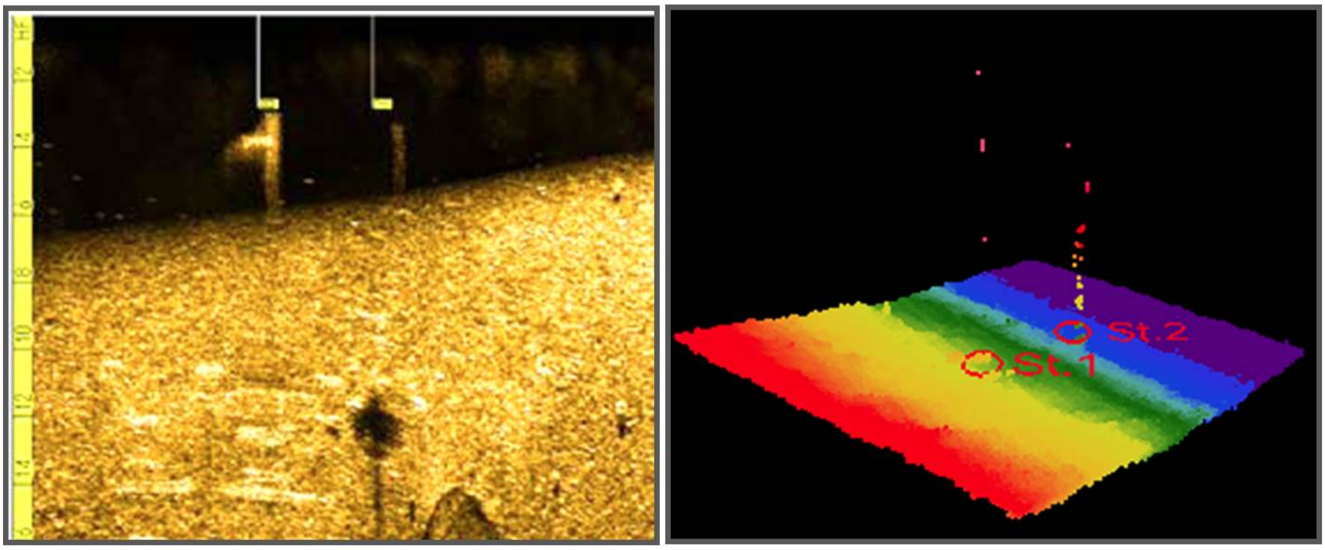

Fig. 1. Water column bubbles imaged on the data of SSS (left) and MBS (right)