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Bubble Detection with Side-scan Sonar in Shallow Sea for Future Application to Marine Monitoring at Offshore CO_2 Storage Sites

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Abstract An important challenge in the offshore storage of carbon dioxide (CO_2) in deep geological formations is how to monitor storage sites to detect CO_2 leakage in the event that it occurs. A promising candidate for the monitoring is to detect CO_2 bubbles in the water column using some kinds of sonar. However, the detectability of bubbles is not well known. Here we show the ability of side-scan sonar (SSS) to detect air bubbles in the water column through an in-situ experiment, where two sizes of air bubbles, about 1 cm and 1-2 mm in diameter, released at the seabed around 6 meters deep are observed with SSS. The principal results are the following. When the slant distance between SSS and bubbles is longer than the distance between SSS and the seabed, the detection of the bubbles is difficult because of the echoes from the seabed. Tiny bubbles are much easier to detect with SSS than bubbles with diameter of about 1 cm if the release rates are the same, and the detection limits of the release rate are estimated to be not larger than 20 ml/min for tiny bubbles, and not smaller than 20 ml/min for bubbles with diameter of 1 cm, under the present experimental conditions. Although the results cannot be directly applied to CO_2 bubbles because CO_2 bubbles are much easier to dissolve in seawater than air bubbles, it is estimated that CO_2 bubbles leaking at 4.76 tonnesCO_2/year could be detected. This leakage rate is smaller than the release rate at a controlled sub-seabed CO_2 release experiment, called QICS, and therefore, SSS will be a useful tool to monitor offshore CO_2 storage sites.

Keywords: *side-scan sonar, bubble detection, CCS, offshore CO_2 storage, leakage, marine monitoring*

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1. Introduction

Carbon dioxide (CO_2) capture and storage (CCS) is a process in which CO_2 is captured at large volume sources such as fossil fuel power plants, is transported to deep geological reservoirs, and is stored there. CCS is thought to be a promising option to reduce emissions of CO_2, and consequently to mitigate global warming [1].

Although the likelihood of CO_2 leakage from the geological reservoirs is believed to be remote, we have to monitor the storage sites to detect leakage of the stored CO_2 as soon as possible in the unlikely event of leakage. First, it is because there are some guidelines and regulations that require the monitoring, such as EU CCS Directive in Europe, and amendments to the 1996 London Protocol for offshore storage and so on [2]. Secondly, it is because reliable monitoring is expected to help gain public acceptance of CO_2 storage. Thirdly, it is because there might be leakage paths or mechanisms overlooked in the selection of the reservoir because of human errors or the limit of modern technology, even though the storage sites and reservoirs are well selected and managed [3].

A promising candidate item to monitor is CO_2 concentration and the like at the earth's surface, vadose zone or atmosphere for onshore storage sites and sediments and water column in the sea for offshore storage sites. If concentration values higher than the usual range are observed, it can be suspected that CO_2 is leaking. However, to grasp the usual range, long-term baseline surveys might be necessary. While a process-based method using ratios of CO_2, O_2, N_2 and CH_4 gases without the need for baseline surveys has been contrived for vadose zone monitoring [4,5], such a kind of method has not been found for marine monitoring. In addition, how long baseline surveys should be conducted remains to be studied for monitoring CO_2 concentration and the like in the sea [6].

The present study focuses on another monitoring method, applicable to shallow sea around offshore CO_2 storage sites, that does not need repeated baseline surveys. If stored CO_2, which is usually a supercritical state in deep geological reservoirs, migrates to the seabed in shallow sea, its phase turns to be gaseous. Although some of the gaseous CO_2 might dissolve in pore water before it reaches the seabed, the remainder would leak out into the water column in the form of bubbles, as was observed in a shallow controlled sub-seabed CO_2 release experiment, called QICS [7,8,9]. Thus, to search CO_2 bubbles in the water column can be a strong candidate for detecting CO_2 leakage.

Bubbles in the water column can be detected with acoustic instruments, such as multibeam echosounder [10]. Those instruments radiate acoustic waves, receive waves reflected by objects in the water column or on the seabed, or the seabed surface, and thus, inform us of the existence and the shape of the objects and the seabed. An experiment where released CO_2 bubbles in the water column were observed with multibeam echosounder, single beam echosounder and sub-bottom profiler showed that multibeam echosounder was the most suitable of the three instruments to detect CO_2 bubbles [11].

Side-scan sonar (SSS) can also be utilized for detecting bubbles in the water column [12,13,14]. However, some fundamental detectability and expertise necessary in the monitoring remain unclear. To obtain the lowest leak rate of bubbles detectable with SSS, and its dependency on the moving speed of SSS and the size of bubbles in aiming for future application to marine monitoring at CO_2 storage sites, we conducted an in situ experiment in which air bubbles were released at the sea bottom in shallow sea, and were searched with SSS.

2. Materials and Methods

2.1. Experiment

The experiment was conducted at a shallow sea area around 6 m deep off Shirahama Station, Aquaculture Research Institute, Kindai University, in the innermost part of Tanabe bay, located on the western coast of Kii Peninsula, Japan. SSS used in the experiment was a 600 kHz SSS, EdgeTech4200MP, which was fixed to a raft boat hull about 1 m below the sea surface.

We used two gas release devices, each of which has 5 outlets arranged in a line at intervals of 5 cm (Figure 1). In one device, air stones were put on the outlets so as to release tiny bubbles, about 1-2 mm in diameter (referred to as "tiny bubbles" hereafter), while air bubbles from the other device were about 1 cm in diameter (referred to as "1 cm bubbles" hereafter). From each outlet in both devices, air bubbles can be released at a rate of 0, 20, 40, or 100 ml/min. We controlled the release rate of bubbles from a device between 20 and 200 ml/min, using all the 5 outlets with the same release rate or using only one outlet. The two devices were set on the seafloor a few meters apart from each other with the lines consisting of 5 outlets perpendicular to the line joining the two devices (Figure 2).

The released bubbles were observed with SSS along two observation lines, parallel to the line joining the two devices (Figure 2); one was within a few meters from the devices (Line A), and the other was about 7 m apart from the devices (Line B). It is noted that the horizontal distance from the devices to Line A is smaller than the height of SSS, i.e. the distance between SSS and the seabed (about 5 m), and that the horizontal distance to Line B is larger than it. The boat moved at a speed of 2 knots or 3-4 knots (1 knot=1.852 km/h).

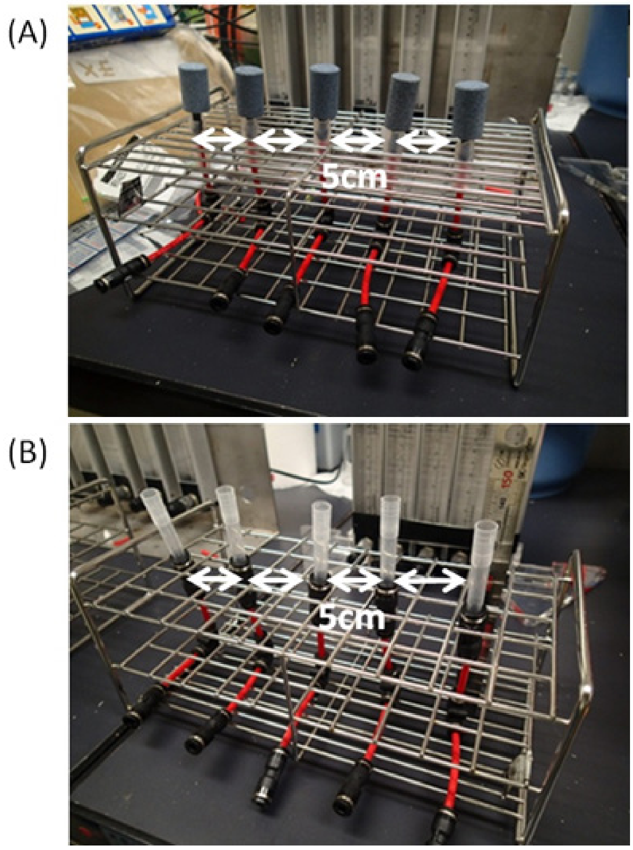

Figure 1. Gas release devices with five outlets arranged at intervals of 5 cm for tiny bubbles (A) and 1 cm bubbles (B)

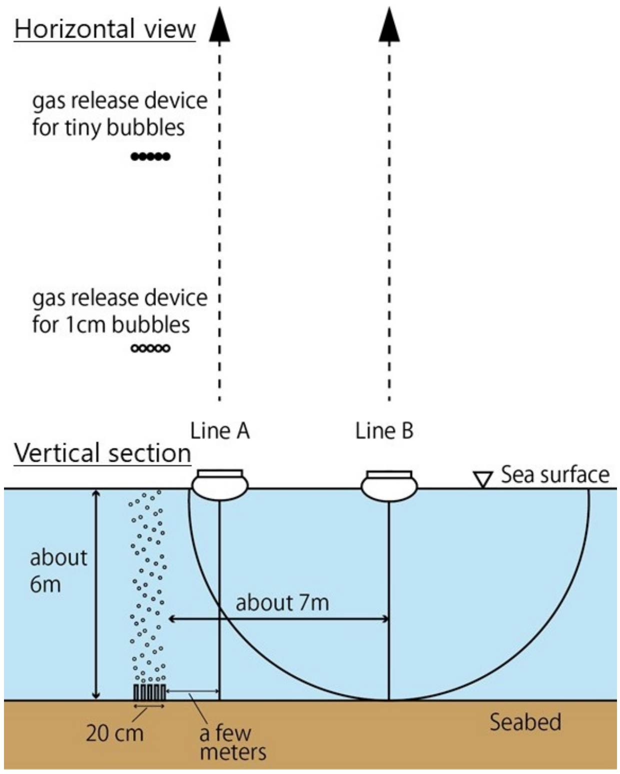

Figure 2. Schematic drawing of the positional relation between observation lines and gas release devices

Combining the release rate (20 ml/min/outlet×1 outlet, 100 ml/min/outlet×1 outlet, 20ml/min/outlet×5 outlets, or 40 ml/min/outlet×5 outlets; hereafter, we omit "outlet(s)" and express release rates like 20 ml/min×1), the size of bubbles (1cm or tiny), the speed of the boat (2 or 3-4 knots), and the observation line (Line A or B), 28 cases were tested and three times observations were made for each case.

2.2. Sonograph

The SSS data were processed to an image, called a sonograph [15], with EdgeTech Discover software. In the sonograph strength of echoes is plotted on a plane the abscissa and ordinate of which are the slant distance from SSS and the location along the moving path of SSS, respectively (Figure 3). In the vertical section perpendicular to the moving path of SSS, there are no echoes from the area within the circle C, the center of which is at SSS and the radius of which is the height of SSS (the distance from the seabed), D, unless something such as bubbles, fish and so on exists there. Consequently, the area with the slant distance from SSS less than D on the sonograph becomes a blank. On the other hand, there are always echoes from the seabed in areas with the slant distance longer than D (outside the circle C).

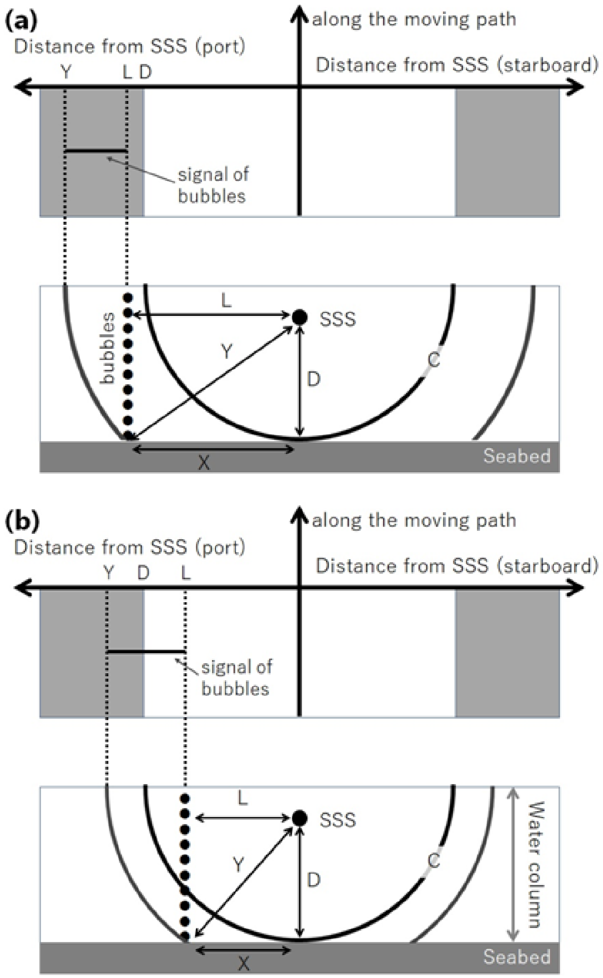

Figure 3. Schematic drawing of the relation between sonograph and vertical section of sea (a) when L > D and (b) when L < D, where L is the distance between SSS and the bubble plume and D is the altitude of SSS

Table 1. Results of the experiment

LINE	bubbles	Boat speed (knots)	Release rate (ml/min)×the number of outlets			
			20×1	20×5	100×1	40×5
A	1cm	2	○	○	●	○
		3.0-4.0	●	○	●	●
	tiny	2	○	○	○	-
		3.0-4.0	○	○	○	-
B	1cm	2	×	×	×	×
		3.0-4.0	×	×	×	×
	tiny	2	×	○	○	-
		3.0-4.0	×	○	○	-

○: 3 times detection; ●: 2 times detection; ×: denotes no detection, of 3 times observations; -: not conducted.

When the distance between an observation line and the release point of bubbles (X in Figure 3) is longer than the altitude of SSS (D in Figure 3), no bubbles exist within the circle C unless bubbles are advected towards SSS. This means that the echo of the whole bubble plume is displayed overlapping with echoes from the seabed (Figure 3a). When X < D, on the other hand, part of the signal overlaps but the remainder does not overlap with echoes from the seabed (Figure 3b). Observations along Line B corresponds to the former, and those along Line A corresponds to the latter in the present experiment.

3. Results

3.1. Observation Line and Speed of the Boat

To detect bubbles from Line B was much more difficult than from Line A. From Line B, 1 cm bubbles were not detected independent of the release rate and the moving speed of the boat, and only tiny bubbles released at 100 ml/min (both 20 ml/min×5 and 100 ml/min×1) were detected. On the other hand, from Line A, both tiny and 1 cm bubbles were detected at any rate tested here (Table 1).

Figure 4(a) is an example of sonographs observed along Line B. Although both tiny bubbles and 1 cm bubbles were released at a rate of 100 ml×1, only signals of tiny bubbles can be seen and those of 1 cm bubbles cannot be found. On the other hand, both tiny and 1 cm bubbles can be seen when observed along Line A (Figure 4d).

Even when observed along Line A, signals of bubbles that overlap with those of the seabed, corresponding to the part of the signal between D and Y on the sonograph in Figure 3b, are hardly seen (Figure 4b-e). These indicate that it is almost impossible to distinguish bubble signals against signals of the seabed when the release rate is as small as in the present experiment.

The moving speed of the boat just slightly influenced the detectability at least between 2 knots and 4 knots. Signals of bubbles were prone to be somewhat more distinct when observed at the lower speed, but the difference was not great (not shown). The higher the moving speed is, the shorter the time necessary for the monitoring is and consequently the lower the cost for the monitoring is. Hence, we should run the boat as fast as possible in the monitoring, and the present results suggest that we may run the boat at least as fast as 4 knots in the monitoring.

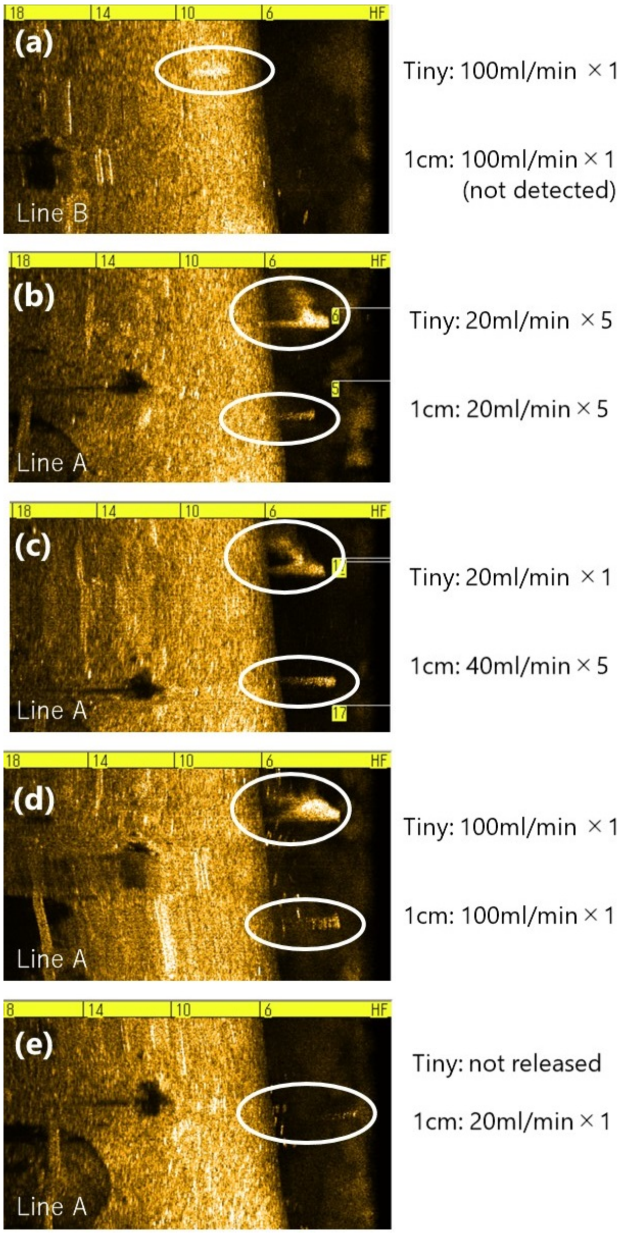

Figure 4. Examples of sonograph observed along Line A (b-e) and Line B (a) at a speed of 2 knots

3.2. Release Rate and Size of Bubbles

The detectability of SSS depended greatly on the size and the release rate of bubbles. Signals of tiny bubbles are much clearer than those of 1 cm bubbles released at the same release rate (Figure 4b and Figure 4d). Also, signals of bubbles became clearer with the increase of the release rate especially for 1 cm bubbles (Figure 4b and Figure 4c). Comparing two cases where the release rate is the same, 100 ml/min, but the number of outlets were different (Figure 4b and Figure 4d), we find no clear difference between them.

3.3. Detection Limit

The minimum release rate of bubbles that can be detected by SSS, i.e. the detection limit, depends on the observation line, or the distance between SSS and the bubble plume.

When observed along Line B, the detection limit of tiny bubbles was 100 ml/min (correctly between 20 ml/min and 100 ml/min), and that of 1 cm bubbles is larger than 200 ml/min; they were not detected in the present experiment.

When observed along Line A, bubble plumes released at any rate in the present experiment were detected, whether the bubble size was tiny or 1 cm. However, the signal of 1 cm bubbles released at 20 ml/min×1 is extremely weak (Figure 4e). In release experiments, we know where the release point is, or where the signal of bubbles should be displayed; thus we can identify such a weak signal as the bubble plume. However, in the actual monitoring of CCS, where we do not know whether bubbles leak, let alone the release point, it might be difficult to notice the existence of such a weak signal, or to suspect it to be bubbles if we could notice the signal. Thus, the detection limit in the actual monitoring is 20 ml/min or probably lower than it for tiny bubbles and larger than 20 ml/min for 1 cm bubbles.

4. Discussion

4.1. Bubble Size

Out of the two sizes of bubbles, the diameter of 1 cm may be a typical size of bubbles emitted from the seabed. It was reported that diameters of bubbles in natural seepage sites ranged between 0.1 and 1.5 cm [16]. Most of bubbles in QICS, where CO_2 gas was released in sediments 11 m beneath the sea floor, were in the range of 0.4-1.1 cm in diameter immediately after the emission from the seabed [8].

The diameter of 1-2 mm may be interpreted as a typical size of bubbles in the water column that are emitted from the seabed as pure CO_2 bubbles with a diameter of around 1 cm. According to a model study [17], bubbles consisting of pure CO_2 with diameters of 6 and 8 mm released at the seabed diminish to be tiny bubbles with a diameter of about 1.5 mm consisting of N_2 and O_2 within the first a few meters rise, and after that they rise in the water column without changing the size greatly.

4.2. Dependency of Detectability on the Size of Bubbles

The detectability of bubbles depends on the size of bubbles. This is thought to be caused by the number of bubbles, or strictly the sum of the cross-sectional area of each bubble. Suppose that bubbles are spherical independent of the size, for simplicity. The volume of a bubble with a diameter of 1 cm is 0.524 ml, so that the release rate of 20 ml/min corresponds to 0.637 bubbles/s. If the terminal velocity is assumed to be 0.225 m/s for 1 cm bubbles [18], the distance between a bubble and the next bubble is 35.3 cm. The distance is 2.83 mm for 2 mm bubbles and 0.22 mm for 1 mm bubbles, calculated in the same way but using terminal velocities of 0.225 m/s and 0.14 m/s [18], respectively. Thus, tiny bubbles are almost continuously released while 1 cm bubbles are intermittently released.

The difference in the emission interval leads to difference in the cross-sectional area of bubbles. The sum of the cross-sectional area of each bubble between the seabed and 1 m above the seabed is 11.1 cm^2 for bubbles with a diameter of 2 mm and 35.7 cm^2 for bubbles with a diameter of 1 mm when the release rate is 20 ml/min, assuming that the size of bubbles does not change. For 1 cm bubbles, on the other hand, it is 2.22 cm^2 at 20 ml/min, and it is 11.1 cm^2 even at 100 ml/min, which is the same as that for tiny bubbles with a diameter of 2 mm and less than that for tiny bubbles with a diameter of 1 mm at 20 ml/min. This estimate is not inconsistent with the result that the signal of tiny bubbles for the release rate of 20 ml/min (Figure 4c) is clearer than the signal of 1 cm bubbles for the release rate of 100 ml/min (Figure 4b and Figure 4d).

4.3. Identification of Leakage Point

If signs of CO_2 leakage are detected in the marine monitoring in CCS, we should investigate whether they are due to CO_2 leakage. In the case of bubble detection with SSS, we have to verify whether the detected bubbles are attributed to the stored CO_2. For the verification, the leakage point should be identified.

As SSS provides us the slant distance from SSS to bubbles, we may roughly estimate the horizontal distance between SSS and the leakage point, X in Figure 3, and thus, the leakage point.

If the whole bubble plume can be identified on the sonograph, then the slant distance between SSS and the leakage point, Y in Figure 3, can be obtained. From Y and D (the altitude of SSS), X can be calculated as

$$X = \sqrt{Y^2 - D^2} \quad (1)$$

In this calculation, it is assumed that the water depth at the leakage point is the same as that at the position of SSS. Where this assumption does not hold, this estimation is not suitable. In addition, as shown in Figure 3, signals of bubbles immediately after the emission always overlap with those of the seabed, and such signals are difficult to detect (Figure 4b-e). Thus, this method may not be suitable if the leakage rate is as small as in the present experiment.

Another estimate method is using L, the distance between SSS and the bubble plume. As shown in Figure 3, L corresponds to the distance to the center side of the edge of the bubble signal on the sonograph. If it can be assumed that bubbles rise straight up without being advected by flow, L equals to X. This method is unsuitable if flow is so strong that bubbles are advected greatly.

The two methods are applied to the results of the case where tiny bubbles released at 100 ml/min×1 were observed along Line B. In this case, all 3 observations succeeded in capturing the whole bubble plume (Figure 5). D, L, and Y in Figure 3 corresponding to encircled numbers 1, 2, and 3, respectively, in Figure 5 are read off on the sonograph, and substituting them into Eq. (1) yields X (Table 2). Two values, L and X, are roughly equal, and therefore, the two methods of estimating X work well under the condition of the present experiment.

Table 2. Values of D, Y, L, and X when bubbles released at a rate of 100 ml/min×1 were observed along Line B

	D [m]	Y [m]	L [m]	X [m]	L-X [m]
1st obs.	6.5	9.5	7.3	6.9	0.4
2nd obs.	6.5	10.0	7.9	7.6	0.3
3rd obs.	6.1	8.7	6.4	6.2	0.2

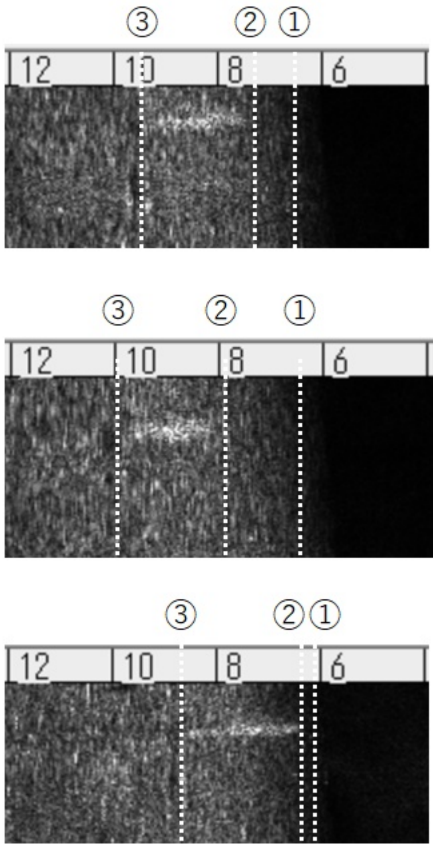

Figure 5. Sonographs of the cases with the release rate 100ml/min×1 observed along Line B

4.4. Application to the Detection of CO_2 Leakage

The purpose of the present study is to obtain knowledge and expertise to use SSS in the marine monitoring of CCS. However, the present results are not directly applicable to detection of CO_2 bubbles, because CO_2 bubbles are much easier to dissolve in seawater, and thus would be much more difficult to detect with SSS than air bubbles.

As discussed in section 4.1, tiny bubbles in the present experiment may be regarded as bubbles that originally consisted of pure CO_2 with a diameter of 8 mm. Assuming that tiny bubbles are 1.5 mm in diameter, tiny air bubbles released at 20 ml/min correspond to CO_2 bubbles with an initial diameter of 8 mm released at $20\times(8/1.5)^3=3034$ ml/min, which is equivalent to 4.76 tonnesCO_2/year at a depth of 6 m, assuming that water temperature is 20º Celsius and density of the water column is 1025 kg/m^3. The estimated leakage rate of bubbles in QICS were about 6.3 tonnesCO_2/year, as about 15% of total injected CO_2 (4.2 tonnes over 37 days) were estimated to be emitted in the form of bubbles [7]. Therefore, if SSS can detect CO_2 bubbles leaking at 4.76 tonnesCO_2/year, it will be a useful tool in the marine monitoring.

As well as bubbles in the water column, SSS can detect pockmarks on the seafloor [19], which are also signs of gas emission. In QICS, it was observed that the bubble emission was strong during low tides, and weak or ceased during high tides [7]. This implies that searching both pockmarks especially during high tides and bubbles especially during low tides leads more effective monitoring to detect CO_2 leakage.

5. Conclusions

Through an in situ experiment in shallow sea about 6 m deep, we clarified detectability of air bubbles with SSS. Air bubbles can be detected if the release rate is larger than around 20 ml/min. Based on the present results, we conjectured that SSS could detect CO_2 bubbles if the leakage rate is larger than 3034 ml/min, which corresponds to 4.76 tonnesCO_2/year. It is expected that SSS will be a promising tool in the marine monitoring at offshore CO_2 storage sites.

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