Mapping of Seafloor Radionuclides off Miyagi using a Towed Gamma Ray Spectrometer

Blair Thornton*, Seiki Ohnishi†, Tamaki Ura‡, and Naoteru Odano†,
*Institute of Industrial Science, The University of Tokyo, 4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan
†National Maritime Research Institute, 6-38-1 Shinkawa, Mitaka-shi, Tokyo 181-0004, Japan
‡Center for Socio-Robotic Synthesis, Kyushu Inst. of Tech., 2-4 Hibikino, Wakamatsu, Kita-Kyushu 808-0196, Japan

***Abstract*—An instrument to continuously map the distribution of radionuclides on the seafloor has been developed to survey radioactive discharge from the Fukushima Dai-ichi Nuclear Power Plant. To date, the system has been deployed off the east coast of Japan to measure the distribution of ^{137}Cs over a total towed distance of more than 320 km. Here, we describe the results of measurements made along two transect north of the plant, off Miyagi, during February 2013, almost two years after the accident. There results reveal the continuous distribution of radionuclides over a total distance of 140 km. The accuracy of the measurements is verified through laboratory analysis of samples obtained during the survey. The results demonstrate that towed in situ measurement techniques provide an effective solution for rapid, low cost monitoring of radioactive material on the seafloor. It is expected that continued monitoring efforts using the device can contribute to our understanding of radionuclide distribution on the seafloor following the accident at the plant.**

I. Introduction

The melt down at Fukushima Dai-ichi Nuclear Power Plant (F1NPP) resulted in an estimated 13×10^{15} Bq of ^{137}Cs being released into the environment. 70 to 80% of the ^{137}Cs released into the atmosphere is thought to have been deposited over the western North Pacific Ocean [1], [2], and a further $3.5 \pm 0.7 \times 10^{15}$ Bq is thought to have been released directly into the ocean in the form of contaminated fluids between March 26 and the end of May 2011 [3]. Whilst on land, dense sampling and airborne survey efforts revealed the distribution of ^{137}Cs in the environment within a few months of the accident [4], [5], the situation on the seafloor is less clear due to the practical difficulties associated with survey at sea. To date, monitoring of seafloor radiation levels has been performed through sampling [6]. However, the costs associated with sampling wide areas of the seafloor at spatial resolutions equivalent to surveys on land are prohibitive, and sampling points on the seafloor are typically separated by several tens of kilometres. Since the information obtained through sampling is discrete, the local scale distribution of radioactive material after the accident remains largely unknown. The lack of information raises concerns regarding our ability to predict the effects of the accident on the marine ecosystem and limits our ability to form effective recovery strategies. In particular, the results of recent surveys performed by the authors using in situ measurement techniques have revealed the existence of ^{137}Cs concentration anomalies on the seafloor within 20 km of F1NPP that occur on spatial scales ranging from a few metres to several hundreds of metres [8]. The results emphasise the need for high resolution measurement techniques to complement the current sampling efforts to survey the marine environment.

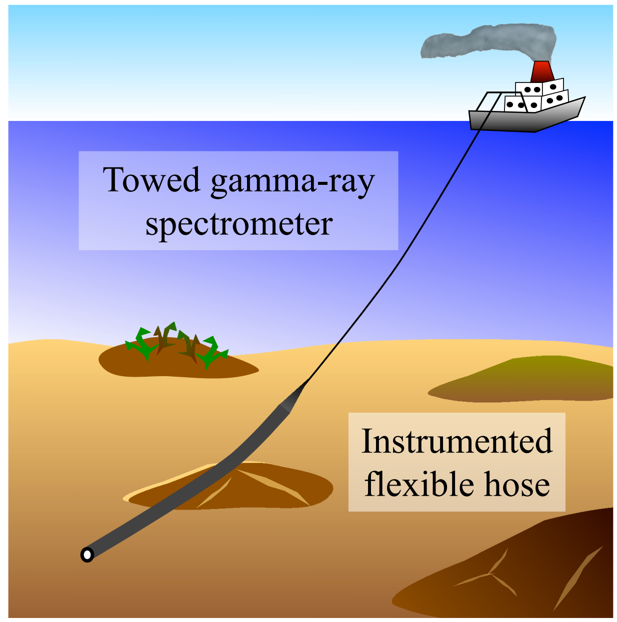

Fig. 1. Illustration of a ship towed gamma ray spectrometer (adapted from [7]).

In situ measurement of radioactivity offers an efficient, low cost alternative to sampling of the marine environment. The sensors typically use passive gamma ray spectroscopy, and can in theory detect any gamma ray emitter present in sufficient quantities. However, the strong attenuation of gamma rays in water means that remote measurements of seafloor radiation, equivalent to airborne measurements on land, are not possible. Measurement of seafloor radiation requires the detectors to be within a few centimetres, or ideally in contact with the seafloor [9]. In order to monitor the distribution over long distances, dedicated towed gamma ray spectrometres have been developed by various groups [10], [11], [12]. Towed gamma ray spectrometres typically consist of a detector contained in a flexible hose that is attached to a ship by a wire or tether cable, as illustrated in Fig. 1. The hose is towed along the seafloor by the ship, allowing the detector

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TABLE I
RADIONUCLIDES TARGETED FOR DETECTION IN THIS WORK.

Isotope	Photon energy (MeV)	Half-life (years)
^{137}Cs	0.662	30.1671
^{134}Cs	0.607, 0.794	2.0652
^{40}K	1.461	1.250×10^9

to maintain continuous contact with the seafloor over long distances. In this application, the targets for detection are the artificial radionuclides ^{137}Cs and ^{134}Cs, associated with nuclear technology, and the natural background emitter ^{40}K, which is the dominant source of radioactivity in un-polluted environments [13]. These radionuclides emit gamma rays of sufficient energy for detection, see Table I, and are known to be present off Fukushima in sufficient quantities for in situ measurements to be possible. One obvious requirement for measurements is for the instrument to maintain contact with the seafloor. For this, towed systems are often equipped with accelerometres, underwater microphones and depth sensors to verify that the system is in contact with the seafloor at any given time. The radioactive count rate of the spectrometer itself can also be used for this purpose, since the concentration of ^{40}K is significantly higher in sediments than in seawater. Even when proper contact is maintained, sources of uncertainty in the measurements include non-uniform vertical distributions of radionuclides, variable seafloor geometry and changes in the density and porosity of marine sediments. In addition to these physical factors, the energy resolution of the detector is also limiting since it may not be possible to completely resolve radioactive emissions with similar energies, e.g. ^{137}Cs at 0.662 MeV and ^{134}Cs at 0.607 MeV. However, despite these challenges, it is generally accepted that the total error in measurement is usually no greater than 30 % of the recorded values [14].

II. INSTRUMENTS AND METHODS

A 500 m depth rated towed gamma ray spectrometer, called the RESQ hose (RESQ: Radiometric Environment Survey and Quantification), has been developed at the University of Tokyo to monitor seafloor radiation off the coast of Japan. The main emphasis of the design of the system is that it should be robust and minimise the risk of snagging on objects of the seafloor. Having said this, the system should be inexpensive, since the risk of damage or loss is considerably higher than most other underwater instruments due to the nature of its operation. In addition, the system should be compact and require minimal equipment to support its operation. The main reason for this is that operational costs can be reduced by using small 10 to 50 tonne fishing vessels rather than large research vessels that typically weigh upwards of 400 tonnes. In addition to reducing operational costs, the use of small vessels is necessary since the system is required to operate in coastal areas where the seafloor is as shallow as 10 m.

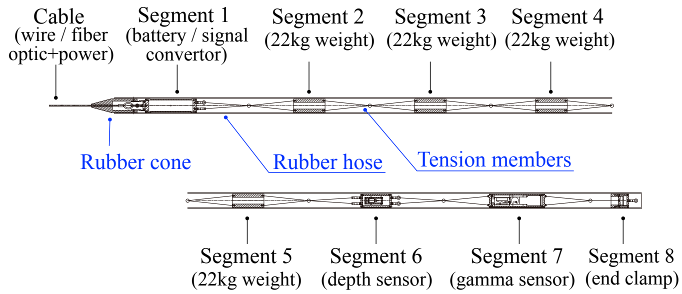

Fig. 2. Construction of the 'RESQ hose' towed gamma ray spectrometer.

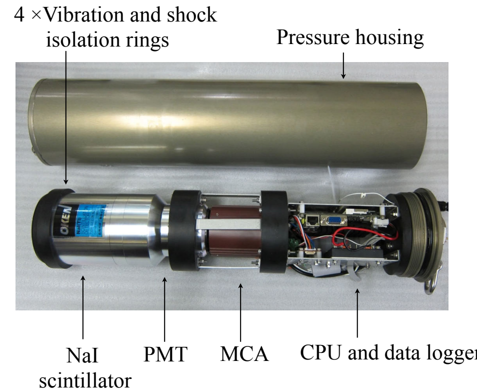

Fig. 3. Gamma ray spectrometer developed in this work. The spectrometer is depth rated to 3,000 m.

TABLE II
SPECIFICATION OF THE TOWED GAMMA RAY SPECTROMETER.

General specification	
Length [m]	3.5
Diameter [m]	0.145
Weight in air [kg]	75
Weight in water [kg]	60
Maximum depth [m]	200
Tow velocity [knots]	1 to 3
Power supply	Li-ion (Max. 24 h)
Instrumentation	
Scintillator	3×3 inch NaI
Energy range [MeV]	0.1 to 1.8
Energy resolution [% at 0.662 MeV]	6.9
Number of channels	1024
Others	Temperature (internal) 3-axis acceleration Microphone Roll, pitch, heading Depth

Fig. 2 shows the construction of the system, which consists of 8 rigid segments, numbered 1 to 8 from the front that are connected using tension bearing wire ropes and underwater electrical cables. The system is covered using a rubber hose that is fixed to the first and last segments. In addition to reducing the risk of snagging, the rubber hose protects the detector from abrasion and impact damage during towing and handling on board the ship's deck, while maintaining enough flexibility for the system to follow the undulations of the seafloor. The system can operate as a stand alone device with a battery in segment 1 that allows for up to 24 h operation. Segments 2 to 5 are stainless steel weights, each weighing 22 kg in air. These buffer the motion of the detector at the aft of the system, and prevent loss of contact due to undulations of the seafloor or fluctuations in cable tension. The system has a pressure sensor in segment 6, used to measure depth, and a NaI passive gamma ray detector, shown in Fig. 3, in segment 7. The detector has been calibrated to measure the gamma ray spectrum between 0.1 and 1.8 MeV over 1024 channels at a sampling rate of 1 Hz, where the energy resolution of the system is 6.9% at 0.661 MeV. The detector is placed in a pressure tight aluminium housing, and contains an internal temperature sensor, a three-axis gyro, a three-axis accelerometer and a microphone. The aluminium housing has a transmission efficiency of 88% for gamma rays at 0.662 KeV. The internal temperature measurements are used to compensate for temperature effects on the gamma ray spectrum. Fig. 4 shows the spectrum accumulated over 6 h during a towed deployment on the seafloor off Iwaki, described in a previous publication [15]. The peaks seen in the spectrum correspond to the gamma emissions of ^{137}Cs, ^{134}Cs, and ^{40}K, where the concentration of each radiunuclide can be quantified by calculating the area under the peaks, after subtraction of the background, and multiplying this area by a conversion factor determined through Monte-Carlo simulations. The Monte-Carlo simulation, described in [15], determines the theoretical response of the detector at each energy using a geometric model of the detector and its environment. The effect of uncertainty introduced by different types of sediment on the detector's response has been assessed, and it has been demonstrated that the effect on the measurements is less than 8% if an average values is used. Since the photoelectric peak of ^{137}Cs cannot be completely resolved from ^{134}Cs at 0.607 MeV, its area is determined as twice the area under the ^{137}Cs peak beyond 0.662 MeV after subtraction of the background. In order to conform with sampling surveys, the photoelectric peak count per unit Bq/kg is determined based on the average concentration of each radionuclide between 0 and 3 cm from the surface of the seafloor, where the values are determined based on wet weight. Wet weight is chosen as the basis for conversion since it more directly represents the environment where in situ measurements are made. The calculation to quantify the measurements of the system assumes that the detector maintains continuous contact with the seafloor. In order to ensure this is the case, data from the three-axis accelerometer and microphone are used together with depth information to verify that the system is in contact at any given time. The data from all the sensors are logged once a second by the CPU in the gamma ray detector. All components in the main detector are isolated using rubber mounting pads that absorb the shocks and vibrations expected during towed operation. The system is 8 m long with an external diameter

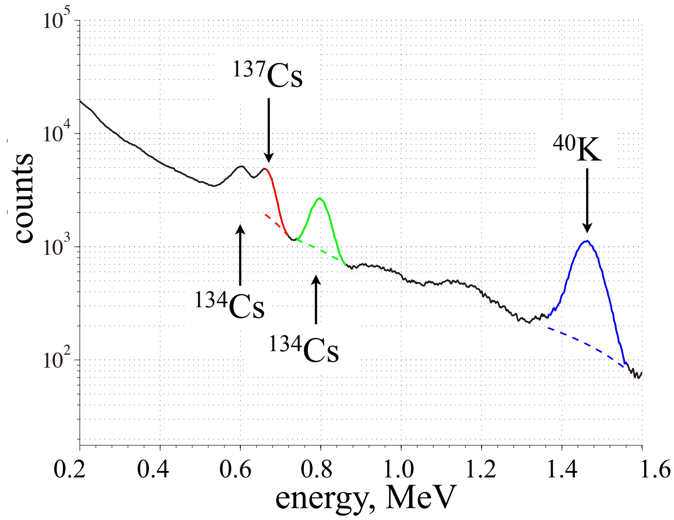

Fig. 4. Accumulated gamma ray spectrum measured by the system during a 22 km survey off Fukushima.

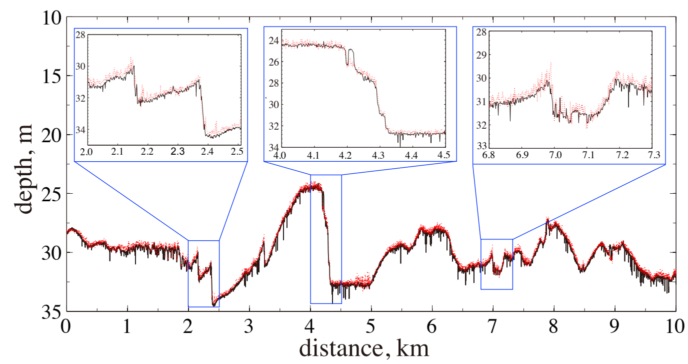

Fig. 5. Comparison of bathymetry data (black) and depth profile of the towed system (red).

of 0.145 m and weighs a total of 135 kg in air and 115 kg in water. During operation the system is attached to a wire and is lowered to the seafloor. The system is towed at velocities between 2 and 3 knots and can be operated at depths of up to 500 m. The length of the wire used is typically between 2 to 3× the depth of the seafloor being measured. Together with the compact size of the system, the fact that it can be operated as a stand alone device allows the system to be deployed from ships of opportunity, requiring only a winch, which is standard on many fishing vessels.

For towed surveys, in addition to measuring the concentration of radionuclides, it is also necessary to determine the location and spatial resolution of the measurements. In our previous work, we described a method to optimise the spatial resolution of the measurements for a given acceptable level of statistical uncertainty in the detectors response [15]. This is achieved by adapting the size of a sampling window in the spatial domain based on the requirements of statistical uncertainty for each individual gamma emitting radionuclide. This allows regions with high radionuclide concentrations to be mapped with a high spatial resolution without sacrificing accuracy in areas with lower activity levels. Regarding localisation of the measurements, most underwater platforms use some form of acoustic localisation system combined with an inertial navigation unit. However, the devices used are expensive and are not suitable for use under the conditions that the towed system is required to operate as it is dragged along rugged underwater terrains. In this work, we choose to geo-reference measurements using catenary models that take as input shipboard GPS, the depth of the instrument, and the length of cable used to tow the system. While improvements in the accuracy of position estimates can be achieved by monitoring the tension in the cable and measuring underwater current profiles, both of which can be incorporating into the present models, for shallow water (< 200 m) applications a simple model can provide position estimates with errors in the order of a few tens of metres, which is considered sufficient since the main interest is in mapping the distribution of radionuclides over several kilometres. Fig. 5 shows the profiles of measurements of the underwater terrain made by a shipboard multi-beam sonar, overlaid with the depth measurements of the towed system after catenary calculations were performed to determine its location on the seafloor. The close agreement between the two profiles demonstrates that the position of the system can be determined with sufficient accuracy. In the case that further improvements in localisation are necessary, terrain matching algorithms can be introduced provided the fine scale bathymetry of the seafloor is known.

III. Deployment at sea

A. *Previous RESQ hose surveys*

To date, the device has been deployed to measure the continuous distribution of radionuclides along transects totalling over 320 km along the east coast of Japan since August 2012. Result of deployments south of the plant (between 25 and 80 km from F1NPP) have been described in [15], where the continuous distribution of radionuclides was mapped along three transects of distances 1.6, 12.5 and 22 km, respectively. Strong variations in the levels of ^{137}Cs were observed, with the levels of radiation changing by almost an order of magnitude over distances of a few tens of kilometres. In [8], the results of 140 km of towed transects measured in a grid within 20 km of the F1NPP were described, and the presence of local anomalies with ^{137}Cs levels more than an order of magnitude higher than the average levels in their vicinity was reported. The sizes of the anomalies varied from a few metres to several hundreds of metres in length along the transects. Several anomalies were found at the bases of vertical features of the underwater terrain, indicating that small meter scale bathymetric features play an important role in determining the distribution of ^{137}Cs near the F1NPP. The difference in the patterns of ^{137}Cs on the seafloor south of the plant, and within a 20 km radius is thought to be a function of the fact that the seafloor south of the plant consists mainly of silts and clays, with only gradual changes in relief, whereas nearer the plant, the seafloor is rocky with abrupt changes in the relief where it is believed that these features locally shield the seafloor from underwater currents to form pockets of fine grained sediments to which ^{137}Cs is known to have a high affinity.

Fig. 6. Deployment of towed gamma ray spectrometer off Miyagi, Japan.

B. *Results of survey off Miyagi in the Sendai bay*

In this work, we describe two transect measured north of the F1NPP off Miyagi during Februrary 2013, nearly 2 years after the accident. While the measurements to date have consisted of a series of transects up to 20 km in length, during this deployment transects of lengths 77.0 and 66.8 km were measured over 5 days, with a total bottom measurement time of just over 35 h. During the 5 days, sampling was performed at 5 locations to verify the measurements of the system and also provide the vertical ^{137}Cs distribution data to model the detector's response. During operation the system was towed at 2 knots using a 12 mm diameter wire (Fig. 6). Seafloor bathymetry was measured using a shipboard acoustic multi-beam, and the length of cable was kept between 2 to 3$\times$ the depth of the seafloor. The location of the ship, depth of the towed system were recorded every second and these, together with the length of cable used to tow the system were used as inputs for the catenary calculations to determine the location of the measurements. The full gamma spectrum was measured every second, with a total of over 126,700 seafloor gamma spectra obtained during the survey. The data has been quantified and smoothed using the methods described by the authors in [15].

Fig. 7 shows the results of the survey where the resolution of the measurements has been optimised to satisfy a 1σ statistical. uncertainty of 5%, with a minimum resolution of 100 m imposed beyond which statistical uncertainty is allowed to increase. Transect AA' follows the 60 m depth contour, where the levels of ^{137}Cs along this transect average 30$\pm$5 Bq/kg. The range of values represents measurement uncertainty taking into account the effects of different sediment types as well as statistical uncertainty in the measurements of the detector itself. The standard deviation of the ^{137}Cs levels along this

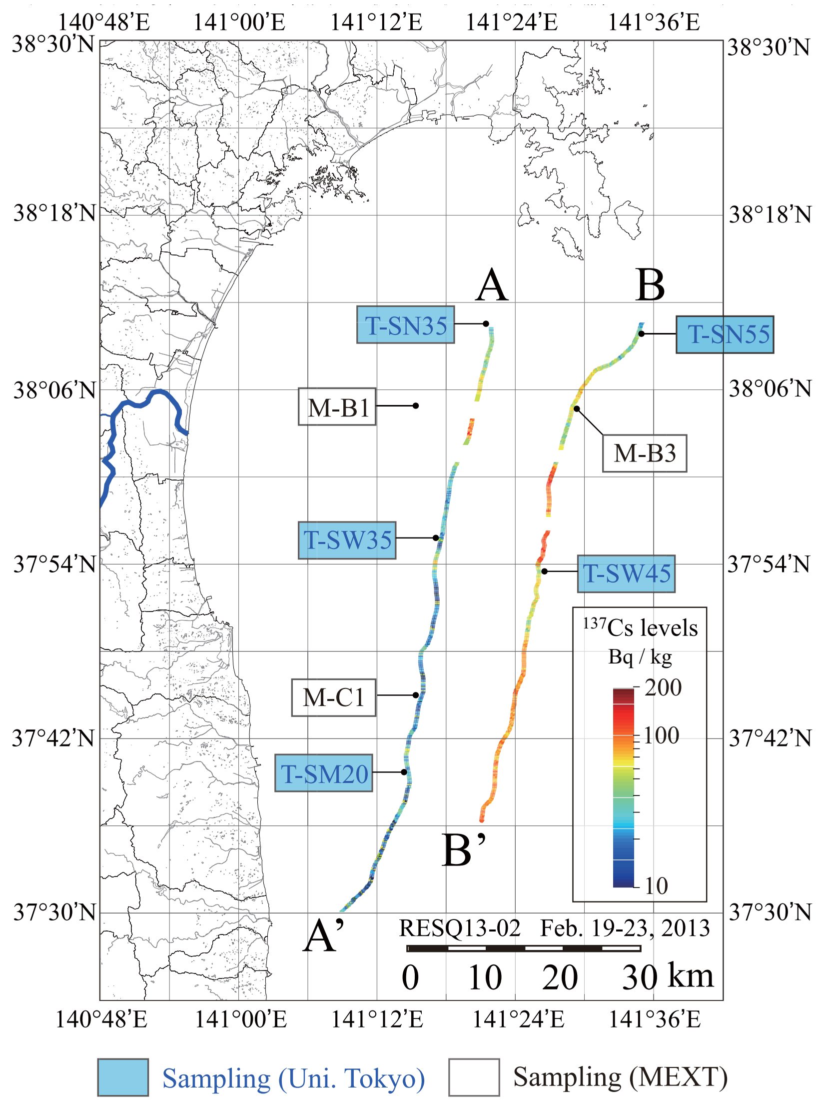

Fig. 7. ^{137}Cs levels on the seafloor in Sendai bay off Miyagi. Measurements totalling over 140 km in length were made using a towed gamma ray spectrometer that was deployed over 5 days between Feb. 19 and 23, 2013 just less than 2 years after the accident. The levels are determined for the top 3 cm of the surface sediments. The transects AA' and BB' follow the 60 and 120 m depth contours respectively. The gaps along the transects are regions where no measurement could be performed as the system had to be raised in order to avoid submarine communication cables that are laid out on the seafloor. The Abukuma river is marked with a blue line.

TABLE III
RESULTS OF LABORATORY ANALYSIS OF SAMPLES.

Name	Sampling date	Latitude	Longitude	Depth (m)	Water content (% by mass)	^{137}Cs (Bq/kg wet)	Sediment type
T-SN35	Feb. 19 2013	38°09′59″ N	141°21′45″ E	57	14.3	14.3	Coarse sand
T-SW33	Feb. 20 2013	37°55′32″ N	141°17′38″ E	60	15.7	20.4	Coarse sand
T-SM20	Feb. 20 2013	37°38′47″ N	141°14′56″ E	61	11.0	16.2	Coarse sand
T-SN55	Feb. 22 2013	38°09′59″ N	141°34′59″ E	125	62.0	28.5	Silty clay
T-SW45	Feb. 22 2013	37°53′48″ N	141°25′45″ E	120	35.5	45.3	Silty sand
M-B1	Jan. 16 2013	38°04′54″ N	141°15′24″ E	44	14.7	7.2	Coarse sand
M-B3	Jan. 16 2013	38°04′54″ N	141°29′18″ E	119	68.1	63.8	Silty clay
M-C1	Jan. 20 2013	37°45′00″ N	141°15′18″ E	55	14.2	6.1	Coarse sand

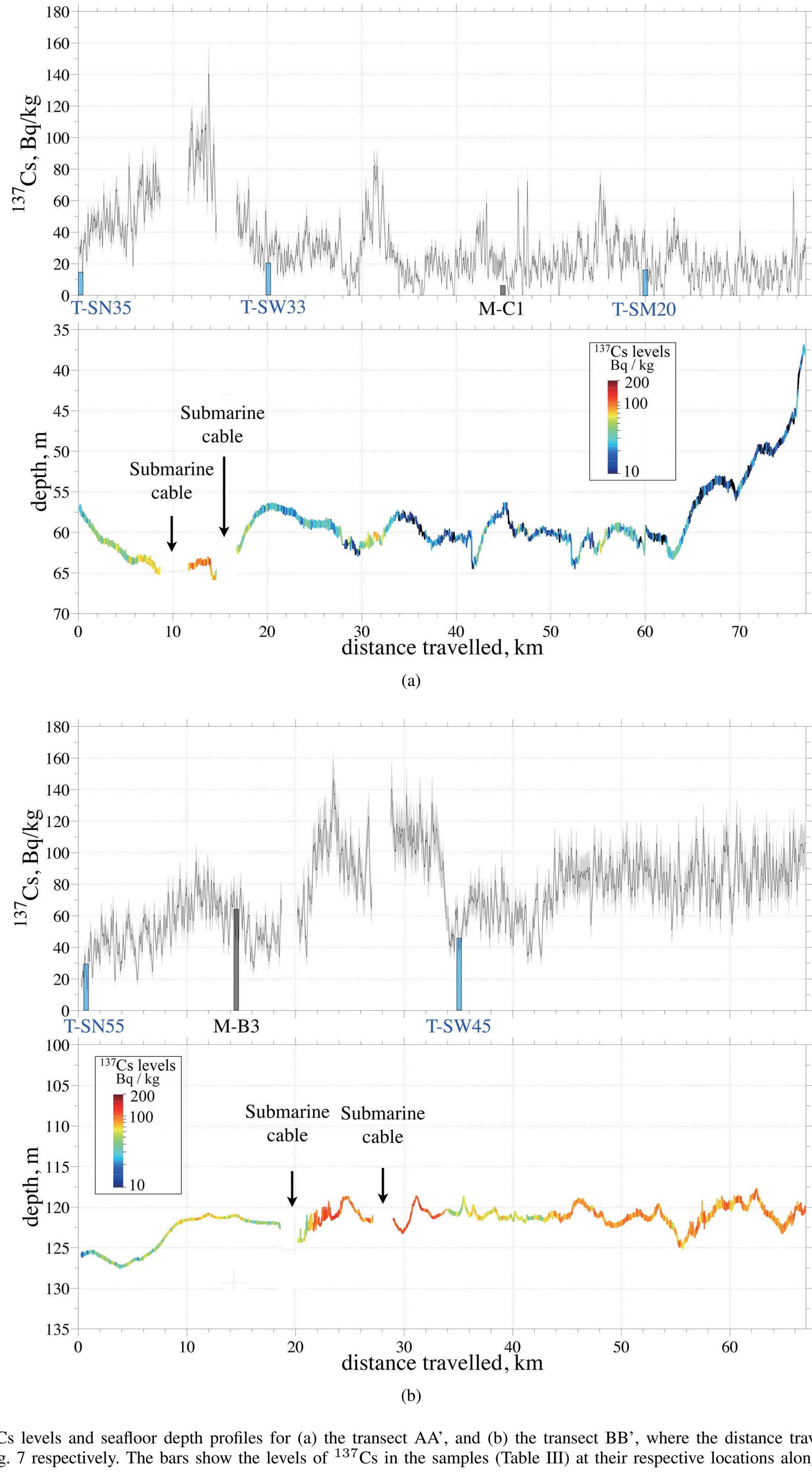

Fig. 8. Plot of ^{137}Cs levels and seafloor depth profiles for (a) the transect AA', and (b) the transect BB', where the distance travelled is measured from points A and B in Fig. 7 respectively. The bars show the levels of ^{137}Cs in the samples (Table III) at their respective locations along the transects.

transect is $\sigma_v = 21{\pm}2$ Bq/kg. The average ^{137}Cs level along this transect is noticeably lower than along transect BB', which is located further out to shore and follows the 120 m depth contour. The levels of ^{137}Cs along transect BB' averaged $74{\pm}10$ Bq/kg with $\sigma_v = 24{\pm}3$ Bq/kg. While in our previous work, we reported the existence of several sharp ^{137}Cs anomalies within 20 km of the plant [15], no such anomalies were found along the transects described here. There is however a noticeable increase in the levels of ^{137}Cs towards the north of the two transects. The maximum levels recorded were $141{\pm}17$ Bq/kg and $147{\pm}18$ Bq/kg along the 60 and 120 m depth contours, respectively, with the levels peaking between latitudes of 37 ° 58' N and 38 ° 06' N along both transects.

The results of the laboratory analysed samples are summarised in Table III. Samples labelled T- were obtained during the cruise. Data for the samples labelled M- were obtained from the data repositories of the Japanese Ministry of Education, Sports, Science and Technology [16]. All samples have been analysed using high resolution Germanium detectors. The data from the samples is shown in the plots in Fig. 8 alongside the results of the in situ measurements. The average and standard deviations of the ^{137}Cs levels detected within a 1 km radius of T-SN35, T-SW33, M-C1, and T-SM20 (the samples along transect AA') are 30 ± 5 Bq/kg ($\sigma_v = 6 \pm 1$ Bq/kg), $29{\pm}5$ Bq/kg ($\sigma_v = 8 \pm 1$ Bq/kg), $5{\pm}2$ Bq/kg ($\sigma_v < 1$ Bq/kg), and $16{\pm}3$ Bq/kg ($\sigma_v = 11 \pm 2$ Bq/kg), respectively. Since the these samples consist of coarse sand, the values would lie near the lower bound of the indicated range of the in situ measurements, i.e. ^{137}Cs levels of 25 Bq/kg ($\sigma_v = 5$ Bq/kg), 24 Bq/kg ($\sigma_v = 7$ Bq/kg), 3 Bq/kg ($\sigma_v < 1$ Bq/kg) and 13 Bq/kg ($\sigma_v = 9$ Bq/kg), respectively. For the samples obtained along the 120 m depth contour (transect BB'), the ^{137}Cs levels detected within a 1 km radius of T-SN55, M-B3 and T-SW45 are $30{\pm}5$ Bq/kg ($\sigma_v = 10 \pm 1$ Bq/kg), $61{\pm}8$ Bq/kg ($\sigma_v = 9 \pm 1$ Bq/kg), and $51{\pm}7$ Bq/kg ($\sigma_v = 8 \pm 1$ Bq/kg) respectively. The recorded values correspond closely with the ^{137}Cs levels of the samples, which are 28.5 Bq/kg, 63.8 Bq/kg, and 45.3 Bq/kg, respectively. It should be noted that since the samples obtained at T-SN55 and M-B3 consist of silty clays, we would expect their values to lie towards the upper bound of the indicated range, i.e., 35 Bq/kg ($\sigma_v = 11$ Bq/kg) for T-SN55 and 69 Bq/kg ($\sigma_v = 10$ Bq/kg) for M-B3. The in situ measurements of the system show close correlation with the results of sampling, and are accurate to within about 10 Bq/kg. The relative accuracy of the system along the 60 m depth contour is lower than along the 120 m depth contour due to lower levels of ^{137}Cs on the seafloor. In particular, for the 60 m depth transect AA', the levels of ^{137}Cs approach the detection limit of the system for the conditions under which it is currently operated.

IV. Discussion

The results described in this work demonstrate that towed surveys are an effective method to survey the continuous distribution of ^{137}Cs over long distances. The levels of ^{137}Cs determined from the in situ measurements are within 10 Bq/kg of the available sampling data, which is sufficiently accurate for our mapping purposes. It is pointed out that this corresponds to quite a large relative error for the regions where the ^{137}Cs levels are low, such as along the 60 m transect described in this work. While it may be possible to further increase the accuracy of the system by operating the system at lower speeds, which would come at the cost of distance covered, or by increasing the 100 m resolution boundary imposed during processing of the data. However, since the main aim of this work is to identify and map out strongly contaminated regions, increasing the accuracy in areas with low levels of radiation is not a major priority at present.

The levels of ^{137}Cs recorded off Miyagi along the two transects described in this work are relatively low compared to previous surveys using this device performed between 25 and 80 km south, and within 20 km of the F1NPP. The levels of ^{137}Cs are higher along the 120 m depth contour, averaging $74{\pm}10$ Bq/kg than along the 60 m depth contour, which averaged $30{\pm}5$ Bq/kg. This is supported by the results of sampling along the transects, which showed good agreement with the in situ measurements. From publicly available data repositories, it appears that the trend of decreasing radiation levels approaching the shore continues up to a depth of 40 m. However, it is noted that the average level of ^{137}Cs off the east coast of Japan prior to the accident was 1.1 Bq/kg [17], and so while the levels near the shore are relatively low, the affects of the accident are still seen. The fact that the levels of ^{137}Cs were found to be higher along the 120 m depth contour is attributed to the difference in the type of sediment. The sediment type along transect further out from shore consists mainly of clays and silts, which ^{137}Cs has a high affinity for. The transect closer to the shore consists mainly of coarse sands. This relationship between sediment type and radiation levels has also been pointed out by Kusakabe et al. 2013 [6] in their analysis of samples obtained off Fukushima. It is noted that, as in the case of the area 25 to 80 km south of the plant off Iwaki and Kita-Ibaraki [15], no abrupt concentration anomalies were found along the transects off Miyagi. Having said this, a gradual increase in ^{137}Cs concentration, peaking at about 150 Bq/kg between 37°58′ N and 38°06′N latitude was observed along both the 60 and 120 m depth contours. The reason for this peak is not known. One possibility is that the ^{137}Cs levels are relatively high in these areas due to the effect of the shape of the Sendai bay on local currents in the area. Another possibility is that the increased concentration may be related to the Abukuma river, a large 239 km long river that passes through both the Fukushima and Miyagi prefectures of Japan. The river has its mouth at 38°02′47″ N 140°55′20″ E (shown in Fig. 7) and has an average annual discharge rate of 112 m^3/s. At this stage, there is insufficient evidence to draw any conclusions regarding this point, but the possibility of secondary contamination from rivers has previously be highlighted as an area of concern [2]. Future survey efforts should investigate both possibilities.

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