Toktrapport/Havforskningsinstituttet/ISSN 15036294/Nr. 9–2019

Cruise report: Investigation of the marine environment around the nuclear submarine "Komsomolets" 6.-10. July 2019 (IMR cruise number 2019109)

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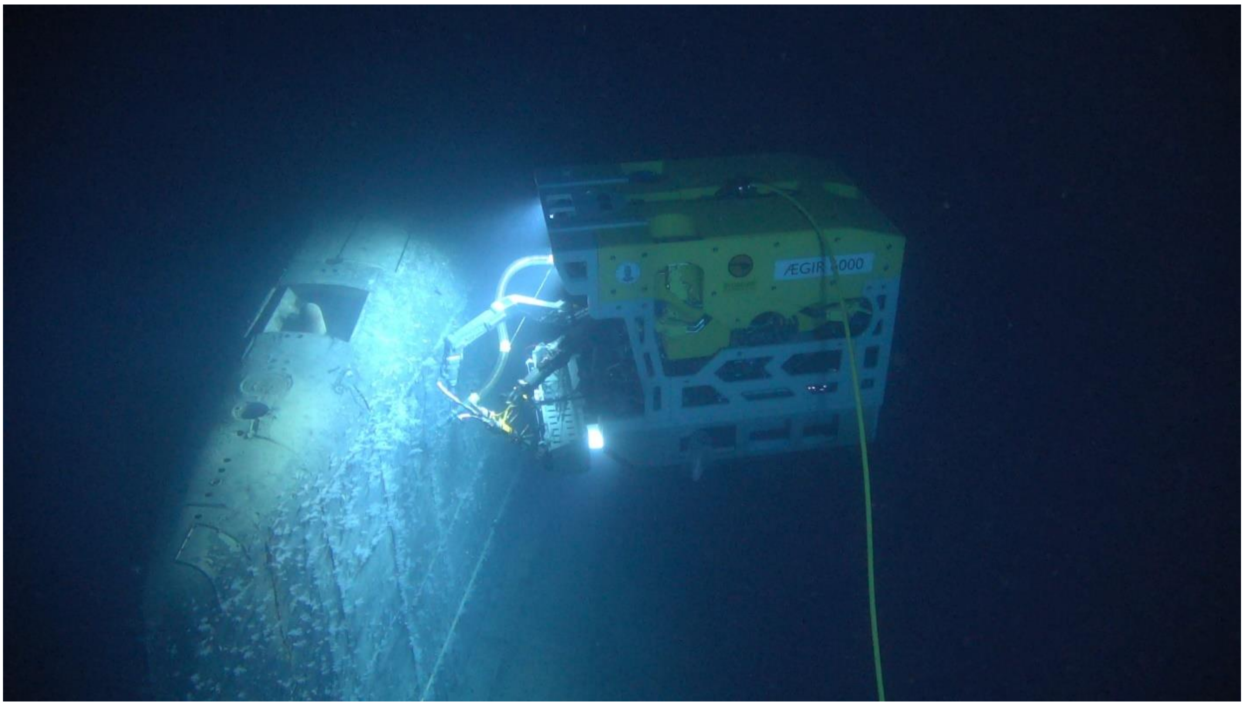

The Remotely Operated Vehicle (ROV) Ægir 6000 investigating "Komsomolets".

Contents

Summary

In July 2019, a research cruise to the wreck of the nuclear submarine “Komsomolets” was carried out with RV “G. O. Sars” and the advanced Remotely Operated Vehicle (ROV) Ægir 6000. The expedition was organised under the Joint Norwegian Russian Expert Group for investigation of radioactive contamination in Northern Areas. Using the ROV, the condition of “Komsomolets” was visually documented and samples of seawater, sediment and biota were taken at specific locations in the immediate vicinity of the submarine. Onboard analyses of seawater sampled directly from the ventilation pipe where releases have previously been documented, showed activity concentrations of ^{137}Cs between <8.0 and 857 Bq/l. This indicates that releases from the reactor are still occurring, 30 years after “Komsomolets” sank. Based on our observations, the releases of ^{137}Cs from “Komsomolets” to the marine environment appear to vary in amount and duration. Samples collected during the expedition will now be further analysed in the laboratory for ^{137}Cs, ^{90}Sr, Pu-isotopes and other radionuclides as well as trace metals to further understand the nature of the releases from the reactor and to determine if any plutonium from the two nuclear warheads has been released into the marine environment. The results will be compiled and published in a report under the Joint Norwegian Russian Expert Group by the end of 2020.

1. Introduction

1.1. Background and organisation of the cruise

The Barents Sea and the polar front in the Norwegian Sea provide home to some of the richest fishing grounds in the world. Knowledge and documentation of the levels of radioactive contamination in these areas is of major importance to the Norwegian fishing industry. The present levels of the common anthropogenic radionuclide cesium-137 (^{137}Cs) in fish in these areas are low, and generally below 0.2 Bq/kg fresh weight (fw). The maximum permitted level for radioactive cesium in food set by the Norwegian authorities after the Chernobyl accident were 600 Bq/kg fw.

The wreck of the Russian nuclear submarine “Komsomolets” is resting in the Norwegian Sea (Figure 1.1), and is known to leak radioactive contamination (Nejdanov, 1993; Gladkov et al., 1994; Kazennov, 2010). A close-up investigation of the condition of the wreck and the radioactive leakages was last conducted by Russian scientists in 2007 (e.g. Kazennov, 2010). A similar Norwegian survey has never been conducted until funding was allocated for this purpose in 2019 through the Institute of Marine Research’s (IMR) grant from the Ministry of Trade, Industry and Fisheries and by the Norwegian Radiation and Nuclear Safety Authority (DSA).

In 1992-1994, three joint Norwegian-Russian expeditions were carried out to dumping sites for radioactive waste in the Kara Sea and at the east coast of Novaya Zemlya (e.g. Strand et al., 1996). More recently, joint Norwegian-Russian expeditions have been carried out to the Stepovogo Fjord at the east coast of Novaya Zemlya (2012) and to the wreck of the nuclear submarine K-159 in the Murmansk Fjord (2014) (JNREG, 2014; 2018). The funding for this year’s cruise to “Komsomolets” was given independently of the Norwegian-Russian cooperation. Nevertheless, based on earlier successful cooperation, there was a desire from the Norwegian part to plan and conduct the cruise under the Joint Norwegian-Russian Expert Group for Investigation of Radioactive Contamination in the Northern Areas.

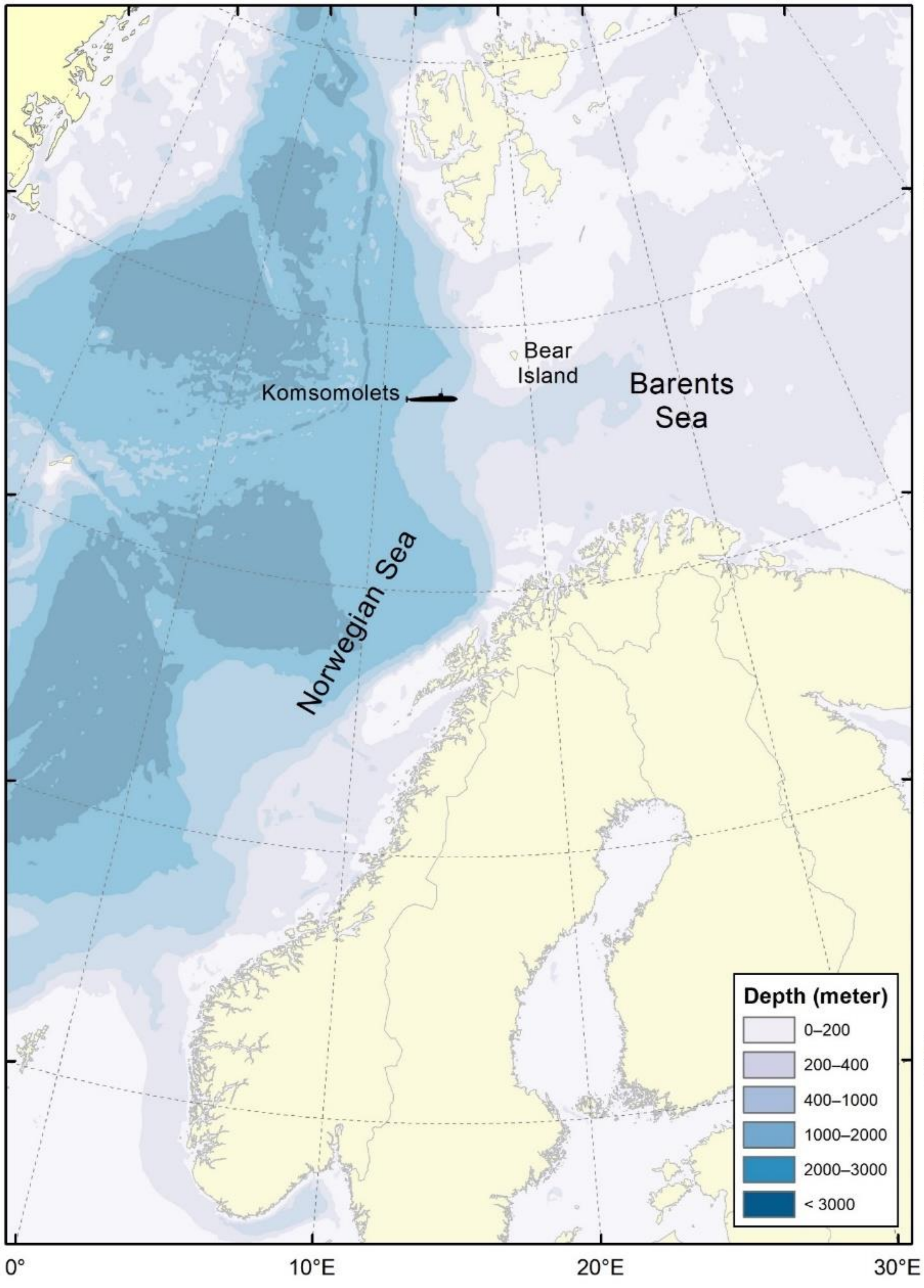

Figure 1.1. "Komsomolets" (K-278) is resting at 73°43′16″ N, 13°16′52″ E, southwest of Bear Island in the Norwegian Sea, at a depth of 1673 m. Figure: Kjell Bakkeplass/IMR.

1.2. Participants

The scientific personnel consisted of participants from Institute of Marine Research (IMR), Norwegian Radiation and Nuclear Safety Authority (DSA) and Norwegian Institute of Life Sciences (NMBU)/Centre of Environmental Radioactivity (CERAD). One scientist from the Russian institute Research and Production Association (RPA) "Typhoon" participated as an observer. Further, a crew of seven people from the University of Bergen (UoB) and IMR was responsible for operations with ROV Ægir 6000. Three journalists from the Norwegian television companies TV2 and Screen Story participated to produce news stories and documentaries from the cruise. Finally, captain Svein-Roger Fredheim and his crew contributed in the best possible way to make the cruise a success. A list of cruise participants is given in Table 1.1 and a selection of happy cruise participants are posing after return to Tromsø in Figure 1.2.

Table 1.1. List of cruise participants.

Name	Role/Responsibility	Institution
Hilde Elise Heldal	Cruise Leader/Radioactivity	IMR
Andrey Volynkin	Scientist/Radioactivity	IMR
Justin Gwynn	Scientist/Radioactivity	DSA
Louise Kiel Jensen	Scientist/Radioactivity	DSA
Hans-Christian Teien	Scientist/Radioactivity	NMBU/CERAD
Shane Sheibener	Scientist/Radioactivity	NMBU/CERAD
Andrey Epifanov	Scientist/Radioactivity (observer)	RPA "Typhoon"
Stine Hommedal	Communication advisor	IMR
Egil Frøyen	Instrument	IMR
Jarle Wangensten	Instrument/ROV	IMR
Jörn Patrick Meyer	Instrument/ROV	IMR
Marco Micheel	ROV/Multibeam	UoB
Stig Vågenes	ROV	UoB
Kjetil Sørlie	ROV	UoB
Bjørn Løfquist	ROV	UoB
Alexander Straume	ROV	UoB
Patrick Vågenes	ROV	UoB
Øystein Bogen	Media	TV2
Aage Aune	Media	TV2
Lars Henriksen Doksæter	Media	(Screen Story/TV2)
Captain Svein-Roger Fredheim and his crew	Vessel operations	IMR

Figure 1.2. Cruise participants in Tromsø 10th of July. From left: Stig Vågenes, Shane Scheibener, Andrey Volynkin, Andrey Epifanov, Justin Gwynn, Hilde Elise Heldal, Louise Kiel Jensen, Hans-Christian Teien, Alexander Straume, Jörn Patrick Meyer. Photo: Stine Hommedal/IMR.

1.3. The nuclear submarine "Komsomolets" and its radionuclide inventory

The Russian nuclear submarine "Komsomolets" (K-278) (Figure 1.3 a-b) sank on the 7th of April 1989 following the outbreak of a fire. The submarine sank after initially surfacing and now lies at a depth of 1673 m, south west of Bear Island in the Norwegian Sea (73°43′16″ N, 13°16′52″ E) (Figure 1.1). Of the 69 crew members, 42 were killed as a result of the accident and eventual sinking.

"Komsomolets" was powered by a single 190 MW OK-650b-3 pressurised water reactor that was shut down in the early stages of the accident and carried two nuclear torpedoes in its armament (Gladkov et al., 1994). The total activity of the inventory of the reactor at the time of sinking has been estimated at 29 PBq with a further 16 TBq of $^{239,240}Pu$ contained within the two nuclear warheads (Gladkov et al., 1994; Høibraaten et al., 1997). In 2019, the remaining activity in the reactor (~3 PBq) is almost entirely due to ^{137}Cs and ^{90}Sr.

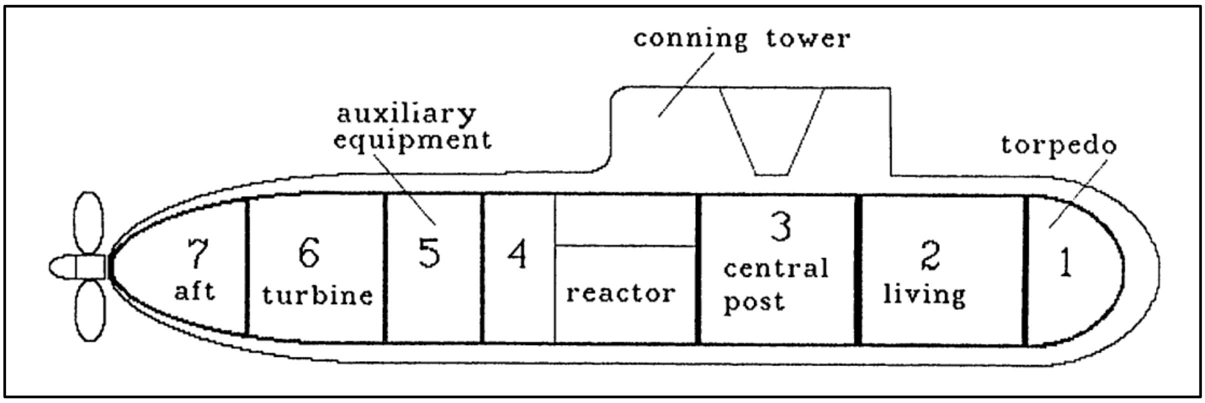

Figure 1.3 a. Layout of the nuclear submarine "Komsomolets" showing the position and use of the various compartments. The escape capsule is attached inside the V-shaped structure in the conning tower. Original source: Gladkov et al., 1994. Taken from Høibråten et al., 2003.

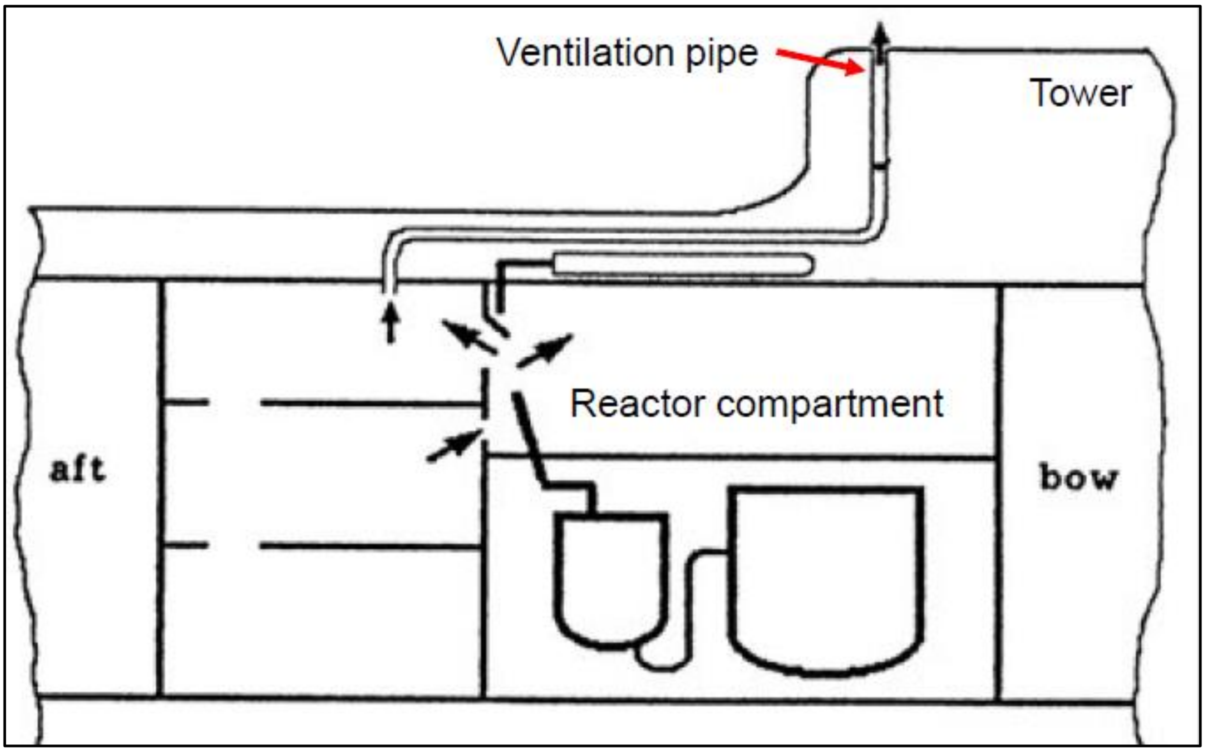

Figure 1.3 b. The reactor compartment of "Komsomolets". A possible route for leaks from the reactor compartment to the surrounding marine environment through a ventilation pipe is shown. Original source: Gladkov et al., 1994. Modified from Høibråten et al., 2003.

1.4. Hydrography and currents in the region near "Komsomolets"

In the region at the "Komsomolets" location, the Norwegian Atlantic Current (NwAC) transports northward relative warm and saline water in the upper layer (Figure 1.4). The NwAC splits into two branches at the entrance of the Barents Sea opening, where one branch flows eastwards into the Barents Sea while another branch flows northward, passing the location of the "Komsomolets", and becomes the West Spitsbergen Current west of Svalbard.

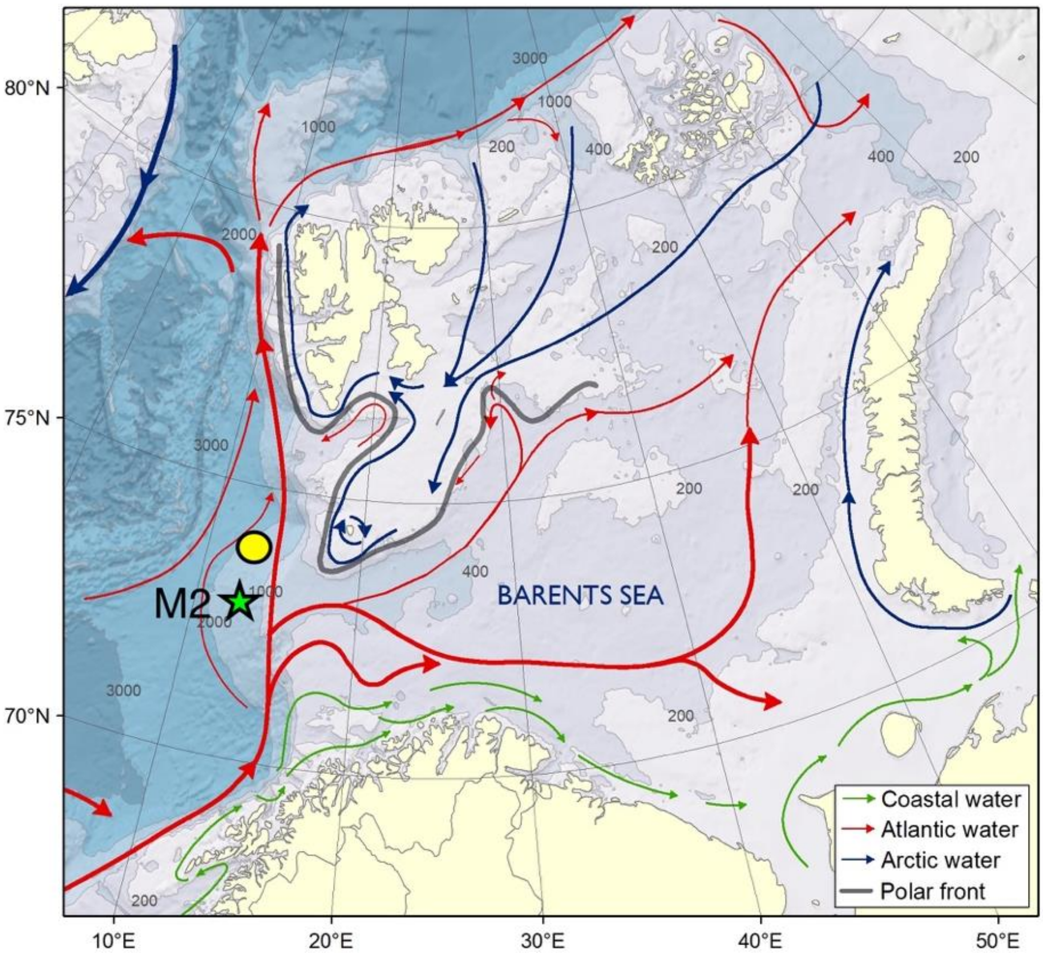

Figure 1.4. Schematic view of the main surface currents in the area. Location of "Komsomolets" is indicated with a yellow dot, the mooring with current measurements, M2, is shown as green star.

In a section that runs westward from the Bear Island, the Bear Island West section, the environment is monitored regularly several times per year as part of IMR's monitoring program. The section is located about 90 km north of "Komsomolets" (Figure 1.5). During a cruise in May/June 2019 with RV "Johan Hjort", the section was taken and the temperature, salinity, and density distributions from this section are shown in Figure 1.6. The layer of Atlantic Water (AW) (salinity>35) is occupying the upper 500 m with temperatures above 3 °C. Below the AW, in the intermediate and deep layers, the salinity change little with depth in contrast to the temperature that decreases for larger depths. In the intermediate/deep layer, and particular below ~1500 m depth, the water mass is nearly homogenous.

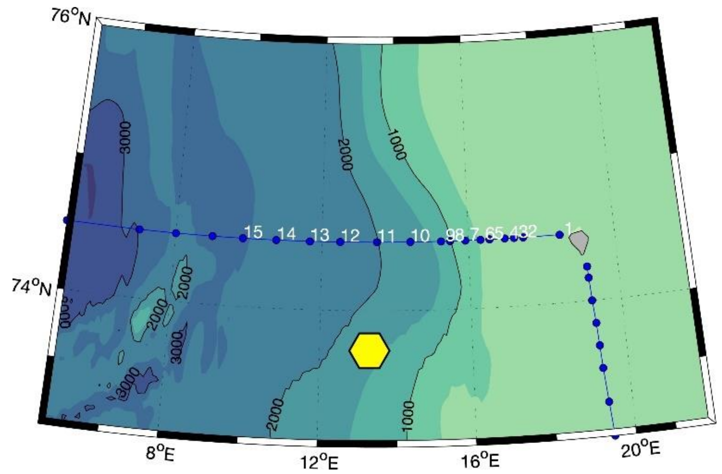

Figure 1.5. The Bear Island-West section with the 15 CTD-stations. The location of “Komsomolets” is indicated with a polygon.

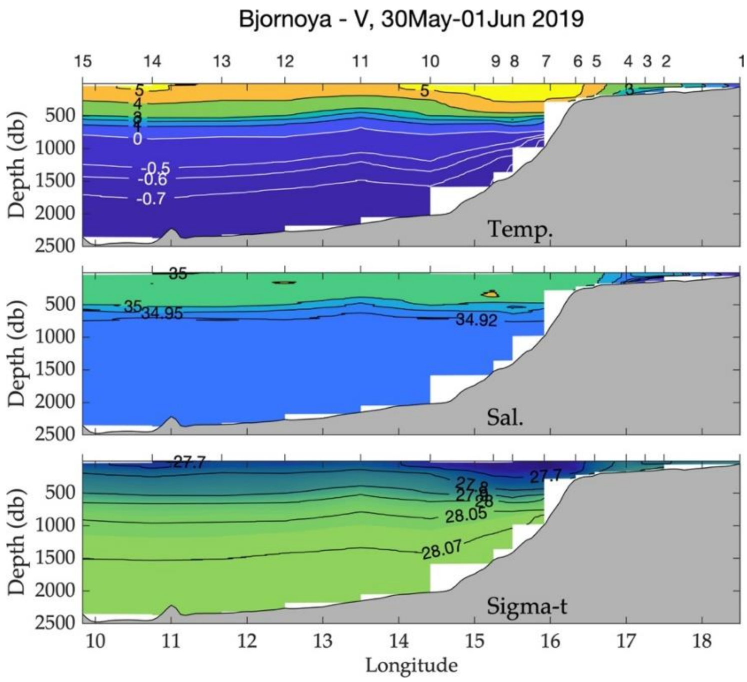

Figure 1.6. Temperature (°C), salinity, density (sigma-theta; kg/m^3) distributions in the Bear Island-West section during 30 May-1 June 2019.

Historically, there exist only few direct measurements of the deep currents in the region near “Komsomolets”. In 1993, a mooring with 4 current meters was deployed near the “Komsomolets” (73° 43.19´N, 13°15.60´E) for the period 3rd May-4th August 1993. The current meters were placed at depths 167, 667, 1567 and 1642 m at a bottom depth of 1697 m, but the uppermost instruments disappeared due to fishing activity. Measurements from the other instruments showed a strong barotropic component (i.e., the current was constant with depths) with alternating pulses along the slope (Blindheim et al., 1994). The dominant tidal component was the semidiurnal period and its amplitude decreased with depth, from about 10-15 cm/s at 667 m to less than 5 cm/s at 1642 m depth. The maximum measured velocity was found at the deepest instrument with a speed of 34.2 cm/s that was directed southwest ward.

In 2001, another mooring with current meters (M2) were deployed south of “Komsomolets” for the period May to November (see Figure 1.4 for location). It was deployed at 1500 m bottom depth with current meters at 790 m and 1290 m depths. Time series of the velocities of the deepest current meter where the semidiurnal and diurnal tidal current are filtered out is shown in Figure 1.7.

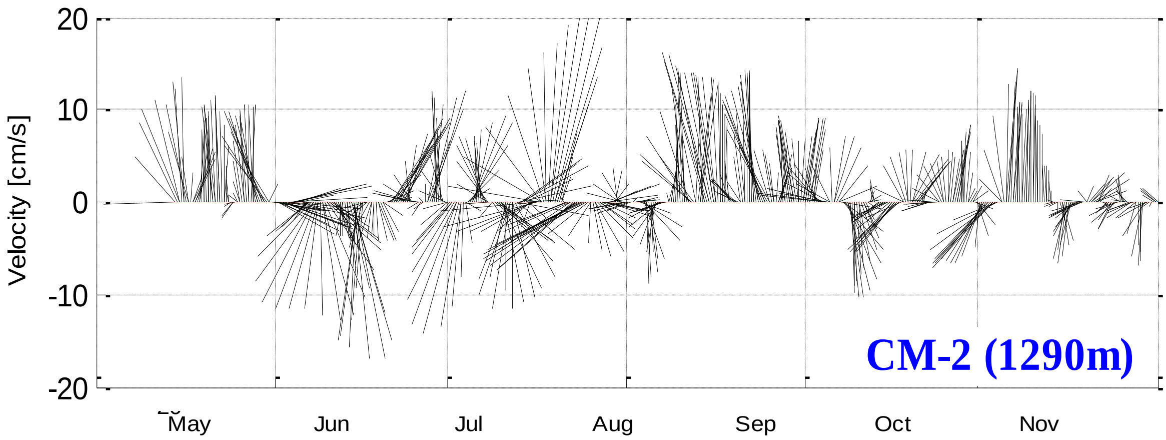

Figure 1.7. Stick plots of low pass filtered (Butterworth filter with cut-off frequency=1/26 h^{-1}) current vectors. 6 h values are plotted. Positive value indicates northward current.

The main current directions seem to be either northward or southward in which the northward direction dominates. Maximum speed of the filtered data is 20 cm/s. In August, there was a persistent northward flow with speed of about 10 cm/s that lasted about one month. Results from the mooring suggest that the barotropic component is significant (i.e., the current was constant with depths) since the two current meters there show similar velocities as long as the shallowest one (at 790 m depth) functioned (not shown). This is in agreement with the results from the other mentioned current mooring.

The dominant tidal component was at the semidiurnal period, and the tidal ellipse of its velocities is shown in Figure 1.8. The tidal current at M2 has a tendency of clockwise ellipse rotation with major and minor axis speeds of 4.5 cm/s and 2.2 cm/s.

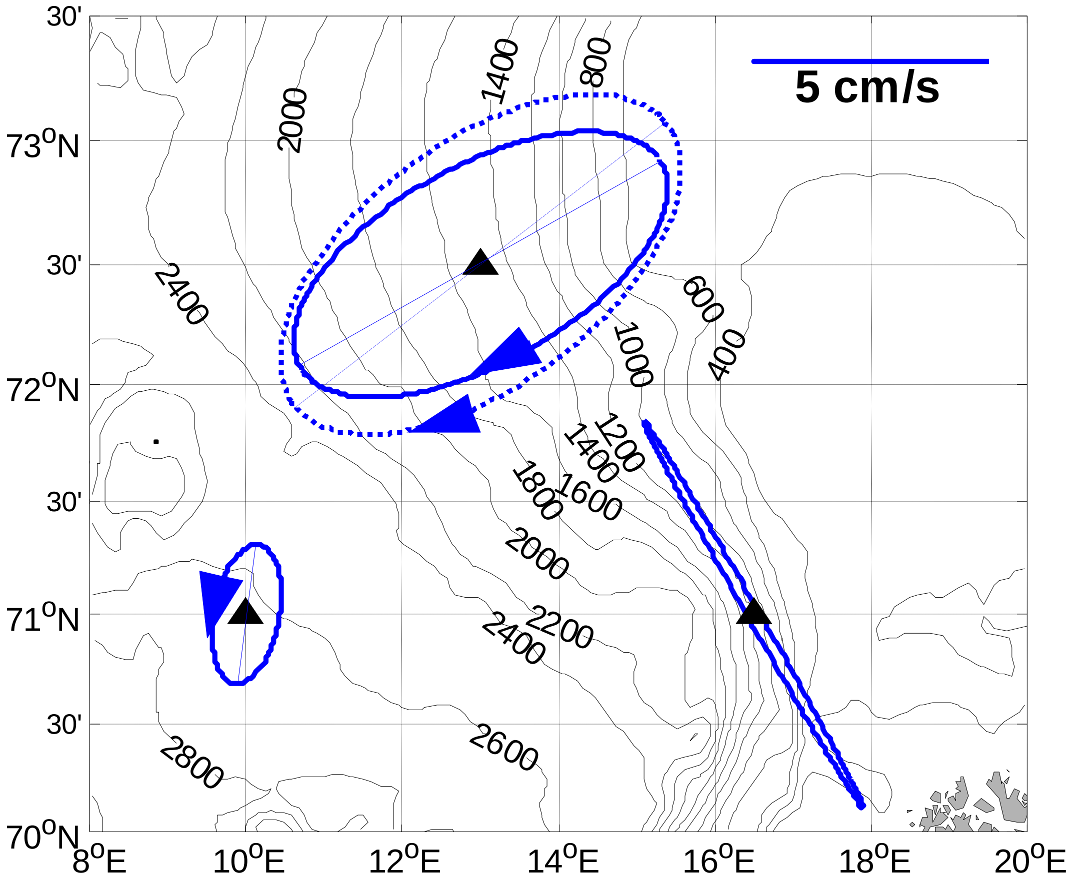

Figure 1.8. Semidiurnal tidal component at ~1300 m depth (solid line) and ~790 m depth (dotted line) at three current moorings. M2 mooring is the northernmost mooring.

1.5. Earlier investigations and monitoring of "Komsomolets"

A number of Soviet and subsequent Russian expeditions have been carried out between 1989 and 2007 with the aid of manned submersibles to investigate the status of the submarine and the surrounding marine environment. In addition, UK and German expeditions collected samples of sediment and seawater in the area around "Komsomolets" in 1989 and 1995, respectively. The White Book-2000 (Sivintsev et al., 2005) summarises and gives a list of references to a selection of these expeditions.

The use of manned submersibles in the Soviet and Russian expeditions allowed for the visual inspection of the submarine and for the collection of samples and *in situ* measurements next to the hull. Initial investigations showed that the front part of the submarine had suffered considerable damage, with holes and cracks in both the outer hull and inner pressure hull (Yablokov et al., 1993). Damage to the outer and inner pressure hull was observed above the torpedo compartment and it was reported that the nuclear material in the warheads were in contact with seawater (Yablokov et al., 1993). The six torpedo tubes along with some holes in the torpedo section were sealed with titanium plates during the expedition in 1994 to reduce the flow of seawater into the torpedo compartment (Kasatonov, 1996).

Releases of radionuclides (^{60}Co, ^{134}Cs and ^{137}Cs) from “Komsomolets” have been detected by *in situ* measurements in a ventilation pipe that forms an open connection between the compartment next to the reactor and the open sea (Nejdanov, 1993; Gladkov et al., 1994; Kazennov, 2010) (see Figure 1.3 b). Activity concentrations of ^{137}Cs detected in this ventilation pipe in 1994 were of the order of 1 MBq/m^3 decreasing to 4 kBq/m^3 in the zone around the outlet (Gladkov et al., 1994). Based on rates of water flow in the ventilation pipe, annual releases of ^{137}Cs from the sunken submarine were estimated at that time to be around 500 GBq/yr (Gladkov et al., 1994). In 2007, annual releases of ^{137}Cs from the ventilation pipe were reported to have decreased by more than 30-fold (Kazennov, 2010), whilst more recently, Vysotsky et al. (2014) estimated releases of ^{137}Cs and ^{90}Sr from “Komsomolets” at 0.1 GBq/yr.

Activity concentrations of ^{90}Sr, ^{137}Cs, Pu-isotopes and ^{241}Am in seawater and sediment samples collected by Soviet, Russian, UK and German expeditions between 1989 and 1995 from the area around “Komsomolets” have not indicated any releases from the submarine (Camplin and Read, 1992; Kuznetsov et al., 1993; Grøttheim, 1999; Nies et al., 1999a, 1999b; Stepanov et al., 1999; Astakhov et al., 2000; Nies et al. unpublished). However, above background activity concentrations of ^{90}Sr and ^{137}Cs were reported in some samples of benthic fauna collected close to “Komsomolets” in 1994, although not for any other year (Kuznetsov et al., 1996, 1999). Additionally, ^{60}Co was reported to have been detected in 3 samples of echinoderms (3.5–27 Bq/kg) collected close to the “Komsomolets” in 1993 (Kuznetsov et al., 1999). Plutonium activity and atom ratios in seawater sampled in the torpedo compartment and in sediments sampled close to “Komsomolets” in 1994 and 1995 were reported to be comparable to background measurements (Stepanov et al., 1999; Astakhov et al., 2000).

Norway's national marine monitoring programme (Radioactivity in the Marine Environment - RAME) charts trends in radionuclides in seawater, sediments and marine biota in the Norwegian marine environment and provides information on levels of radioactive contamination to relevant stakeholders. As part of this work, it is important for Norway to maintain an up-to-date overview of any source of radioactive contamination that may cause concern for fisheries and the general public. Norway has carried out monitoring of the marine environment in the area around “Komsomolets” annually since 1990. When sampling from surface vessels using traditional sampling gear lowered to the bottom, it is almost impossible to know the exact position of the sampling gear when the samples (seawater or sediment) are collected, or how the position of the samples collected relates to the actual location of the submarine. This is due in part to the great depth at which “Komsomolets” lies, but also to the varying strengths and direction of bottom currents in the area (Aleinik et al., 1999; Lukashin, 2008). In 2013 and 2015, monitoring was carried out using an acoustic transponder on the sampling gear that allowed samples to be collected at precise locations, ~20 m from the hull of the submarine. Even with the use of an acoustic transponder, there is still a need to maintain a safe operating distance from “Komsomolets” to avoid the possibility of fouling the sampling gear on the submarine. A complete overview of all the results of the Norwegian monitoring of “Komsomolets” between 1990 and 2015 is given in Gwynn et al. (2018). This study also compares the Norwegian findings with a compilation of the available data from previous Soviet, Russian, UK and German expeditions. Data from Norwegian monitoring between 1990 and 1994 have been previously reported in the non-peer reviewed internal reports by Blindheim et al. (1994) and Kolstad (1995). Additionally, some data for other years have been reported in the non-peer review RAME reports by the Norwegian Radiation and Nuclear Safety Authority (www.dsa.no) as well as in the MSc thesis by Flo (2014). Selected data for sediment from the Norwegian monitoring of “Komsomolets” in 1999 have been published previously by Heldal et al. (2002).

2. Cruise itinerary

RV “G. O. Sars” left Tromsø on the 6th of July at approximately 9:00 in the morning. After a test of the ROV at CTD St. 231 between approximately 15:00 and 16:00, we headed directly to “Komsomolets” at 73°43’16” N, 13°16’52” E, where we arrived at approximately 15:00 in the afternoon on the 7th of July. Station work started right away and continued until approximately 12:00 at the 9th of July, when we headed back to Tromsø. RV “G. O. Sars” reached Tromsø approximately at 16:00 at the 10th of July. The weather conditions were calm during the whole cruise. The expedition route is shown in Figure 2.1.

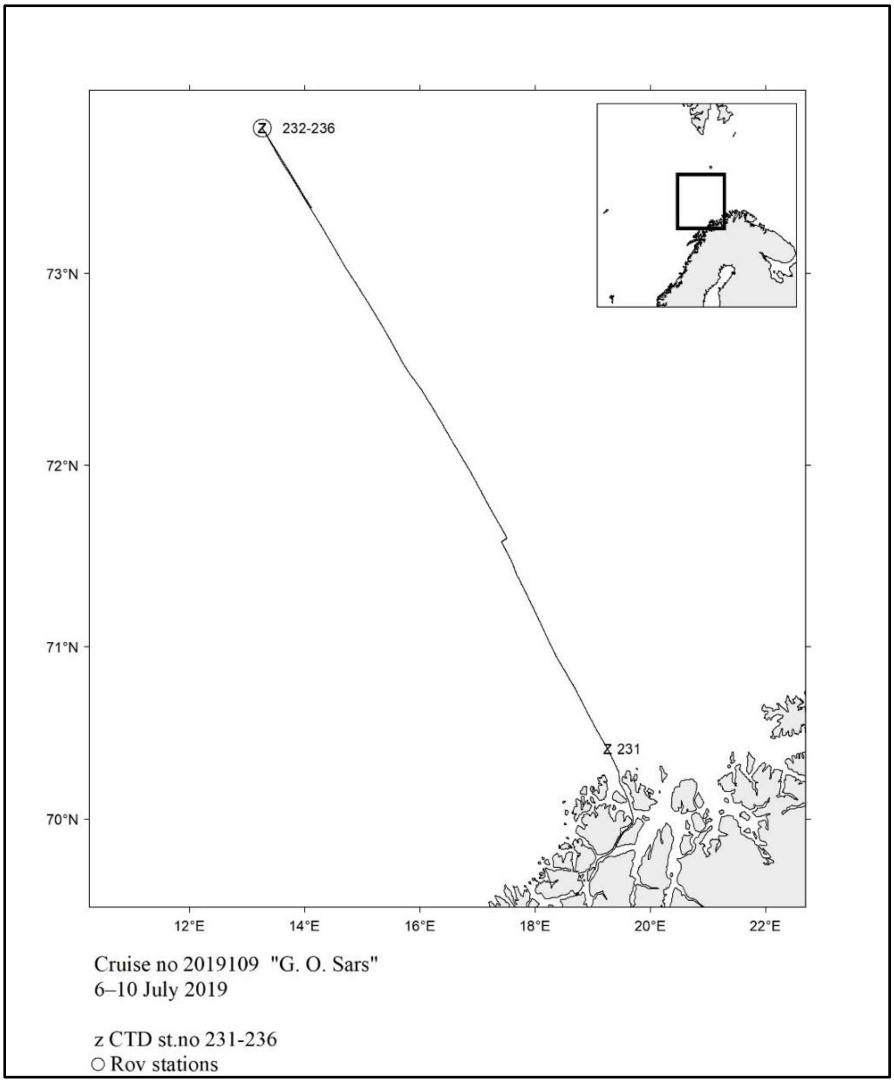

Figure 2.1. Expedition route for RV “G. O. Sars” 6-10 July 2019. Tromsø-“Komsomolets”-Tromsø. Figure: Karen Gjertsen/IMR.

3. Equipment and station work

3.1. RV “G. O. Sars”

RV “G. O. Sars” (Figure 3.1) was delivered in 2003 and is owned by the Institute of Marine Research (75%) and the University of Bergen (25%). Technical specifications are given in Table 3.1. "G. O. Sars” is equipped for all types of marine research and was for many years the only Norwegian research vessel that could handle the Remotely Operated Vehicle (ROV) Ægir 6000 (see below). RV “Kronprins Haakon”, built in 2016-2017, is now also capable of handling ROV Ægir 6000.

Figure 3.1. RV “G. O. Sars”. Photo: Erlend Astad Lorentzen/IMR

Table 3.1. Technical specifications of RV “G. O. Sars”

Shipyard	Flekkefjord Slipp & Maskinfabrikk
Built	2003
Length	77.5 m
Beam	16.4 m
GRT	4067 brt
Machinery	Diesel electric, 8100 kw
Top speed	17 knots, cruising speed 11-13 knots
Accommodation	19 single-berth, 13 double-berth cabins

3.2. CTD (Conductivity, Temperature, Depth) Measurements

Depth profiles of temperature, salinity and other parameters were recorded onboard RV “G. O. Sars” using a Sea-Bird SBE 911 CTD-system equipped with the following sensors:

- 1 internal Digiquartz pressure sensor
- 2 Sea-Bird SBE 3 temperature sensors
- 2 Sea-Bird SBE 4 conductivity sensors
- 1 Sea-Bird SBE 43 oxygen sensor
- 1 Chelsea Technologies Aquatrack 3 fluorometer
- 1 Biospherical Instrument QCP-2300 PAR sensor
- 1 Teledyne Benthos PSA-916 altimeter
- 1 Biospherical Instruments QSR-2200 SPAR sensor

Figure 3.2. The CTD system onboard RV “G. O. Sars”. Photo: Stine Hommedal/IMR.

The CTD system was mounted on a Rosette Sampler with 12 10 l bottles (Figure 3.2). The system was used to collect large volumes of seawater close to “Komsomolets”. At the site of “Komsomolets”, five CTD-casts were taken (stations 232-236). Vertical temperature and salinity profiles of the CTD-casts are shown in Figure 3.3. Both temperature and salinity from all five CTD-casts present a similar stratification of the surrounding water masses. AW is observed in the upper 400 m. Below ~600 m depth the salinity variation is small, but a local minimum (34.91) at about 1000 m depth in the intermediate layer is observed. The temperature decreased with depth, except near the bottom, in a 100 m thick layer, where it was constant. This indicates a 100 m thick thoroughly bottom nepheloid layer.

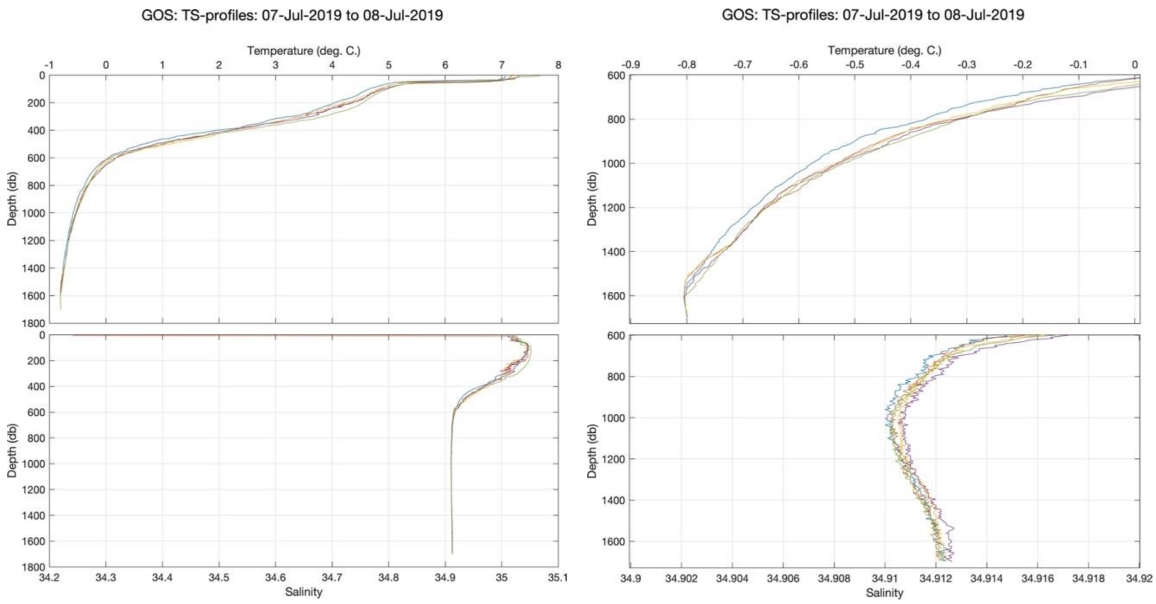

Figure 3.3. Temperature and salinity profiles at “Komsomolets” (CTD St. 232-236). Right figure is a zoom of the left figure.

3.3. Acoustic Doppler Current Profilers (ADCP)

At the site of “Komsomolets”, currents in the upper water column were measured continuously with two Acoustic Doppler Current Profilers (ADCP) mounted to the vessel; a 75 kHz and a 150 kHz ADCP (Teledyne RDI Ocean Surveyor). The range of the two ADCPs were 622 m and 414 m, respectively. The configurations of the ADCPs are given in Tables 3.2 and 3.3.

Table 3.2. Configurations of the 75 kHz ADCP onboard RV “G. O. Sars”

75 kHz	
Narrowband mode	Off
Broadband mode	On, single ping ensemble
Cell Length	8 m
Blank distance	8 m
Number of bins	75
Ambiguity velocity	Default (39.0 cm/s)
NP0	
WP1	
WS0800	
WF0800	
WN075	
WV390	

Table 3.3. Configurations of the 150 kHz ADCP onboard RV “G. O. Sars”

150 kHz	
Narrowband mode	Off
Broadband mode	On, single ping ensemble
Cell length	4 m
Blank distance	4 m (4.0 + 4.0 = 8.0 m)
Number of bins	100
Ambiguity velocity	Default (39.0 cm/s)
WP00001	
NP00000	
WS0400	
WF0400	
WN100	
WV390	

The speed of the current in the upper 400 m from the ADCP is shown in Figure 3.4. During the days with measurements the speed decreased. The semidiurnal tidal current can also be observed. Maximum speed is about 40 cm/s.

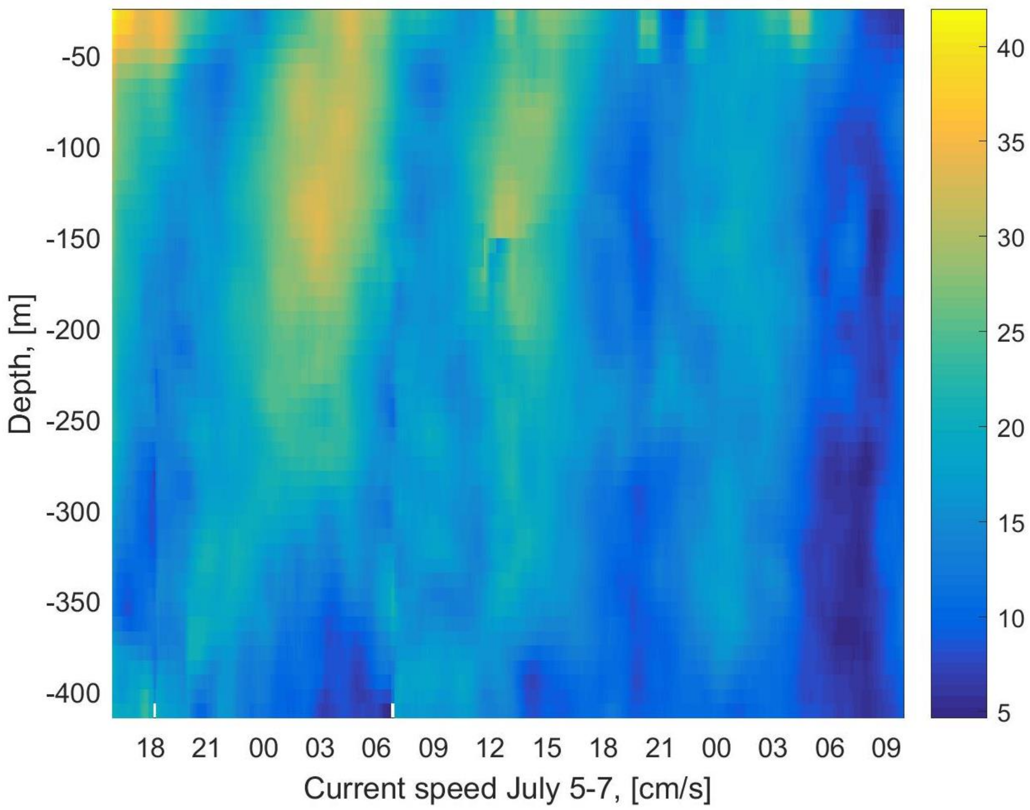

Figure 3.4. Speed of the current from the ship's ADCP during 5-7 July.

Visual observations from the ROVs camera via the control room during the sampling period indicated that the direction of the bottom current around "Komsomolets" was variable.

3.4. The Remotely Operated Vehicle (ROV) Ægir 6000

The ROV Ægir 6000 (https://oceanlab-no.weebly.com/) is an unmanned submersible that can carry and deploy a variety of sampling equipment, sensors and camera systems (Figure 3.5). The equipment we used during the cruise to "Komsomolets" is listed in Table 3.4. Ægir can be deployed with a Tether Management System (TMS) that stores and deploys the tethering cable (1000 m range) when the ROV is submerged, enabling it to be decoupled from the motion of the ship and allowing it to operate at a larger radius from the mother ship. The TMS has a cage-like containment system for transporting the ROV during deployment and has sample storage facilities. With camera systems on both the TMS and the ROV itself, Ægir 6000 can record pictures and film of itself in action in the deep sea. Other facts about Ægir 6000 are given in fact box below.

Figure 3.5. Launching of ROV Ægir 6000 at the 7th of July, equipped with three 1 l biosyringes and two 2 l Niskin bottles. Dive 1.

Facts about Ægir 6000

- ROV Ægir 6000 is funded by the Research Council of Norway and serves as part of the national research infrastructure
- Owned by the University of Bergen (UoB)
- The Institute of Marine Research (IMR) and Christian Michelsen Research (CMR) are partners in the infrastructure consortium
- Officially launched 1st July 2015
- Can dive to 6000 m
- Capable of carry and deploy a variety of sensory equipment and numerous cameras
- Designed for operation from both RVs “G. O. Sars” and “Kronprins Haakon”

Table 3.4. Equipment and camera systems belonging to ROV Ægir 6000 used during the cruise.

Equipment	Purpose
Centre camera	Recording film
Top camera	Recording film
TMS camera	Recording film
Multibeam Kongsberg EM2040	Imaging of the seabed on a cm scale
Biosyringe, 1 l	Sampling of seawater
Niskin bottle, 2 l	Sampling of seawater
Push cores	Sampling of sediment profiles and pore water
Blade cores	Sampling of sediment profiles
Vacuum sampler	Sampling of biota
Manipulator arms	Multiple purpose, including sampling of biota

Station work started by using the ROV’s multibeam system to create a detailed image (cm scale) of the ocean floor in the area where “Komsomolets” is resting (Figure 3.6).

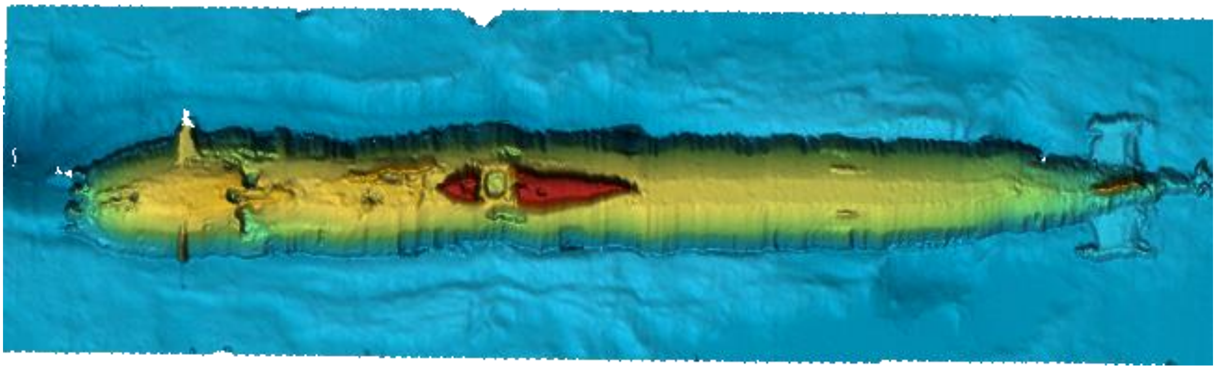

Figure 3.6. Multibeam image of “Komsomolets”, seen from above.

3.5. Sample collection

A complete overview of all collected samples is given in Appendix 1-5. Sampling and pre-treatment of surface seawater, bottom seawater, sediments and biota is briefly described in this chapter.

For collecting smaller volumes of seawater in the proximity to “Komsomolets”, we used three 1 l biosyringes (Figure 3.7 a) and two 2 l Niskin bottles (Figure 3.7 b). These were transported to and from “Komsomolets” with Ægir 6000. For collecting sediment samples, we used blade cores (Figure 3.7 c) and push cores (Figure 3.7 d and e). The cores were transported to and from “Komsomolets” with an auxiliary basket (Figure 3.7 d).

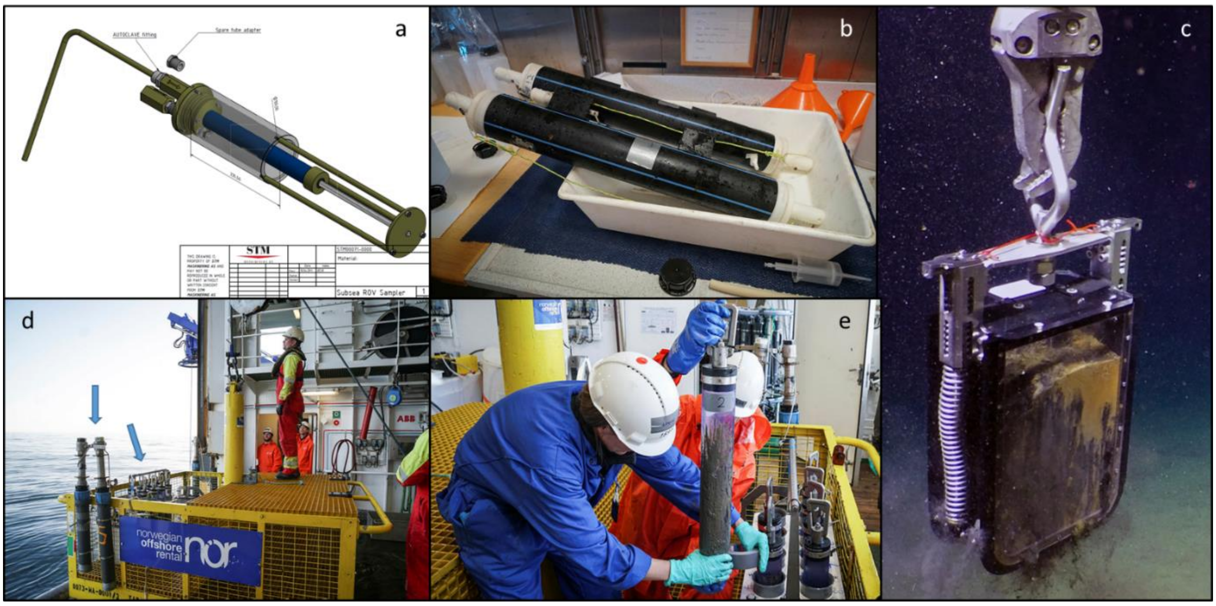

Figure 3.7 a. Biosyringe used for sampling of seawater (image reproduced with permission from STM Maskinering AS). b. Niskin bottles used for sampling seawater. c. Blade core with sample. d. Auxiliary basket with push cores (indicated with blue arrow) and blade cores (not shown) ready to be de-ployed. e. Push core with sample retrieved from basket.

3.5.1. Sampling and pre-treatment of surface seawater

Samples of surface seawater were collected at CTD St. 232 for analyses of ^{3}H, ^{90}Sr, ^{129}I, ^{137}Cs, ^{236}U, ^{238}Pu, $^{239,240}Pu$ and ^{241}Am (Table 3.5). The samples were taken from the ships seawater intake at approximately 6 m. We do not expect to detect any releases from "Komsomolets" in surface seawater in the Norwegian Sea, but the results give us information about the general radionuclide levels in surface seawater in the Norwegian Sea, and the results adds up to a time series starting in 1991 (Gwynn et al., 2018).

Table 3.5. Samples of surface seawater taken at CTD St. 232.

Sample code	Radionuclide/analyte	Sample volume (l)	Filter pore size
W1*	^{238}Pu, $^{239,240}Pu$ and ^{241}Am	300	1 µm
W2*	^{90}Sr	50	1 µm
W3*	^{137}Cs	75	1 µm
W4	^{236}U, ^{239}Pu and ^{240}Pu	80	0.45 µm (40 l); 10 kDa (40 l)
W5	^{129}I	2	0.45 µm (1 l); 10 kDa (1 l)
W6	^{3}H	1	0.45 µm
W7	Analyses on ICP-MS	fractions of 50 ml	0.45 µm

*Samples are part of the national monitoring program RAME (see chapter 1.3).

The samples W1-W3 were filtered through 1 µm filters. The samples for ^{90}Sr (W2) and ^{137}Cs (W3) were thereafter filled in 25 l labelled plastic cans. The sample for ^{90}Sr was acidified to pH 2 with concentrated HCl, and will be transferred to a laboratory on shore and analysed later. ^{137}Cs will be determined at IMR according to the method described by Roos et al. (1994) by precipitation with ammonium-12-molybdophosphate (AMP) and ^{134}Cs as a yield tracer.

After 1 µm filtration, the sample for ^{238}Pu, $^{239,240}Pu$ and ^{241}Am (W1) was transferred directly to a processing tank, with exact collected volume determined by a flow meter. Prior to sample collection, the processing tank was washed twice with copious amounts of the sample water. The sample was acidified to pH 2 with concentrated HCl, followed by the addition of a combined ^{242}Pu/^{243}Am tracer, 2 g of $FeCl_3 \cdot 6H_2O$ and 100 g of $K_2S_2O_5$. The sample was then allowed to mix for at least 1 hour by aeration, before increasing the pH to 10 with the addition of 6 M NaOH. The sample was then allowed to stand for at least 12 hours to allow the precipitate to settle. The supernatant was carefully removed, to allow collection of the precipitate in a volume of less than 10 l in a labelled plastic can. The processing tank was washed with a small volume of 0.1 M HCl and distilled water, with each washing added to the collected sample. Finally, the precipitate was re-dissolved by the addition of concentrated HCl at approximately 15 ml/l. The sample will be transferred to DSA for additional chemical separation and analysis by alpha spectrometry.

For samples W4-W7, size and charge fractionation techniques were carried out onboard the ship in order to obtain information on the speciation (physico-chemical forms) of the radionuclides and trace metals. Using filtration (0.45 µm Pall filters) and ultrafiltration (Pall hollow fibre cartridges of 10 kDa nominal cut-off) interfaced with ion chromatography (Chelex-100 cation exchange resin) the following fractions were obtained:

- Particles > 0.45 µm
- Pseudocolloids 10 kDa-0.45 µm
- Low molecular weight (LMW) forms <10 kDa
- Positively charged LMW forms (< 10 kDa) as cations

The hollow fibres were carefully washed between each sample with 0.1 M NaOH, 0.1 M HNO_3 and MilliQ water prior to pre-conditioning with sample water prior to sample collection.

Samples W4-W7 were filtered through the same 0.45 μm filter. Material retained on the filter thus represents the particulate fraction. Samples W4-W5 were also 10 kDa ultrafiltered.

The samples for ^{236}U, ^{239}Pu and ^{240}Pu (W4) were acidified to pH 2 using ultrapure HCl and added ^{242}Pu yield tracer. The samples were transferred to NMBU/CERAD for further processing and analysis. Accelerator Mass Spectrometry (AMS) will be used for analyses of ^{236}U, ^{239}Pu and ^{240}Pu.

The samples for ^{129}I (W5) were not acidified. The samples were transferred to NMBU/CERAD for further processing and analyses with Accelerator Mass Spectrometry (AMS).

The samples for ^{3}H (W6) was not acidified. The samples will later be analysed in a laboratory on shore.

Several samples were taken for analyses on ICP-MS (W7). The samples were size and charge fractionated and stored in 50 ml Greiner tubes. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) will be used to measure ^{238}U, ^{127}I (stable) as well as metals and trace elements at NMBU/CERAD.

Measured isotope ratios (e.g. ^{236}U/^{238}U, ^{240}Pu/^{239}Pu) in the different fractions will enable us to distinguish between potential contamination from “Komsomolets” and other, far-field sources such as weapon grade Pu from Russian reprocessing sites and tropospheric or global fallout.

3.5.2. Sampling and pre-treatment of bottom seawater

3.5.2.1. Samples taken 3 m above ventilation pipe

To investigate potential releases from the reactor compartment, samples of seawater were collected 3 m above the ventilation pipe of “Komsomolets” using the CTD system/Rosette Sampler with 12 10 l bottles (see Chapter 3.2). The ROV Ægir 6000 grabbed the CTD system/Rosette Sampler and brought it to the desired position 3 m above the ventilation pipe (Figure 3.8). Each cast collected approximately 120 l of seawater. Thus, approximately 240 l of seawater were collected 3 m above the ventilation pipe from two CTD casts (CTD St. 233/234) for analyses of ^{3}H, ^{90}Sr, ^{129}I, ^{137}Cs, ^{236}U, Pu-isotopes and ICP-MS analyses (Table 3.6).

The sample treatment was identical to that described in Chapter 3.5.1 except that the sample for ^{129}I was not ultrafiltered through the 10 kDa cartridge. An extra sample of 1 l was also collected for gamma screening

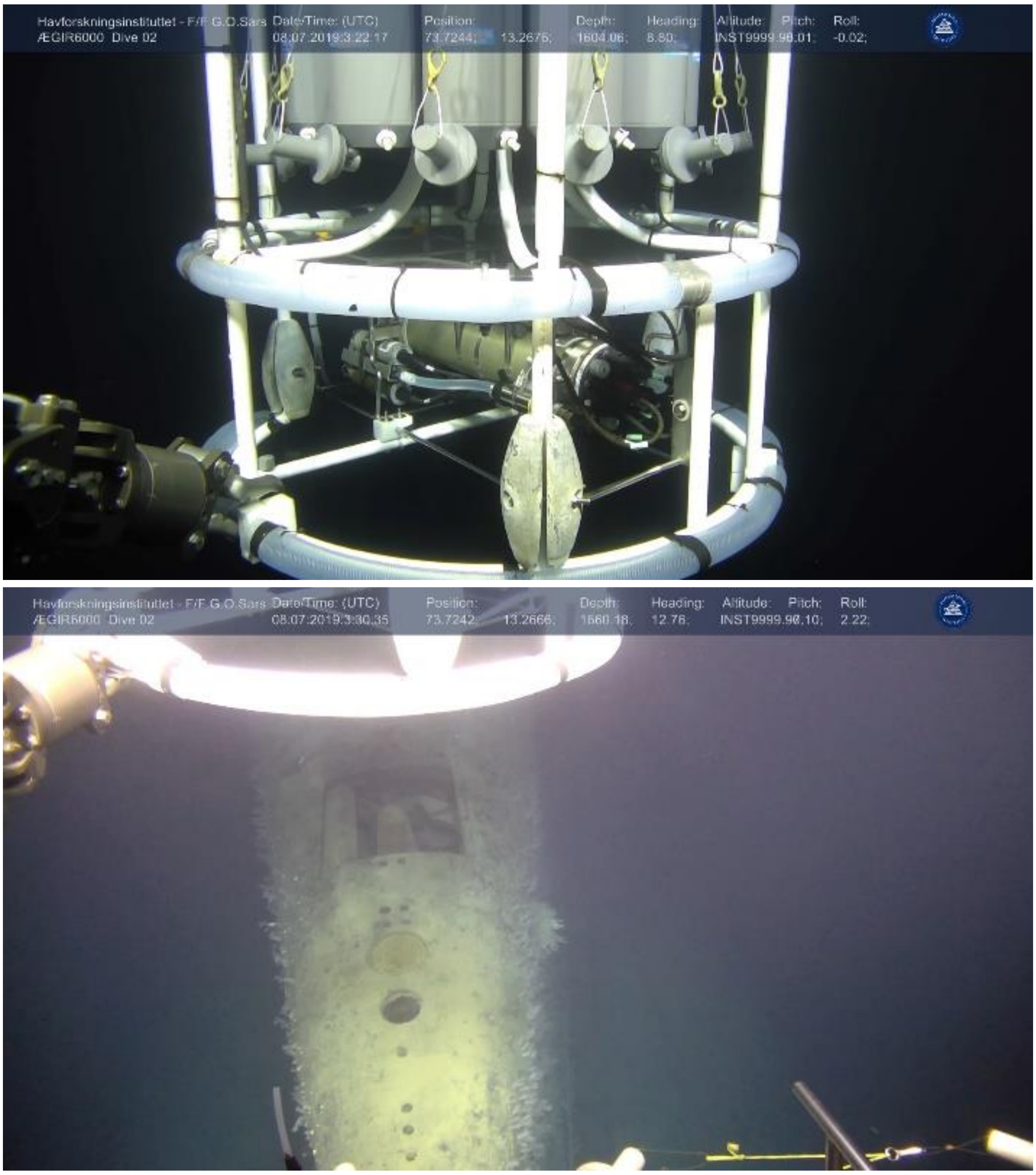

Figure 3.8. Sampling of seawater 3 m above the ventilation pipe. The ROV Ægir 6000 brought the CTD system/Rosette Sampler to the desired position for sample collection (the ROV arm is visible in the left part of the picture).

Table 3.6. Samples of seawater taken 3m above ventilation pipe (CTD St. 233/234)

Sample code	Radionuclide/analyte	Sample volume (l)	Filter pore size
W8*	^{90}Sr	50	1 µm
W9*	^{137}Cs	75	1 µm
W10	^{236}U, ^{239}Pu and ^{240}Pu	80	0.45 µm (40 l); 10 kDa (40 l)
W11	^{129}I	1	0.45 µm
W12	^{3}H	1	0.45 µm
W13	Analyses on ICP-MS	fractions of 50 ml	0.45 µm

*Samples are part of the national monitoring program RAME (see chapter 1.3)

3.5.2.2. Samples taken near torpedo compartment

Samples of seawater were collected at two locations near the torpedo compartment, to detect any releases of Pu isotopes from the 2 nuclear warheads in the torpedo compartment. The camera on ROV Ægir 6000 was used to position the CTD system/Rosette Sampler to the desired positions for sample collection (Figure 3.9). One sample was collected beside port front dive plane (Table 3.7) and one sample was collected beside tower edge of covering over torpedo compartment on port side (Table 3.8).

Figure 3.9. Sampling of seawater beside port front dive plane (upper) and beside tower edge of covering over torpedo compartment on port side (lower).

Table 3.7. Samples of bottom seawater taken at CTD St. 236 (flask 1-6) beside port front dive plane.

Sample code	Radionuclide/analyte	Sample volume
W14	^{236}U, ^{239}Pu and ^{240}Pu	40 l 0.45 µm filtered
W15	Analyses on ICP-MS	150 ml 0.45 µm filtered

Table 3.8. Samples of bottom seawater taken at CTD St. 236 (flask 7-12) beside tower edge of covering over torpedo compartment on port side.

Sample code	Radionuclide/analyte	Sample volume
W16	^{236}U, ^{239}Pu and ^{240}Pu	40 l 0.45 µm filtered
W17	^{129}I	1 l 0.45 µm filtered
W18	Analyses on ICP-MS	100 ml 0.45 µm filtered

3.5.2.3. Samples taken inside and outside ventilation pipe and near reactor compartment

In total 16 samples of 1-2 l seawater were taken inside and outside the ventilation pipe and near the reactor compartment (Figures 3.10 and 3.11). An overview of the collected samples is given in Table 3.9. The samples will be analysed for ^{137}Cs, ^{90}Sr, Pu- and U-isotopes.

Table 3.9. Smaller seawater samples taken with the use of ROV Ægir 6000.

Sample code	Sampling location	Radionuclide/analyte	Sample volume*
RW1, RW6, RW7, RW10, RW12, RW14	Inside ventilation pipe	^{137}Cs, ^{90}Sr, ^{239}Pu, ^{240}Pu, ^{236}U, ^{129}I, trace metals	1 l
RW2	1 m above ventilation pipe	^{137}Cs, ^{90}Sr	1 l
RW3	5 m above ventilation pipe	^{137}Cs, ^{90}Sr	1 l
RW4	Reactor compartment starboard side	^{137}Cs, ^{90}Sr	2 l
RW5	Reactor compartment port side	^{137}Cs, ^{90}Sr	2 l
RW8	Above grill near ventilation pipe	^{137}Cs, ^{90}Sr	1 l
RW9, RW11	Over ventilation pipe in cloud	^{137}Cs, ^{90}Sr	2 l
RW13, RW15	40 cm above ventilation pipe	^{137}Cs, ^{90}Sr	2 l
RW16	Next to ventilation pipe	^{137}Cs, ^{90}Sr	1 l

*Sample volumes of 1 l were taken with biosyringes, and sample volumes of 2 l were taken with Niskin bottles.

Figure 3.10. Collection of 1 l seawater inside the ventilation pipe with a biosyringe.

Figure 3.11. Collection of 2 l seawater on starboard side of reactor using a 2 l Niskin bottle.

3.5.3. Sampling and pre-treatment of sediments

Sediment samples were collected using push cores and blade cores (see Figure 3.7). Both types of cores were mounted in the auxiliary basket (Figure 3.7 d), which was then lowered to the seafloor near to "Komsomolets". The ROV Ægir 6000 was used to collect push cores (inner diameter of 7 cm and lengths between 55 and 80 cm) and blade cores from the auxiliary basket and take sediment samples at planned locations around the hull of the submarine. Both types of cores were taken using the manipulator arm on the ROV, by forcing the cores into the sediment (Figure 3.12). Cores full with sediment were then returned to the auxiliary basket by the ROV and when all cores had been used, the auxiliary basket was returned to the surface.

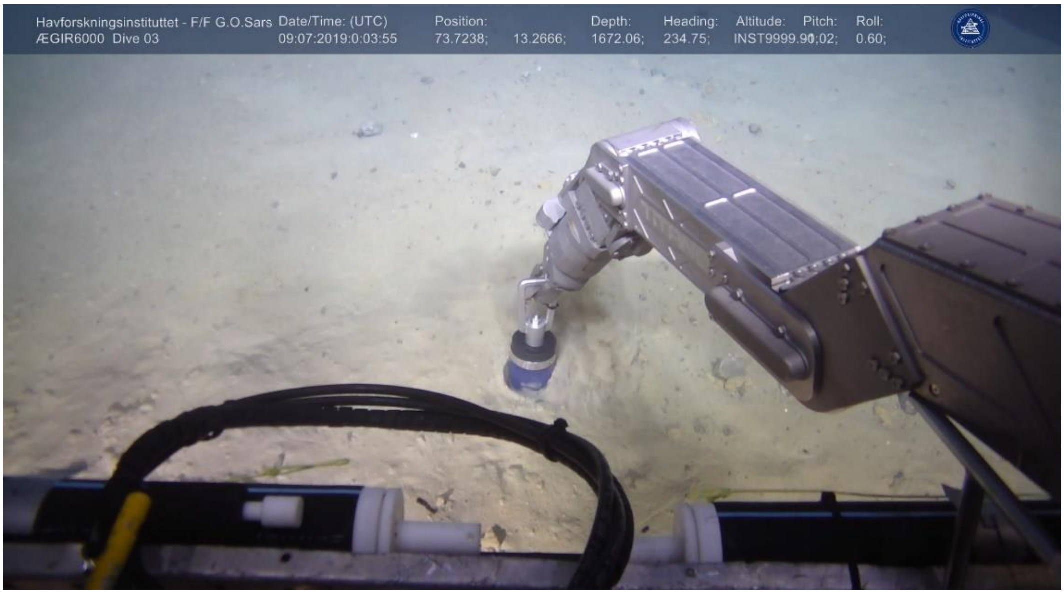

Figure 3.12. The manipulator arm of Ægir 6000 forces a push core into the seabed close to "Komsomolets".

Onboard, all push cores were closed with lids in both ends and thereafter stored in the ships freezer room. The four blade cores were opened onboard, with half of each core sliced at 1cm intervals from 1 to 5 cm, with the remaining core sliced into 2 further samples (5 to 7 cm and 7 to 10 cm). Surface sediment samples (0 to 2 cm) were sliced from the other half of 2 blade cores (port and starboard side of the reactor).

The push core samples were transported to IMR where they will be sliced into 1 cm (0-10 cm) and 2 cm (the remaining core) slices, freeze dried and homogenised. Analyses of gamma-emitters, ^{239}Pu and ^{240}Pu, metals and trace metals will later be performed at different laboratories. We attempted to collect in total 22 push core samples, but 5 samples were lost while one core only contained the upper 2 cm of the sediment and was treated as a surface sample. An overview of where the samples were collected is given in Figure 3.13. A detailed overview of the collected sediments is given in Appendix 3.

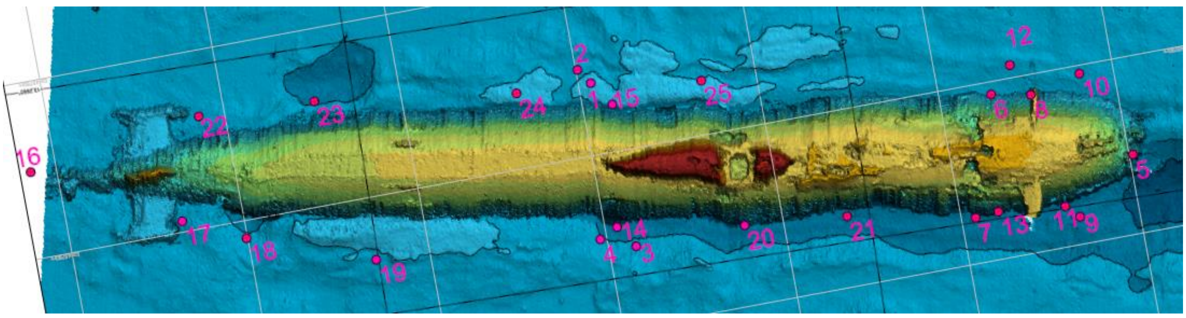

Figure 3.13. Overview of collected push cores and blade cores. 1-11= Push cores 1-11. 12-15= Blade cores 1-4. 16-25: Push cores 12-21. See Appendix 3 for details.

3.5.4. Sampling and pre-treatment of biota

A vacuum sampler and the ROV's manipulator arm were used to collect various biota samples from the hull of "Komsomolets", as well as from the sediment around "Komsomolets" (Figures 3.14 and 3.15). The samples were roughly sorted onboard RV "G. O. Sars" by species, genus or family and thereafter transferred to IMR, where the samples were identified by experts. An overview of the collected samples is given in Table 3.10. The samples will be analysed for different radionuclides at IMR, DSA and NMBU.

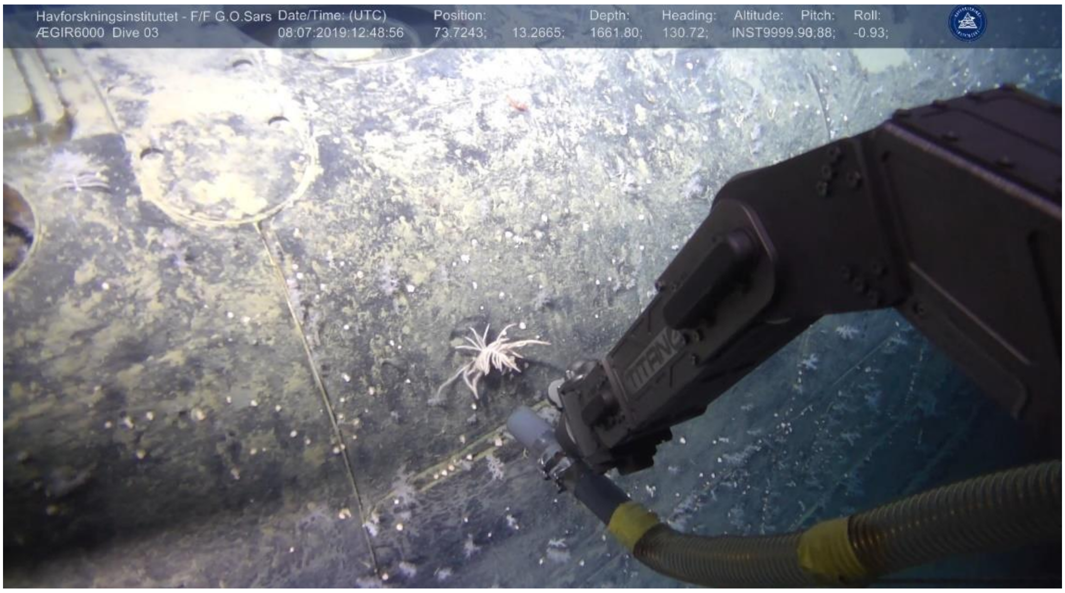

Figure 3.14. Sampling of the carnivorous sponge *Cladorhiza gelida* using a vacuum sampler.

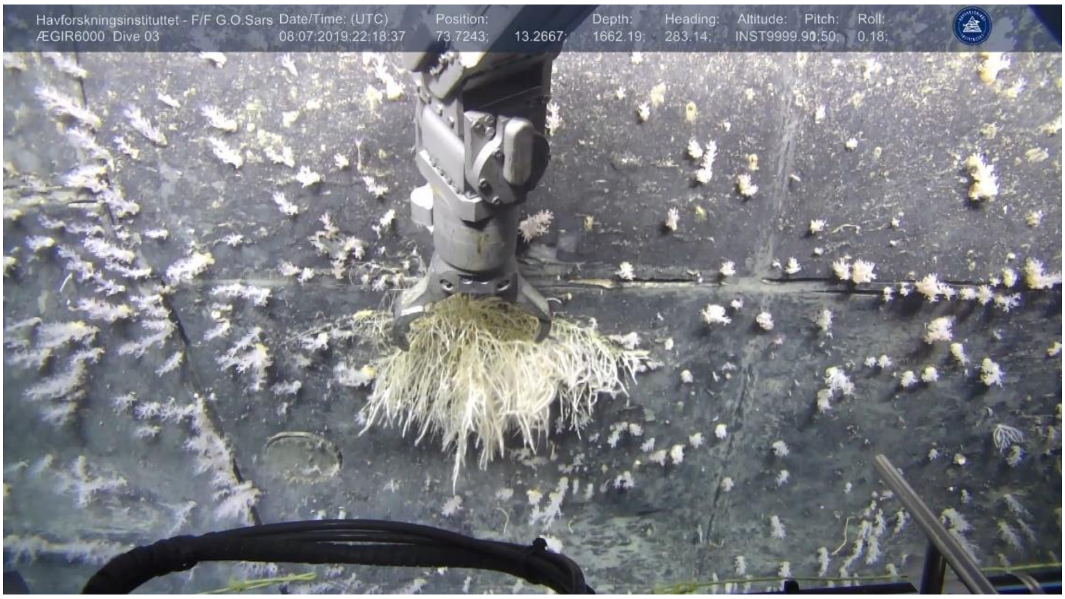

Figure 3.15. Sampling of the carnivorous sponge *Cladorhiza gelida* using the ROV's manipulator arm.

Table 3.10. Overview of collected biota samples.

Phylum/ Subphylum	Class/ Subclass	Order	Family	Genus/ Species	Note
Porifera	Demospongiae	Poecilosclerida	Cladorhizidae	*Cladorhiza gelida*	
Cnidaria	Hydrozoa				Stem
Cnidaria	Anthozoa	Alcyonacea	Nephtheidae	*Gersemia* sp.	
Cnidaria	Anthozoa	Actiniaria			
Annelida	Polychaeta	Phyllodocida	Polynoidae		Two or more spe-cies
Arthropoda/ Crustacea	Malacostraca	Amphipoda			
Arthropoda/ Crustacea	Copepoda				
Mollusca	Solenogastres				
Echinodermata	Asteroidea	Notomyotida	Benthopectinidae	*Pontaster tenuispinus*	
Unknown					Eggs

3.6. On board counting facilities and preliminary results

3.6.1. *In situ* Geiger counter

A VEL subsea Geiger counter from Vastveit Elektronikk AS (specifications given in Table 3.11) was mounted on the ROV (Figures 3.16-3.17). The Geiger counter detects and measures beta particles, gamma- and x-rays. A cable ensured direct transmission of data from the Geiger counter to the control room onboard RV “G. O. Sars” (Figure 3.17). The Geiger counter was used to screen the hull of “Komsomolets” for radioactive contamination before we started sample collection. According to the specifications given by the manufacturer, the lower detection limit is 0.01 µSv/hr. It is not possible to measure such low levels under the conditions we used the instrument. We did not measure any radioactivity levels around “Komsomolets” above the normal background in the marine environment, which is approximately 0.1-0.2 µSv/hr.

Table 3.11. Specifications given by the manufacturer for the VEL Subsea Geiger counter.

Detector	Geiger-Muller tube, Halogen-quenched Thin Wall Beta-Gamma Detector
Radiation detected	Beta, Gamma and X-ray.
Energy sensitivity	Beta / gamma / X-rays: min 35 keV Gamma sensitivity: 450 CPM/mR/hr Calibrated to Cesium-137 (Cs-137)
Accuracy	±10% Typical, ±15% Maximum
Measurement range	0.001 to 500 mR/hr 0.01 to 5,000 μSv/hr 1 to 500,000 μR/hr 1 to 225,000 CPM (450 CPM/mR/hr) 0 to 3,750 CPS (7.5 CPS/mR/hr) Total Count: 0 to 4,294,967,295 (32 Bit Integer)
Measurement statistics	Continuous availability of Elapsed Time, Average, Minimum and Maximum dose rate in either μR/hr, mR/hr, μSv /hr, CPS or CPM. Time stamp on new maximum.
Interface	The sensor will run on a standard Windows PC and comes with its own soft-ware. The sensor can be run on RS 232, or RS 485.
Timed measurement	Selectable 1, 5, 10, 20, 30, 60 and 90 minute intervals
Rate Alarm	Alarm can be set in mR/hr or μSv /hr to any value within the measurement
Temperature range	-20ºC to 51ºC

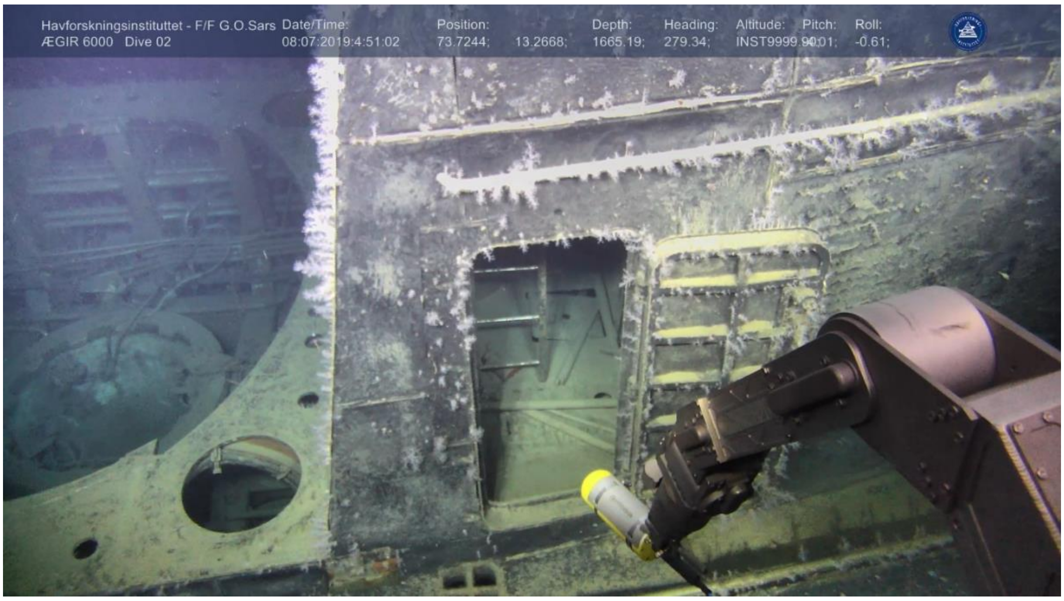

Figure 3.16. Screening of the tower of “Komsomolets” with the VEL Subsea Geiger counter (yellow instrument). The left part of the picture shows the area where the escape capsule originally was mounted.

Figure 3.17. From the ROV control room onboard RV "G. O. Sars". The left red arrow point at two screens showing the work of the ROV. When this picture was taken, the ROV was screening the hull of "Komsomolets" with the VEL Subsea Geiger counter (see Figure 3.16). The upper right arrow points at the specter of the VEL Geiger counter. The VEL Geiger counter did not detect any radioactive contamination around the wreck of "Komsomolets".

3.6.2. NaI-measurements

A gamma-spectrometer with a NaI detector was used for onboard estimation of the content of gamma-emitters (mainly ^{137}Cs) in the samples. Gamma analysis was performed with Canberra 802 3x3 inches NaI detector equipped with Osprey multichannel analyser and 5 cm detector lead shielding. The spectra were analysed with Genie 2000 gamma analysis software. The gamma-spectrometer used was pre-calibrated using a full Lorakon box containing a known amount of ^{137}Cs. Background was counted and automatically subtracted from the spectra. A quality control sample containing a known amount of ^{137}Cs in sample geometry was counted each day.

Samples were transferred to 200 ml plastic containers (Lorakon boxes) and were counted for up to 1 hour, giving a detection limit of approximately 8 Bq/kg for ^{137}Cs. In total 15 samples were analysed on board RV "G. O. Sars", 12 water samples and 3 surface sediment samples. Five of the water samples showed a positive signal for ^{137}Cs. One of the samples showing the highest ^{137}Cs activity concentrations (sample collected 08.07.2019 15:55) was analysed before and after filtration with a 0.45 µm filter. The results show that most ^{137}Cs in the sample was dissolved. Subsequent screening of the 0.45 µm filter with a dose rate meter (see chapter 3.6.3 for instrument description) showed low levels of radioactive contamination, but the equipment did not allow for determination of which radionuclide was present. Results from preliminary measurements are given in Table 3.12.

Table 3.12. Results from preliminary measurements of the ^{137}Cs content in samples performed onboard RV "G. O. Sars". More precise results will be obtained using HPGe detectors in the lab.

Sample type and location	Sampling time	Sampling date	ROV dive No.	Meas-ured Cs-137 (Bq/kg)
Seawater from ventilation pipe	23:25	07.07.2019	Dive 1	<8.0
Seawater from reactor comp starboard side	23:46	07.07.2019	Dive 1	<8.0
Seawater from reactor comp port side	23:53	07.07.2019	Dive 1	<8.1
Seawater from 3 m above ventilation pipe	00:28/02:27	08.07.2019	Dive 2	<8.0
Seawater from ventilation pipe	05:50	08.07.2019	Dive 2	<8.0
Seawater from ventilation pipe	10:30	08.07.2019	Dive 2	89.5 ±7.0
Seawater from above grill near ventilation pipe	15:55	08.07.2019	Dive 3	857 ±62
Seawater from above grill near ventilation pipe, filtered	15:55	08.07.2019	Dive 3	840 ±60
Seawater sampled over ventilation pipe in cloud	22:25	08.07.2019	Dive 3	<8.4
Seawater from ventilation pipe	22:30	08.07.2019	Dive 3	86.7 ±6.9
Seawater sampled over ventilation pipe in cloud	23:52	08.07.2019	Dive 3	<8.2
Seawater from ventilation pipe	10:18	09.07.2019	Dive 4	83.6 ±6.5
Seawater sampled next to ventilation pipe	10:40	09.07.2019	Dive 4	14.9 ±2.5
Surface sediment from starboard side of reactor com-partment	21:33	08.07.2019	Dive 3	<7.4
Surface sediment from port side of reactor compart-ment	21:46	08.07.2019	Dive 3	<8.2
Surface sediment from starboard side	03:03	09.07.2019	Dive 3	<8.0

3.6.3. Dose rate measurements

Relevant personnel were provided TLD-dosimeters and electronic dosimeters to wear when working on board RV “G. O. Sars”. None of the electronic dosimeters showed any received dose. All TLD-dosimeters were read at the DSA laboratory after the cruise, and none of them showed a dose above the detection limit of 0.005 mSv.

Sample equipment and samples were checked with a dose rate instrument. A 6150 AD2 Automess dose rate meter both with and without AD-17 probe was used to check the radiation level before further work was started (Figure 3.18). The probe is sensitive to alpha, beta, and gamma radiation. No surface contamination of the equipment was detected and none of the samples collected showed radiation levels above approximately 0.2 µSv/h, which represents a normal background level.

Figure 3.18. Andrey Volynkin (IMR) and Justin Gwynn (DSA) are checking the radiation levels close to ÆGIR 6000 before samples are taken.

4. Preliminary conclusions and further work

Based on sampling of bottom sediments, seawater and biota, and preliminary gamma-spectrometric measurements in samples collected close to “Komsomolets”, the preliminary conclusions are as follows:

- Activity concentrations of ^{137}Cs in seawater collected inside a ventilation pipe ranged from <8.0 to 857 Bq/l, indicating that releases from the reactor are still occurring 30 years after “Komsomolets” sank.
- The releases of ^{137}Cs from “Komsomolets” to the marine environment appear to vary in activity and duration.
- Our findings are in accordance with earlier findings by Russian expeditions.

The following visual observations were made of “Komsomolets”

- “Komsomolets” is lying upright at a depth of 1673 m.
- Damage to the outer hull could be seen clearly in the forward section of the submarine.
- Damage to the inner hull could be seen in the area of the torpedo compartment.
- The coverings placed over the torpedo compartment on the port and starboard sides of the submarine in 1994 by a Russian expedition were observed and appeared to be intact.
- The coverings placed over the six torpedo tubes in 1994 by a Russian expedition were observed and appeared to be intact.

- No obvious damage to the outer hull of the aft section of the submarine could be observed, except for 2 areas where 'rubber' outer hull deck plates were missing.
- No obvious signs of large scale corrosion could be observed.
- Benthic organisms were observed over the entirety of the outer hull of "Komsomolets".

The following observations were made based on hydrography and currents in the region near "Komsomolets":

- The upper 400 m of the water column is represented by Atlantic Water.
- The maximum current speed in the upper 400 m observed from the ship's ADCP was 40 cm/s.
- Data from 2001 (i.e. not this study) show that deep currents (at 1300 m depth) in the region near "Komsomolets" have typical speeds of about 10 cm/s, mainly directed northward or southward. The deep currents have a semidiurnal tidal period with speeds of few cm/s and the direction of the tidal current is rotating in an ellipse.
- The CTD-data indicates a 100 m thoroughly bottom nepheloid layer.
- Visual observations from the ROV control room during the sampling period indicated that the direction of the bottom current around "Komsomolets" was variable.

Further sample preparation and analyses will now take place at IMR, DSA and NMBU/CERAD. The content of ^{137}Cs, ^{90}Sr, Pu-isotopes and other radionuclides as well as trace metals will be determined in the samples to further understand the nature of the releases from the reactor and to determine if any plutonium from the two nuclear warheads has been released into the marine environment. The results will be compiled and published in a report under the Joint Norwegian Russian Expert Group by the end of 2020.

Acknowledgements

We would like to thank the crew onboard RV "G. O. Sars" and the ROV crew for assistance with sample collection. Further, thanks are due to Kjell Arne Mork and Henrik Søiland for interpretation of the CTD and ADCP data, and writing section 3.2 and 3.3. Thanks are also due to Arne Hassel, Alexander Plotkin and colleagues for identification of the benthic species. Karen Gjertsen and Kjell Bakkeplass have contributed with figures and maps.

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Appendix 1. Surface and bottom seawater samples collected with CTD system/Rosette Sampler with 12 10 l bottles

CTD Station	Main sample code	Sample time	Sample date	ROV dive No.	Sample vol.	Sample purpose	Lat		Long		Depth	Sampling location
232	W1	17:47	7.7.19	N/A	300 l	Pu/Am	73.72	N	13.27	E	1680	Surface
232	W2	17:47	7.7.19	N/A	50 l	Sr-90	73.72	N	13.27	E	1680	Surface
232	W3	17:47	7.7.19	N/A	75 l	Cs-137	73.72	N	13.27	E	1680	Surface
232	W4	17:47	7.7.19	N/A	80 l	Pu	73.72	N	13.27	E	1680	Surface
232	W5	17:47	7.7.19	N/A	2 l	I-129	73.72	N	13.27	E	1680	Surface
232	W6	17:47	7.7.19	N/A	1 l	H-3	73.72	N	13.27	E	1680	Surface
232	W7	17:47	7.7.19	N/A	1 l	ICP-MS	73.72	N	13.27	E	1680	Surface
233/ 234	W8	00:28/ 02:27	8.7.19	Dive 2	50 l	Sr-90	73.72	N	13.27	E	1670	3 m above ventilation pipe
233/ 234	W9	00:28/ 02:27	8.7.19	Dive 2	75 l	Cs-137	73.72	N	13.27	E	1670	3 m above ventilation pipe
233/ 234	W10	00:28/ 02:27	8.7.19	Dive 2	80 l	Pu	73.72	N	13.27	E	1670	3 m above ventilation pipe
233/ 234	W11	00:28/ 02:27	8.7.19	Dive 2	1 l	I-129	73.72	N	13.27	E	1670	3 m above ventilation pipe
233/ 234	W12	00:28/ 02:27	8.7.19	Dive 2	1 l	H-3	73.72	N	13.27	E	1670	3 m above ventilation pipe
233/ 234	W13	00:28/ 02:27	8.7.19	Dive 2	1 l	ICP-MS	73.72	N	13.27	E	1670	3 m above ventilation pipe
236	W14	15:34	8.7.19	Dive 3	40 l	Pu	73.72	N	13.27	E	1670	Beside port front dive plane
236	W15	15:34	8.7.19	Dive 3	150 ml	ICP-MS	73.72	N	13.27	E	1670	Beside port front dive plane
236	W16	15:41	8.7.19	Dive 3	40 l	Pu	73.72	N	13.27	E	1670	Beside tower edge of covering over torpedo compartment on port side
236	W17	15:41	8.7.19	Dive 3	1 l	I-129	73.72	N	13.27	E	1670	Beside tower edge of covering over torpedo compartment on port side
236	W18	15:41	8.7.19	Dive 3	100 ml	ICP-MS	73.72	N	13.27	E	1670	Beside tower edge of covering over torpedo compartment on port side

Appendix 2. Bottom seawater samples collected with ROV

Station ID	Main sample code	Sample time	Sample date	ROV dive No.	Sample vol	Lat		Long		Sampling location
Metal syringe (No. 3)	RW1	23:22	7.7.19	Dive 1	1 l	73.72	N	13.2667	E	From ventilation pipe
Plexiglass syringe (No. 1)	RW2	23:29	7.7.19	Dive 1	1 l	73.72	N	13.2667	E	1 m above ventilation pipe
Plexiglass syringe (No. 2)	RW3	23:31	7.7.19	Dive 1	1 l	73.72	N	13.2667	E	5 m above ventilation pipe
Niskin 4	RW4	23:46	7.7.19	Dive 1	2 l	73.72	N	13.2668	E	Reactor compartment starboard side
Niskin 5	RW5	23:53	7.7.19	Dive 1	2 l	73.72	N	13.2664	E	Reactor compartment port side
Metal syringe (No.3)	RW6	05:50	8.7.19	Dive 2	1 l	73.72	N	13.2667	E	From ventilation pipe
Plexiglass syringe (No. 1)	RW7	10:30	8.7.19	Dive 2	1 l	73.72	N	13.2667	E	From ventilation pipe
Plexiglass syringe (No. 1)	RW8	15:55	8.7.19	Dive 3	1 l	73.72	N	13.2665	E	Above grill near ventilation pipe
Niskin 5	RW9	22:25	8.7.19	Dive 3	2 l	73.72	N	13.2667	E	Over ventilation pipe in cloud
Metal syringe (No.3)	RW10	22:30	8.7.19	Dive 3	1 l	73.72	N	13.2667	E	From ventilation pipe
Niskin 4	RW11	23:52	8.7.19	Dive 3	2 l	73.72	N	13.2667	E	Over ventilation pipe in cloud
Metal syringe (No.3)	RW12	09:14	9.7.2019	Dive 4	1 l	73.72	N	13.2667	E	From ventilation pipe
Niskin 5	RW13	09:17	9.7.2019	Dive 4	2 l	73.72	N	13.2667	E	40 cm above ventilation pipe
Plexiglass syringe (No. 1)	RW14	10:18	9.7.2019	Dive 4	1 l	73.72	N	13.2667	E	From ventilation pipe
Niskin 4	RW15	10:20	9.7.2019	Dive 4	2 l	73.72	N	13.2667	E	40 cm above ventilation pipe
Plexiglass syringe (No. 2)	RW16	10:40	9.7.2019	Dive 4	1 l	73.72	N	13.2667	E	Next to ventilation pipe

Appendix 3. Sediment samples collected with push cores and blade cores

Station ID	Main sample code	Sample time	Sample date	ROV dive No.	Lat		Long		Sampling location
Push core 1	PC1	18:00	8.7.2019	Dive 3 (Basket 1)	73.7242	N	13.2663	E	Port side of reactor
Push core 2	PC2	18:14	8.7.2019	Dive 3 (Basket 1)	73.7242	N	13.2663	E	Port side of reactor
Push core 3	PC3	18:35	8.7.2019	Dive 3 (Basket 1)	73.7243	N	13.2669	E	Starboard side of reactor
Push core 4	PC4	19:04	8.7.2019	Dive 3 (Basket 1)	73.7242	N	13.2668	E	Starboard side of reactor
Push core 5	PC5	19:16	8.7.2019	Dive 3 (Basket 1)	73.7248	N	13.2668	E	In front of the submarine under the torpedo tubes
Push core 6	PC6	19:32	8.7.2019	Dive 3 (Basket 1)	73.7246	N	13.2666	E	Port side in line with the edge of the covering over the torpedo compartment (tower side)
Push core 7	PC7	19:41	8.7.2019	Dive 3 (Basket 1)	73.7246	N	13.2670	E	Starboard side in line with the edge of the covering over the tor-pedo compartment (tower side)
Push core 8	PC8	19:50	8.7.2019	Dive 3 (Basket 1)	73.7247	N	13.2666	E	Port side (bow side of the front dive plane)
Push core 9	PC9	20:12	8.7.2019	Dive 3 (Basket 1)	73.7247	N	13.2670	E	Starboard side (bow side of the front dive plane)
Push core 10	PC10	20:29	8.7.2019	Dive 3 (Basket 1)	73.7247	N	13.2665	E	Port side between cores 5 and 8
Push core 11	PC11	20:43	8.7.2019	Dive 3 (Basket 1)	73.7247	N	13.2670	E	Starboard side between cores 5 and 9
Push core 12	PC12	01:40	9.7.2019	Dive 3 (Basket 2)	73.7237	N	13.2663	E	Stern of submarine
Push core 13	PC13	02:04	9.7.2019	Dive 3 (Basket 2)	73.7238	N	13.2666	E	Starboard side, EMPTY
Push core 14	PC14	02:45	9.7.2019	Dive 3 (Basket 2)	73.7239	N	13.2666	E	Starboard side, CONTENT OF CORE LOST
Push core 15	PC15	03:03	9.7.2019	Dive 3 (Basket 2)	73.7240	N	13.2668	E	Starboard side, ONLY SURFACE SAMPLE (ANALYSED ON BOARD)
Push core 16	PC16	03:21	9.7.2019	Dive 3 (Basket 2)	73.7244	N	13.2669	E	Starboard side
Push core 17	PC17	03:42	9.7.2019	Dive 3 (Basket 2)	73.7245	N	13.2669	E	CONTENT OF CORE LOST
Push core 18	PC18	04:07	9.7.2019	Dive 3 (Basket 2)	73.7238	N	13.2662	E	Port side
Push core 19	PC19	04:28	9.7.2019	Dive 3 (Basket 2)	73.7240	N	13.2662	E	Port side
Push core 20	PC20	05:04	9.7.2019	Dive 3 (Basket 2)	73.7242	N	13.2663	E	Port side, EMPTY
Push core 21	PC21	05:30	9.7.2019	Dive 3 (Basket 2)	73.7244	N	13.2663	E	Port side, core fell out of top and was open, but surf looked ok
Push core 22	PC22	05:47	9.7.2019	Dive 3 (Basket 2)	-	N	-	E	Core pipe stuck in sediment

Blade core 1	BC1	20:58	8.7.2019	Dive 3 (Basket 1)	73.7247	N	13.2665	E	Port side of torpedo compartment (tower side of front dive plane)
Blade core 2	BC2	21:13	8.7.2019	Dive 3 (Basket 1)	73.7246	N	13.2670	E	Starboard side of torpedo compartment (tower side of front dive plane)
Blade core 3	BC3	21:33	8.7.2019	Dive 3 (Basket 1)	73.7243	N	13.2669	E	Starboard side of reactor compartment
Blade core 4	BC4	21:46	8.7.2019	Dive 3 (Basket 1)	73.7243	N	13.2664	E	Port side of reactor compartment

Appendix 4. Pore water collected from push cores.

Station ID	Main sample code	Sample time	Sample date	ROV dive No.	Sampling location
Push core 1 to 4	PCW1	18:00 - 19:04	8.7.19	Dive 3 (Basket 1)	Port and starboard side of reactor (water collected from all 4 cores)
Push core 5 to 11	PCW2	19:16 - 20:43	8.7.19	Dive 3 (Basket 1)	Around torpedo compartment (water collected from all 7 cores)
Push core 12	PCW3	01:40	9.7.19	Dive 3 (Basket 2)	Stern of submarine

Appendix 5. Biota collected with ROV

Main sample code	Sample time	Sample date	ROV dive No.	Species
RB1	14:45	08.07.2019	Dive 3 (Ch. 1)	Porifera: Demospongiae: Cladorhizidae: *Cladorhiza gelida*
RB2	14:45	08.07.2019	Dive 3 (Ch. 1)	Arthropoda: Crustacea: Amphipoda
RB3	14:45	08.07.2019	Dive 3 (Ch. 1)	Annelida: Polychaeta: Polynoidae
RB4	14:55	08.07.2019	Dive 3 (Ch. 5)	Porifera: Demospongiae: Cladorhizidae: *Cladorhiza gelida*
RB5	14:55	08.07.2019	Dive 3 (Ch. 5)	Cnidaria: Anthozoa: Neptheidae: Gersemia sp.
RB6	00:00	09.07.2019	Dive 3 (Ch. 3-4)	Cnidaria: Anthozoa: Neptheidae: Gersemia sp.
RB7	00:00	09.07.2019	Dive 3 (Ch. 3-4)	Annelida: Polychaeta: Polynoidae
RB8	00:10	09.07.2019	Dive 3 (Ch. 3-4)	Mollusca: Solenogastres
RB9	00:22	09.07.2019	Dive 3 (Drawer)	Porifera: Demospongiae: Cladorhizidae: *Cladorhiza gelida*
RB10	00:22	09.07.2019	Dive 3 (Drawer)	Cnidaria:Hydrozoa (stem only)
RB11	00:22	09.07.2019	Dive 3 (Drawer)	Arthropoda: Crustacea: Amphipoda
RB12	00:22	09.07.2019	Dive 3 (Drawer)	Annelida: Polychaeta: Polynoidae
RB13	00:22	09.07.2019	Dive 3 (Drawer)	Arthropoda: Copepoda
RB14	00:22	09.07.2019	Dive 3 (Drawer)	Cnidaria: Anthozoa: Actiniaria
RB15	00:28	09.07.2019	Dive 3 (Ch. 2)	Echinodermata: Asteroidea: Benthopectinidae: *Pontaster tenuispinus*
RB16	10:07	09.07.2019	Dive 4 (Ch.1-3)	Porifera: Demospongiae: Cladorhizidae: *Cladorhiza gelida*
RB17	10:07	09.07.2019	Dive 4 (Ch.1-3)	Cnidaria: Anthozoa: Neptheidae: Gersemia sp.
RB18	10:07	09.07.2019	Dive 4 (Ch.1-3)	Mollusca: Solenogastres
RB19	10:07	09.07.2019	Dive 4 (Ch.1-3)	Eggs from unknown species
RB20	10:07	09.07.2019	Dive 4 (Ch.1-3)	Annelida: Polychaeta: Polynoidae