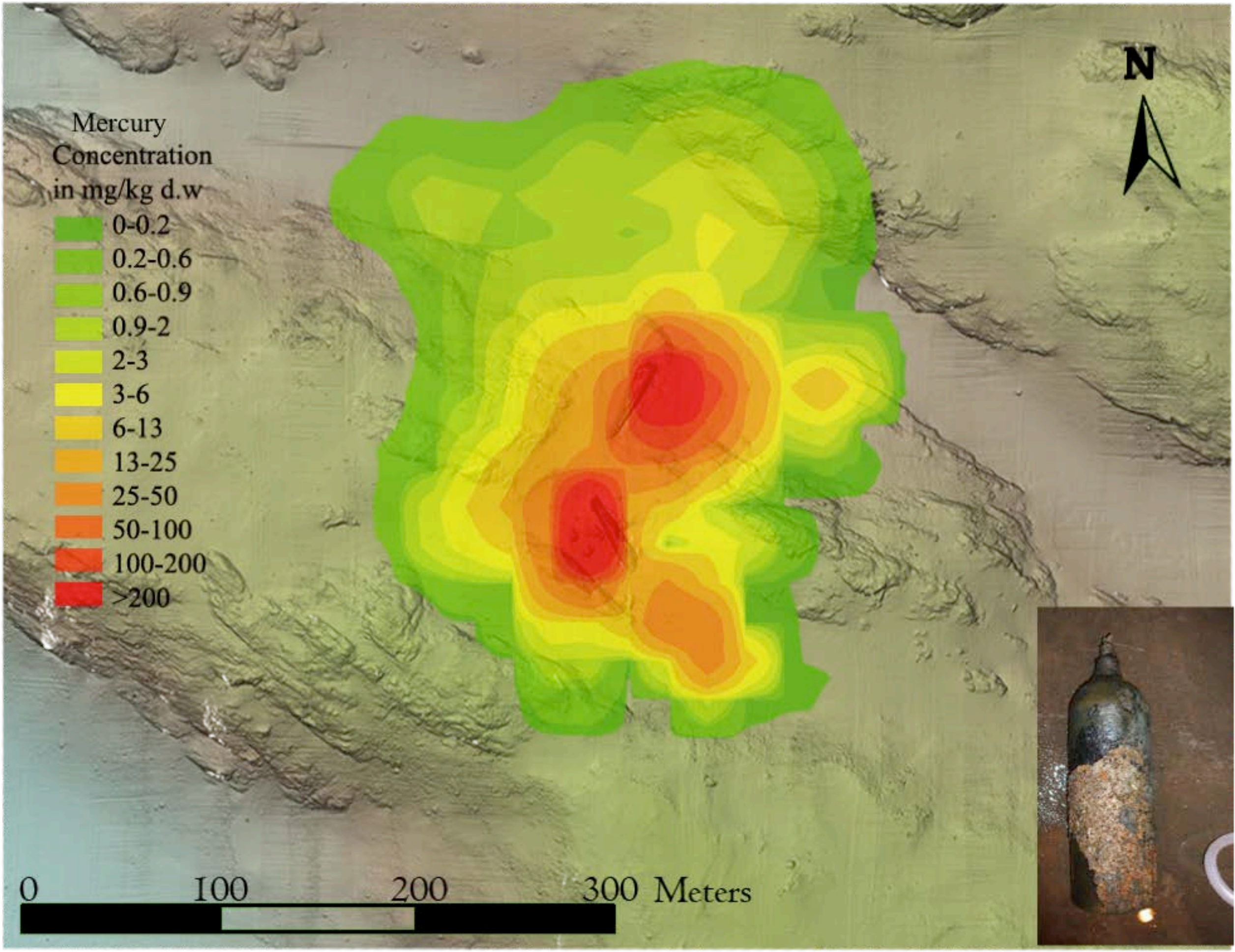
Kuria Ndungu, Björnar A. Beylich, André Staalstrøm, Sigurd Øxnevad, John A. Berge, Hans Fredrik Veiteberg Braaten, Morten Schaanning, Rune Bergstrøm. Petroleum oil and mercury pollution from shipwrecks in Norwegian coastal waters. Science of The Total Environment. Volumes 593–594, 2017, pages 624-633, ISSN 0048-9697.

The article has been published in final form by Elsevier at http://dx.doi.org/10.1016/j.scitotenv.2017.03.213


Mercury Concentration in mg/kg d.w
0-0.2
0.2-0.6
0.6-0.9
0.9-2
2-3
3-6
6-13
13-25
25-50
50-100
100-200
>200
N
0
100
200
300 Meters

# Petroleum oil and mercury pollution from shipwrecks in Norwegian coastal waters

Kuria Ndungu[a]*, Björnar A. Beylich[a], André Staalstrøm[a], Sigurd Øxnevad[a], John A. Berge[a], Hans Fredrik Veiteberg Braaten[a], Morten Schaanning[a] and Rune Bergstrøm[b]

[a]Norwegian Institute for Water Research (NIVA), NO-0349 Oslo, Norway

[b]Norwegian Coastal Administration, NO-3187, Horten, Norway

ABSTRACT:

Worldwide there are tens of thousands of sunken shipwrecks lying on the coastal seabed. These potentially polluting wrecks (PPW) are estimated to hold 3-25 million t of oil. Other hazardous cargo in PPW include ordnance, chemicals and radioactive waste. Here, we present and discuss studies on mercury (Hg) and oil pollution in coastal marine sediment caused by two of the more than 2100 documented PPW in Norwegian marine waters. The German World War II (WWII) submarine (U-864) lies at about 150 m below the sea surface, near the Norwegian North Sea island of Fedje. The submarine is estimated to have been carrying 67 t of elemental Hg, some of which has leaked on to surrounding sediment. The total Hg concentration in bottom surface sediment within a 200 m radius of the wreckage decreases from 100g/kg d.w. at the wreckage hotspot to about 1 mg/kg d.w. at 100 m from the hotspot. The second wreck is a German WWII cargo ship (*Nordvard*), that lies at a depth of ca. 30 m near the Norwegian harbor of Moss. Oil leakage from *Nordvard* has contaminated the bottom coastal sediment with polycyclic aromatic hydrocarbons (PAH). The findings from this study provide useful insight to coastal administration authorities involved in assessing and remediating wreck-borne pollution from any of the tens of thousands of sunken shipwrecks.

---

* Corresponding author email: knd@niva.no

## INTRODUCTION

The commerce and warfare of the 20th century left a legacy of tens of thousands of sunken vessels (Laffon et al., 2006, Michel et al., 2005). Although shipwrecks play an important role (such as recreational diving sites) in the cultural tourism industry (Jeffery, 1990), there is growing concern in their potential environmental impacts from eventual release of their cargo and fuel (Michel et al., 2005, NOAA, 2013). There are nearly 7000 documented non-tank vessel shipwrecks (more than 400 gross tonnes-GT) and an estimated 1500 oil tankers (more than 150 GT) lying on sea bottoms worldwide (see Figure 1) (Michel et al., 2005). It is important to note that the estimate by Michel et al (2005) is limited to ships using petroleum-based fuel or with petroleum cargo and that there are many thousands smaller (i.e. below 150 GT) wrecks. These potentially polluting wrecks (PPW) carry a combined volume of petroleum hydrocarbon (PH) oil estimated to between 4 and 23 billion t. Military vessels and ordinance, especially from World War II (WWII), constitute a majority of the global PPW. For example, approximately 32,000 t of chemical weapons, containing about 11,000 t of highly toxic agents, were dumped in the Bornholm Basin, east of the island of Bornholm in the southern Baltic Sea after WWII (Sanderson et al., 2010). The main chemical agents dumped were blistering agents such as mustard gas and arsenic-containing compounds (Sanderson et al., 2010). Similarly, the former Soviet Union dumped thousands of tonnes of nuclear waste, including radioactive fuel and nuclear submarines, mainly in the Barents and Kara seas, but also elsewhere in the global ocean (Champ et al., 2001; Yablokov, 2001).

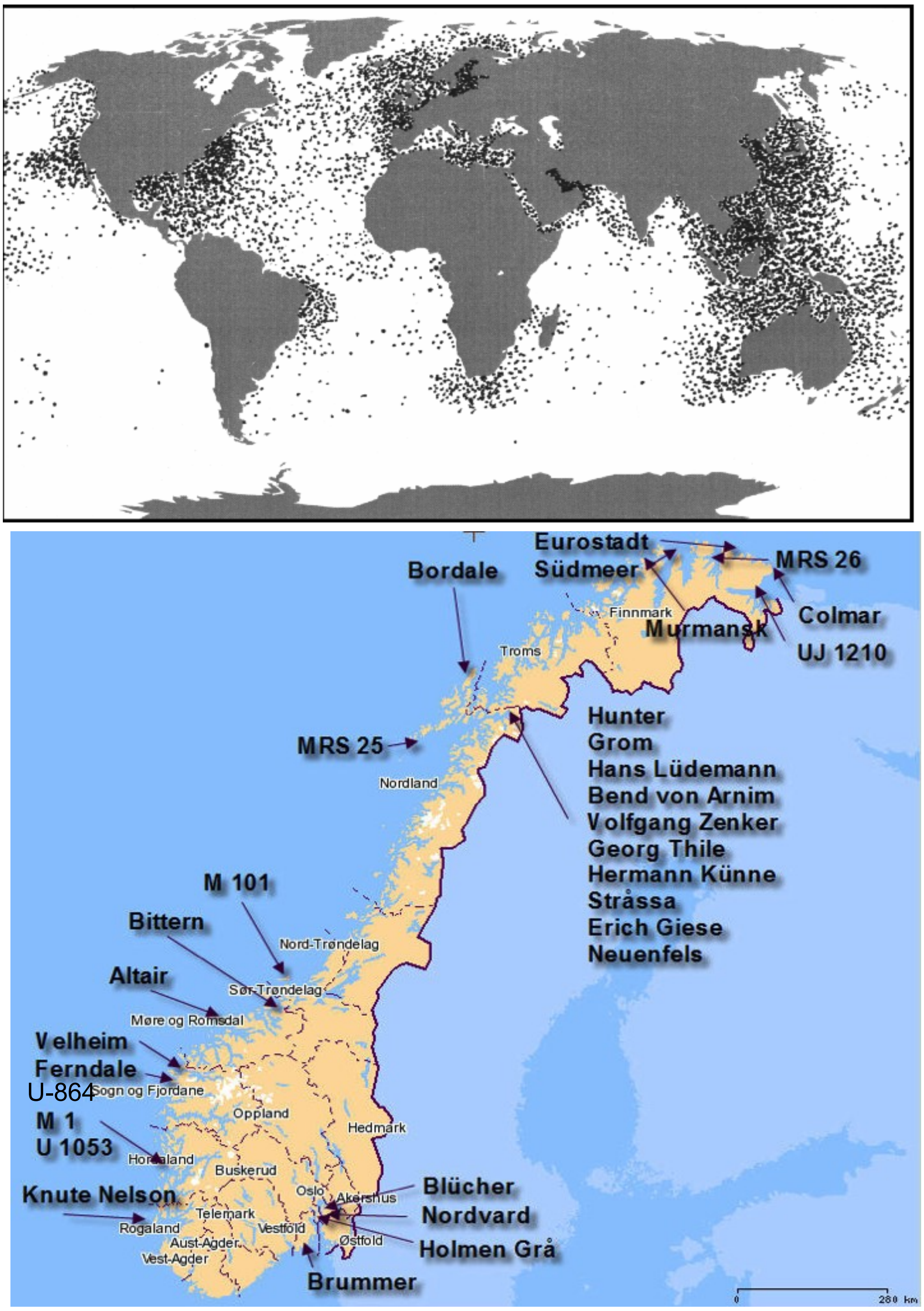


Figure 1. Top: Dots showing approximate locations of about 8000 potentially polluting shipwrecks (PPW) on ocean bottoms (i.e. oil tankers with a gross tonnage (GT) of more than 150 GT and non-tank vessels with more than 400 GT). The PPWs include more than 1500 oil tankers still holding an estimated 23-66 billion liters of oil. Regions with high PPW density include, N. W. Atlantic 1400, N. E. Atlantic 800, N. W. Pacific 1200, South Asian Pacific 2700. Bottom: Map showing 30 PPW of the more than 2100 wrecks on the Norwegian waters prioritized by the Norwegian Coastal Administration for continuous monitoring and remediation. The prioritized PPW include U-864 holding an estimated 67 t of elemental mercury at the time of sinking. Figures adapted from (Bergstrøm 2014, Michel et al., 2005)

.

### *Potentially Polluting Wrecks in Norwegian waters*

Due to the high number of PPW lying on the coastal seabed, environmental regulatory bodies often need to prioritize which wrecks to monitor or remediate. For most PPW, that decision is usually based on estimated volume of petroleum oil and environmental sensitivity of the wreck location. For example, the US National Oceanic and Atmospheric Administration (NOAA) has prioritized 87 of the more than 20 000 wrecks in US waters for further monitoring and assessment. The NOAA priority list is based on vessel contents, condition, environmental sensitivity, and other factors (NOAA, 2013). The Norwegian Coastal Administration (*Kystverket*) estimates that there are about 2100 sunken ships larger than 100 deadweight tonnage lying in Norwegian marine waters (Kystverket, 2006). Of those, about 1700 wrecks have been categorized as creating no potential pollution risk based on the age of the sunken vessel, estimated amount of oil, type of cargo and the vulnerability of the marine environments where they are situated. About 350 of the shipwrecks were classified to be of moderate pollution risk. Thirty of the remaining wrecks (all sunk during WWII) are deemed to pose a high polluting risk (Figure 1, bottom, (Bergstrøm, 2014; Faksness et al., 2015). Although there has been a concerted effort in cataloging the location of WWII PPW globally (e.g. ; Girin, 2004, Monfils et al., 2006, NOAA, 2013) there has been little effort directed at assessing and quantifying the environmental damage caused by PPW. Only a handful of studies have documented the environmental consequence of oil spillage from PPW (Faksness et al., 2015; Hahladakis et al., 2013; Rogowska et al.; 2015, Rogowska et al.; 2010, Sanderson et al., 2007; Schiel et al., 2016, Ventikos et al.; 2013; Viarengo et al., 2007). The main objective of this paper is to present a synthesis of our work at Norwegian Institute for Water Research (NIVA) and Norwegian Coastal Administration (Kystverket) between 2003 and 2016 on contamination from two Norwegian WWII PPW.  This work has been described in previous NIVA and Kystverket reports (e.g., Skei 2003; Urinasrud 2005, 2006; Øxnevad and Beylich 2013; Kystverket 2016), but has not been presented in peer-reviewed literature or in English. We hope to provide useful insight so that scientists and administrators involved in assessing and remediating wreck-borne pollution can learn from our experience.

## Materials and Methods

### *Historical Background and location*

#### *The U-864 submarine wreck*

The German submarine U-864 was sunk by a British submarine on 9 February 1945, about two nautical miles (4 km) west of the Norwegian North Sea island of Fedje (Figure 2 and supplementary information). By the time of its sinking, U-864 is estimated to have been carrying 65 t of elemental Hg, believed to be stored in more than 1860 steel canisters in its keel. According to historical records, the submarine was on its way to Japan (from Germany via Norway) (Kystverket, 2016a and Kystverket, 2016b). A torpedo from the British submarine destroyed the middle section (including an unknown number of Hg canisters) but the bow and stern sections (thought to hold most of the remaining Hg canisters) are still lying on the seabed at depths of 150-175 m (See images at (Kystverket, 2016b), Figure 2 and supplementary information for station coordinates). Since the discovery of the wreck by The Royal Norwegian Navy in March 2003, the NCA has commissioned several studies to monitor and assess the pollution risk posed by Hg. The risk involves Hg-pollution to the surrounding environment from canisters that may have been destroyed by the explosion or leaked after many years of corrosion.

### *Topography of the U-864 seabed site*

The seabed sediment at the wreckage site inclines to the northwest at about 15 degrees (Figure 2). The stern section of the U-864 (about 43 m long) lies at an approximate depth of 150 m, about 30 m to the south, and uphill of the bow, on a relatively flat area of the seabed. The composition of the seabed sediment can be summarized as consisting of a top layer consisting of gravelly sand and sandy clay that overlies a layer of unconsolidated glacial debris deposited on bedrock. The seabed to the east of the bow wreck site is characterized by a ridge with steep outcropping bedrock. The depression in between these ridge-top rock outcrops are filled with sand and gravel. The deepest area to the north is characterized by a valley widening of approximately 50 m to about 100 m towards the northeast. The bottom of the valley is nearly flat with thick sediment layers (Figure 2)

### *Nordvard*

Nordvard (7700 DWT) was one of the 30 wrecks deemed by the Norwegian Coastal Administration to pose a significant oil spill risk to the surrounding marine environment (Figure 1 and Figure 3). It was sunk by British aircraft fire on 29 December 1944 in Mossesundet (the Moss straight, near the harbor of Moss) in the Skagerrak region (Kystverket, 2006). Nordvard was built as a conventional dry cargo ship and was used as a floating workshop and supply ship for submarines and surface vessels. By the time of sinking, her cargo contained various oil products in smaller tanks and oil drums in the cargo holds (Kystverket, 2006). The heavily corroded, wreck lies at a depth of about 30 m. By the time of sinking, the vessel was estimated to be carrying about 160 t of bunker oil (Bergstrøm, 2014). However, 360 t of oil were eventually removed from the wreck in 2007, more than twice the original estimate (Bergstrøm, 2014). An unknown quantity has also leaked onto the surrounding sediment over the years.

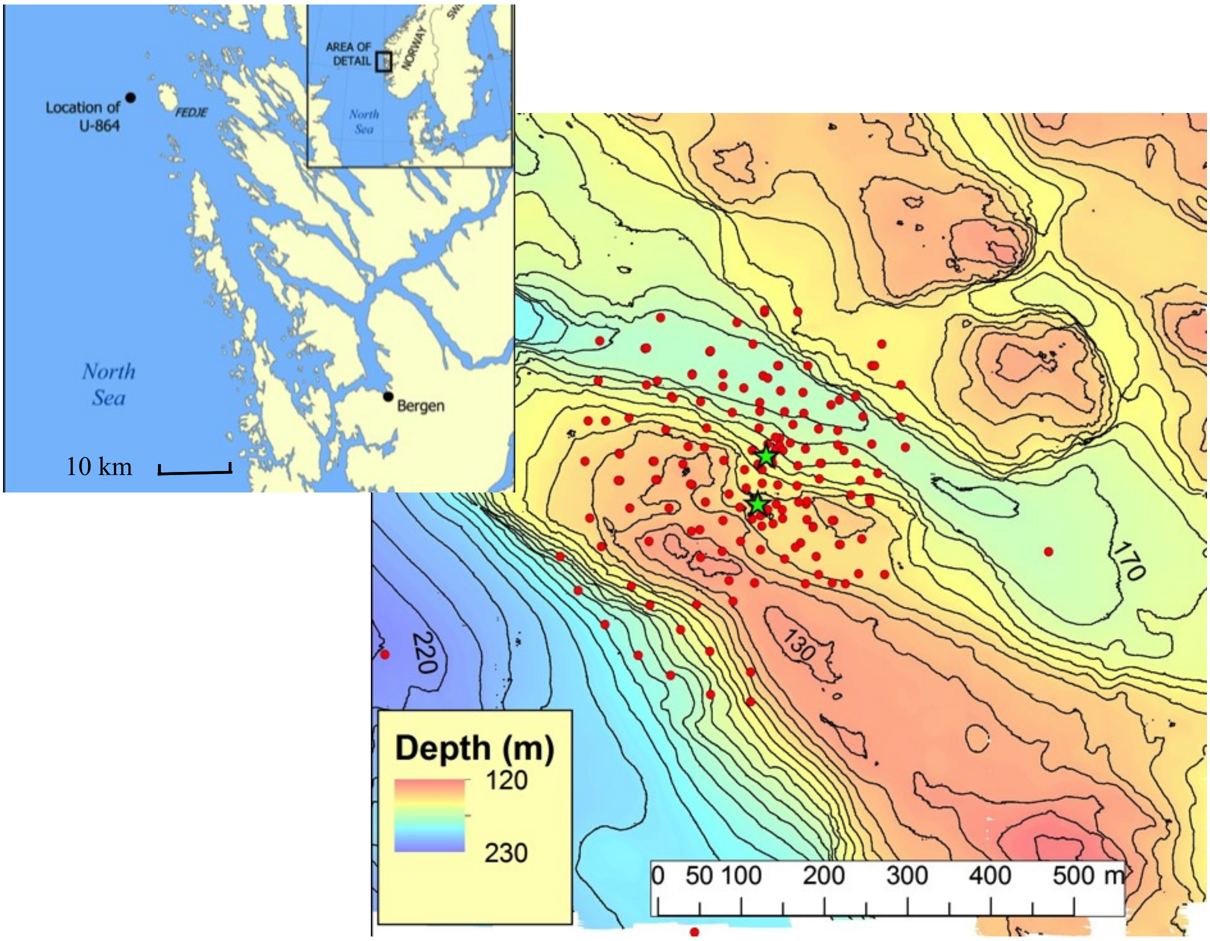


Figure 2. U-864 wreck site near Fedje showing points on the wreck vicinity where sediment samples were taken for Hg analysis to map out the areal extent of Hg contamination on the seabed. The position of the two wrecks is indicated by the green dots.

*Sediment sampling*

*U-864 wreck site*

Sediment samples from the U-864 wreck site at Fedje (Figure 2 and supplementary information) were collected during several occupations of the wreck site between 2003 and 2013 (Øxnevad and Beylich, 2013; Skei, 2003; Uriansrud et al., 2005). Surface sediment was sampled by a remotely operated vehicle controlled from the ship deck. Sediment was also sampled using a Van Veen grab sampler. During the January 2013 occupation, seven sediment cores, length two to three meters, were also collected using a vibro corer (see supplementary information). Sediment samples were transported to a shore laboratory and stored in the dark at a temperature of 5°C until analysis.

*Nordvard wreck site*

Surface sediment was sampled in 2008 from 17 stations at the *Nordvard* wreck site at

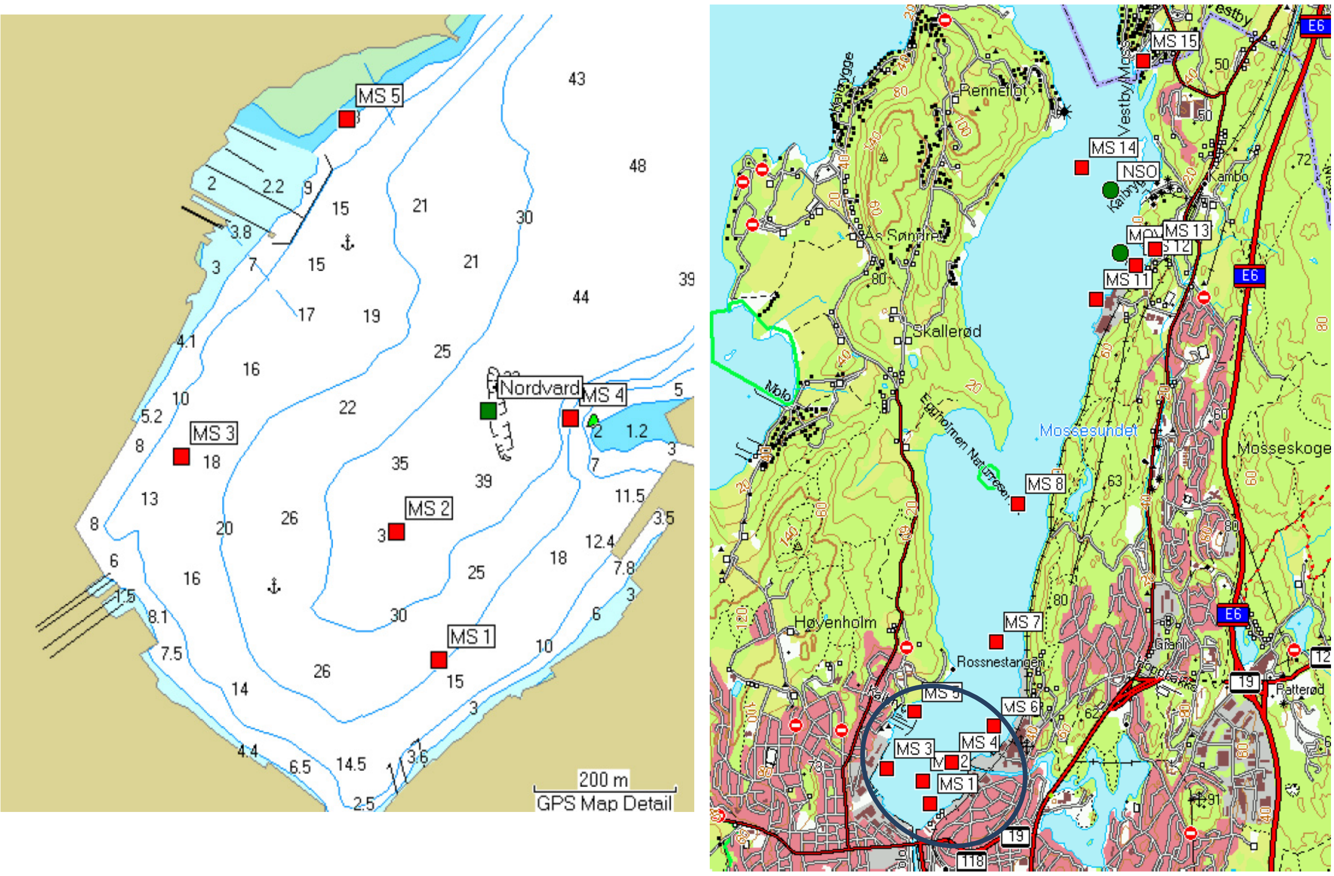


Figure 3. Sediment sample sites on Moss Channel in the vicinity of the WWII wreck *Nordvard*. The left figure is an enlargement of the wreck site depicted by the blue circle on the right figure. Contour lines show depth in meters (See supplementary information for locations of sample station MS 16 and MS 17).

Mossundet in Southern Norway (Figure 3 and supplementary information) using a Van Veen grab sampler (Berge et al., 2009).

### *Sediment total mercury (THg) analysis*

Total Hg (THg) in sediment samples from the U-864 wreck site (Figure 2) was measured using a Lumex RA-915 THg Analyzer coupled to a PYRO-915 pyrolyzer (Lumex Ltd., St. Petersburg, Russia). The pyrolyzer temperature was set at 520-580 °C. The instrument was calibrated using PACS-2, a marine sediment certified reference material (CRM) from the National Research Council (NRC) of Canada (having a certified THg concentration of 3.04 ± 0.20 mg/kg). Another marine sediment CRM, MESS-3 (NRC of Canada) was used for quality control (QC). Sediment samples were analyzed wet to avoid potential Hg loss during drying. Sediment CRM for QC was analyzed at least after every tenth sample. The THg recovery from the concurrent analysis of MESS-3 CRM was between 90-110 % of the certified value.

### *Total petroleum hydrocarbon (TPH) and PAH determination*

#### *TPH analysis*

Total petroleum hydrocarbon (TPH) were extracted from sediment samples following USEPA guidelines SW-846; specifically method 3500C for organic extraction and sample preparation. Briefly, 10-20 grams of wet sediment (spiked with tetracontane as an internal standard) was added to a 1:2 (v/v) mix of cyclohexane:acetone and the mixture shaken for 30 minutes. Distilled water was then added and the mixture again briefly shaken and centrifuged at 3000g for 10 minutes. Part of the supernatant cyclohexane phase was pipetted off and passed through a Florisil column.

Calibration and spiking solutions were prepared using fuel oil no. 2 (ISO 2012) and n-alkanes (n-C10, n-C15, n-C20, n-C30 and n-C40, Sigma–Aldrich). These solutions were used to verify the suitability of the gas chromatographic system for the resolution of n-alkanes, as well as for the detector response (Becker et al., 2006). The n-C10 and n-C40 Hydrocarbons were also used as retention time window standards. Analyses was performed on an Agilent 7890N GC fitted with a FID detector and a Chromopach® VF-1MS capillary column (15 m x 0.25 mm i.d.) with a nominal film thickness of 25 µm. The injection temperature was 280 °C and injection volume 1µm. Hydrogen was used as carrier gas at a flow rate of 2 mL/min. The oven temperature was held at 35 °C for 2 min and ramped at 5 °C/min to 60 °C. The temperature was then increased to 280 °C at 15 °C/min and held for 10 min. The amount of TPH was determined as the sum of resolved and unresolved components eluted from the GC capillary column between the retention times of n-decane and n-tetracontane. The TPH concentrations were normalized to sediment dry weight. Mineral oil contaminated sediment reference material-ERM-CC015 (originally BAM-U015) having a certified TPH concentration of 2000 ± 161 mg/kg was also run concurrently with samples. The TPH recovery from BAM-U015 CRM was between 80-120%

*PAH Analysis*

The experimental procedure for PAH analysis is based on the method reported by Ruus et al. (2005). Sediment sub samples were first homogenized prior to adding internal standards (200 ng each of naphthalene $d_8$, acenaphthene $d_8$, phenanthrene $d_{10}$, chrysene $d_{12}$, perylene $d_{12}$, and anthracene $d_{10}$). The PAHs were then extracted with dichloromethane and cyclohexane (1:1, v/v) using an Accelerated Solvent Extraction (ASE) (Dionex ASE-200; Dionex Corp., Sunnyvale, CA, USA) at a temperature of 100 °C and a pressure of 2000 psi. After the extraction the solvent volume was reduced, and the resulting extracts cleaned by gel permeation chromatography (GPC) and solvent exchanged to cyclohexane (Ruus et al., 2005).

The NIST 1944 marine sediment certified reference material (National Institute of Standards and Technology, Gaithersburg, MD, USA) was run concurrently with sediment samples.

The extracts were analysed for 16 PAH (Σ $PAH_{16}$); Naphthalene, Acenaphthylene, Acenaphthene, Fluorene, Phenanthrene, Anthracene, Fluoranthene, Pyrene, Benzo(a)anthracene, Chrysene, Benzo(b)fluoranthene, Benzo[k]fluoranthene, Benzo(a)pyrene, Dibenz[a,h]anthracene, Benzo[ghi]perylene, Indeno[1,2,3-cd]pyrene) on a GC-MS (Agilent GC 6890 with MSD 5973) operated in selected ion monitoring mode. The GC was fitted with a J&W DB-5MS capillary column (30m x 0.25mm i.d.; 0.25 μm film thickness, stationary phase of 5% phenyl polysoxilane). The GC inlet was operated in the splitless mode. The initial oven temperature was held at 60 °C for 2 min then raised to 250 °C at 7 °C /min and then to 310 °C at a rate of 15 °C /min. The injector temperature was 300 °C, the transfer line temperature 280 °C and the MS source temperature 230 °C. The column flowrate was 1.2 ml/min. Quality analysis and quality procedures included checks on, calibration curves, method blanks, internal standard recovery, standard deviation of duplicates, method control samples, matrix spike duplicates and analysis of NIST 1941 CRM, all of which were satisfactory. The average internal standard and matrix spike duplicates recovery was 80 ± 20% while the average recovery from the NIST SRM samples was 60-80%.

## Results and Discussion

### *Extent of Hg contamination at the U-864 Wreckage site*

#### *Surface sediments*

After discovery of the U-864 wreckage in 2003, the first task was to establish the extent of Hg contamination at the seabed site (Skei, 2003). Mercury concentration measured in sediment from that initial sampling indicated high contamination in the immediate vicinity of the wrecks (up to 10 % w/w THg (Skei, 2003)). More extensive sampling in subsequent campaigns established that THg concentration in sediment beyond about100 meter radius from the wreckage hotspot dropped to less than 1 mg/kg d.w. Thus the area around the wreck having a sediment Hg concentration higher than 1 mg/kg d.w. is estimated to be about 30 000 m$^2$ (Figure 4 and supplementary information). Most of the Hg in the sediments is believed to originate from canister leakage following the initial sinking, while other canisters have corroded and leaked more Hg to the surrounding seabed since (Figure 4). It is still unknown how much of the estimated 1860 elemental Hg canisters remain in the wreck and how much has leaked to the surrounding sediment (Kystverket, 2016a). As would

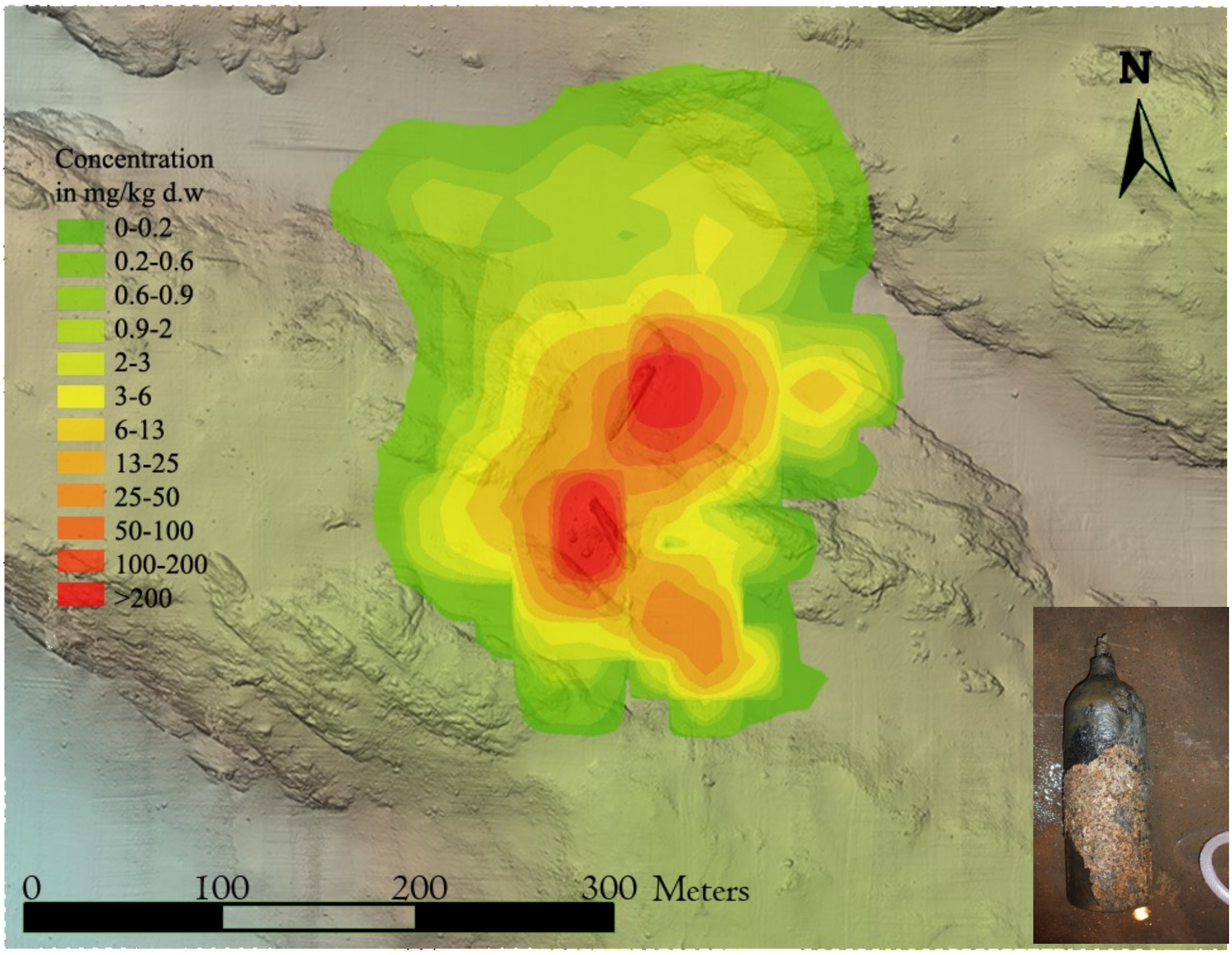


Figure 4. Mercury contamination on the U-864's seabed site and a photo of a corroded and leaky 2.5 L steel Hg canister recovered at the site. At the time of sinking, U-864 is estimated to have been carrying about 67 t of liquid Hg in about 860 metallic canisters like the one shown above.

be expected, the highest Hg concentration was measured in the sediment adjacent the wreckage (Figure 4). Laboratory sediment microcosm studies carried out to estimate Hg release from bottom sediment to overlying water has reported Hg fluxes of about 500 ng/m$^2$/d, (Ndungu et al., 2016) i.e. an annual leakage of about 5 g of Hg from the total contaminated area (0.03 km$^2$). The Hg concentration in the deeper sediments was varied but generally low (see supplementary information). The mean subsurface Hg concentration measured in the 10-300 cm deep segments from five sediment cores sampled close to the wrecks (Supplementary information and Figure 4) was 0.13 mg/kg (0.13 ± 0.18 mg/kg, mean ± standard deviation, n = 25). The subsurface sediment data excludes two cores from which the THg concentration in subsurface slices was higher than that of the surface, most likely an effect of contamination during slicing (see supplementary information).

### *Other large scale marine sediment Hg contamination studies*

We are not aware of any other published studies on Hg pollution of marine sediments from a shipwreck. The wreckage of a 17th century Turkish ship lying on the seabed near Sharm el Sheikh in the Red Sea contains elemental Hg stored in amphoras (Raban, 1973), but we are not aware of any published study on Hg pollution from the wreck (Raban, 1973; Black et al., 2012). The level of industrial Hg pollution in Minamata Bay, Japan, and the subsequent remediation efforts (albeit at a much bigger scale) might be similar to our study (Hosokawa, 1993). In Minamata Bay, more than 1.5 million m$^3$ of bottom sediment covering an area of about 2 km$^2$ contaminated with Hg (up to 600 mg/kg), was dredged and capped with clean sediment (Hosokawa, 1993). According to the Norwegian Environment Agency (NEA) guidelines, marine sediment having a THg concentration in the range 0.63-0.86 mg/kg is classified as moderately polluted. The NEA defines a background Hg concentration as <0.15 mg/kg (Bakke et al., 2010), three times higher than the international guideline for the North-East Atlantic (0.05 mg/kg), suggested by the 15-member OSPAR commission (OSPAR

Commission, 2006). However, as Burton (2002) noted in his review of sediment quality guidelines in use around the world, the suggested Hg background concentration varies widely, examples including 0.13 mg/kg in Canada and 0.3 mg/kg in the Netherlands (Burton, 2002).

### *Hg contamination from U-864 to the marine food web*

Despite the high Hg concentration in sediment from the wreck site, Hg concentration measured in in fish and seafood flesh sampled from the area has consistently been lower or similar to that of fish caught elsewhere on the Norwegian coast (Kvangarsnes et al., 2012). For example, the mean Hg concentration in tusk muscle (*Brosme brosme*, the main fish species in the area inhabiting the wreck depth at about 150 m) caught in 2009 close to the U-864 site was 0.21 ± 0.08 mg/kg w.w. (mean ± stdev, range, 0.11-0.41, n=25, (Kvangarsnes et al., 2012). The Hg concentration in tusk caught at the wreckage site was slightly lower than the mean of tusk caught at nine other stations along the Norwegian coastal current (0.37 mg/kg w.w., range 0.09-1.00 mg/kg, n=183, (Kvangarsnes et al., 2012). All concentrations were however below the European Commission's upper regulatory limit of Hg concentration in fish muscle (including tusk) meant for human consumption set at 0.5 mg/kg w.w. (EC, 2006). In laboratory exposure experiments however, Olsvik et al (2011) reported enhanced Hg concentration in the liver of juvenile Atlantic cod (*Gadus morhua*) exposed to Hg-contaminated sediment collected from the U-864 wreck site (Olsvik et al., 2011). Slightly higher Hg concentrations (compared to reference sites) of Hg in Crabs (*Cancer pagurus*) from the U-864 site were reported by Rua-Ibarz et al. (2016) in a recent study. Rua-Ibarz et al. (2016) attributed the high Hg concentration to the feeding habits of C. *pagurus*`, which may result in direct ingestion of metallic Hg. Their observation was based on the presence of metallic Hg in C. *pagurus*` digestive system (and thus, in the brown meat). Apart from C. *pagurus*, Rua-Ibarz et al., (2016) did not find any other indication of Hg from the U-864 wreck in the marine food chain.

### *Other biogeochemical studies related to the U 864 wreck site*

The seabed sediment in the vicinity of the wreck is predominantly contaminated with elemental Hg. Monomethylmercury (MeHg) is however the most toxic and bioaccumulative form of Hg. There is therefore an inherent risk that the elemental Hg in the sediment might be transformed to the more toxic MeHg form. The concentration of MeHg in the sediment is however very low (<0.05% of total Hg, (Ndungu et al., 2016)

Microbial methylation of Hg is primarily carried out by dissimilatory sulfate and iron-reducing bacteria (Kerin et al., 2006; Gilmour et al.; 2011, Yu et al., 2012) and to some extent methanogens (Gilmour et al., 2013), under anoxic conditions in sediment and soils. Anaerobic Hg methylation usually requires the presence of an appropriate organic substrate (Johnson et al., 2010, Ndungu et al., 2016, Randall and Chattopadhyay 2013). However, the U-864 wreck lies in an erosion zone with strong bottom currents (Jaccard et al., 2014) and the bottom sediment at the site therefore have very low organic matter (OM) content (about 1 wt %, (Ndungu et al., 2016) which is probably the reason why Hg methylation is negligible despite the high elemental Hg concentration (Ndungu et al., 2016, Rua-Ibarz et al., 2016). Despite the low natural OM deposition, there is a small risk of microbial Hg methylation if allochthonous OM is introduced to the more than 0.03 km$^2$ of bottom sediment with Hg concentration above 1 mg/kg. Most of the oil was emptied from the wreck in 2013, there is however a small risk that lubricants or residual bunker oil might leak on the already Hg-contaminated sediment. Dissimilatory sulfate reducing bacteria can degrade petroleum oil (Chaerun et al., 2004; Malik et al., 2008) and in the process probably methylate the inherent elemental Hg. With this in mind, mesocosm studies using Hg-contaminated sediment from the U-864 site were recently carried out to investigate how/if introduction of OM would affect methylation of in situ elemental Hg (Ndungu et al., 2016). The boxcosm study was designed to simulate three possible scenarios, i) the current *in situ* sediment conditions around the U-864 wreck site, ii) a situation where OM are more available at the sediment surface than at the current *in situ* conditions and iii) a situation where the sediment is capped with a thin layer of clay. The Hg-contaminated sediment was amended with varying doses of green (chlorella) algae (about 50 wt % carbon) as the source of OM. Sulfate reducing and other bacteria (that potentially methylate Hg) can degrade petroleum oil (Chaerun et al., 2004; Malik et al., 2008) but chlorella was likely to be degraded faster and more efficiently than petroleum oil by resident sulfate reducing bacteria within the six-month duration of the experiment. As shown in Figure 5 below, introduction of labile organic carbon (in this case algae) to the Hg-contaminated marine sediment (where sulfate is abundant) increased MeHg formation.

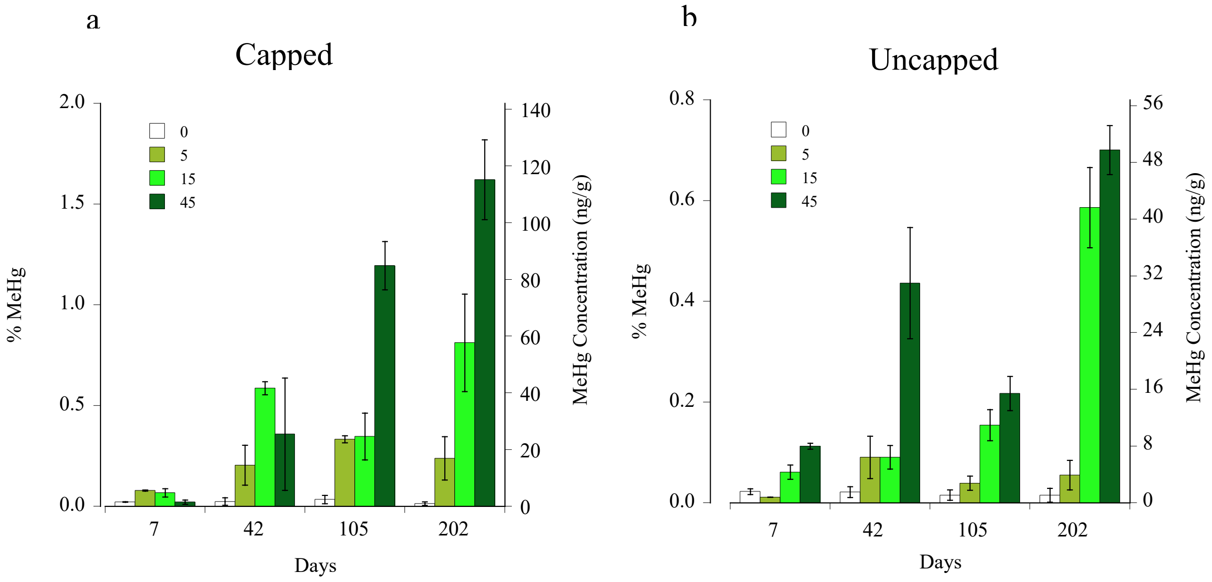


Figure 5. Time series for MeHg concentration in boxcosms containing a) capped and b) uncapped Hg-contaminated marine sediment sampled from the U-864 wreckage site (note the different Y-axis scales). The bars represent the average MeHg concentration in the Hg-contaminated layer enriched with 0, 5, 15 and 45 grams of algae per liter of wet sediment. The error bars represent the standard deviation on the MeHg concentration in the three one-centimeter core sections from the contaminated layers in each boxcosm (adapted from Ndungu et al (2016).

The results of the study also showed that, within the six-month duration of the study and in the absence of bioturbating fauna, a three centimeter sediment clay cap was effective in retaining Hg in the sediment and thus reducing fluxes of Hg species to the overlying water. Capping would also isolate the Hg-contaminated sediment from direct surficial deposition of OM that could potentially fuel methylation (Ndungu et al., 2016)

### *Site remediation*

Until recently, only monitoring and biogeochemical studies had been carried out at the U-864 wreck site since its discovery in 2003. However, the NCA initiated remediation work at the site in the summer of 2016 (Van Oord, 2016). The work involved filling part of the site with sand and gravel to stabilize one of the two wrecks located at the top of a steep slope on the seabed (Kystverket, 2016b, Van Oord 2016). The NCA has however not made a final decision on the best way to remediate the site, i.e. whether to raise the wreckage and cap the Hg-contaminated site, or whether to entomb the entire site including the wrecks (Kystverket, 2016b).

### *Petroleum oil and PAH pollution from Nordvard wreck*

Excluding oil tanker accidents, there are only a handful of reported studies that have quantified the environmental pollution extent of oil leakage from PPW. This is in spite of the more than 8000 documented PPWs globally (but does not include ships with a gross tonnage below 150 and those not using petroleum-based fuel or carrying petroleum cargo (Monfils et al., 2006)). Assessing oil pollution effects on coastal waters and sediment immediately after a spill (e.g. (Chaerun et al., 2004; Perez-Cadahia et al., 2007), is relatively straight forward. Oil pollution from historical shipwrecks is however more complicated, especially because such pollution might occur in small quantities over decades in a coastal environment that has other petroleum oil and PAH sources (Berge et al., 2009; Rogowska et al.; 2015, Rogowska et al., 2010; Viarengo et al., 2007). Figure 6 (and supplementary information) shows the TPH and PAH concentrations measured in sediment collected from the *Nordvard* wreck site near Moss harbor in Southern Norway (Berge et al., 2009). There is a high linear correlation between sediment TPH and PAH concentration ($R^2 = 0.80$), suggesting one common source.

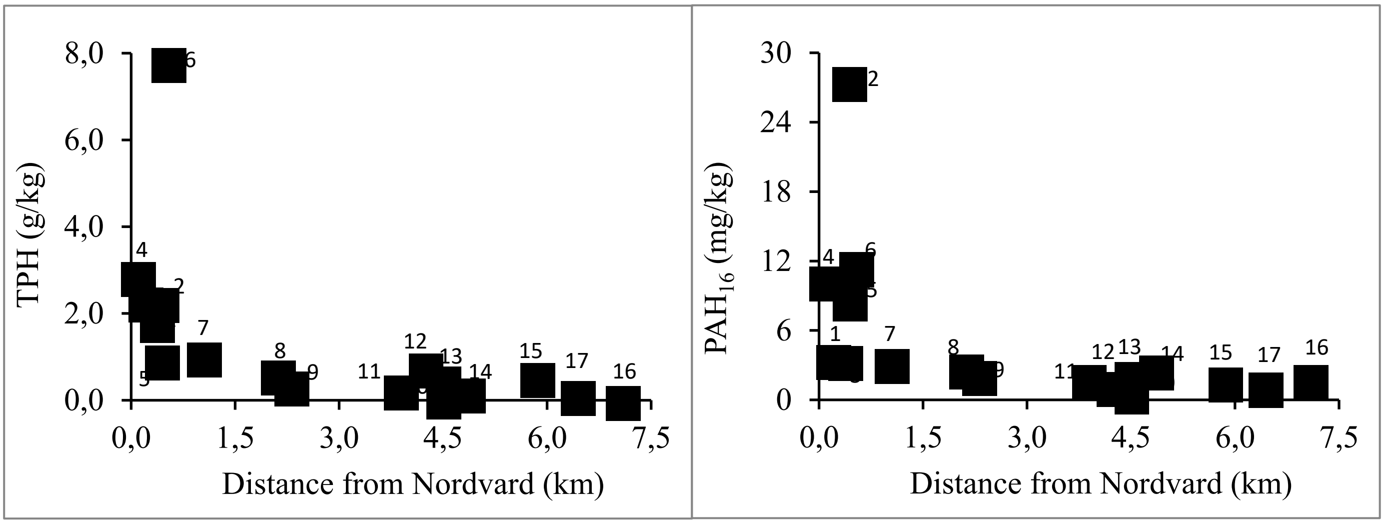


Figure 6. Concentrations of PAH and TPH in bottom sediment sampled in the vicinity of the WWII wreck *Nordvard*. The numbers correspond to sample station numbers shown on the map in Figure 3.

The lowest TPH concentration (28 mg/kg, Figure 3 and Figure 6) was measured in the station furthest from the wreck (supplementary information). Of other marine studies, Readman et al. (2002) reported TPH concentrations of 2-7 mg/kg in sediment from the Ukranian Black Sea coast, while Volkman et al. (2002) and Kucuksezgin et al. (2006) reported TPH concentrations an order of magnitude lower (0.2-2 mg/kg) in sediment from the Australian Great Barrier Reef and the Mediterranean Sea, respectively. Thus even the lowest TPH concentration in the Moss straight is still an order of magnitude higher than what has been reported from the more pristine Barrier Reef and Mediterranean Sea sediment (Kucuksezgin et al., 2006; Volkman et al., 1992). This high TPH concentration at seven km from the wreck site shows the significance of other TPH inputs at the site, and also the difficulty of delineating the TPH contribution from *Nordvard* wreck diverse point and non-point PAH sources such as aerosol deposition and marine traffic emissions. Moss harbor has numerous ship wharfs and a long history of industrial activity, all of which are likely to also have contributed to oil pollution during the last century (Berge et al., 2009). However, the high linear correlation between PAH and TPH concentration combined with the characteristic exponential decay (i.e. the rate of decrease of both TPH and PAH concentration with distance is proportional to the concentration) suggests a common point source. This inability to delineate between petroleum oil and PAH pollution from PPW and conventional point and non-point sources has been a constant theme during PPW assessment and monitoring. Another example is the WWII wreck *Velheim* (Figure 1), which also lies in a coastal seabed, close to a town with a long history of industrial pollution. *Velheim* has been leaking oil for many years and it is equally difficult to distinguish between oil and PAH contamination in nearby sediments from *Velheim* and that from other sources.

### *Shipwrecks are a small but important source of oil pollution to the Norwegian coastal environment*

Petroleum oil pollution from PPW represents a small but important source of oil pollution to the marine environment (NRC, 2003). The significance of this oil pollution source is related to the geographical locations of the wrecks: most of the PPW are located in or near densely populated coastal environments such as harbors (Figure 1). The NCA has emptied oil in eight of the 30 PPW and continues to monitor the situation of the remaining 22 wrecks (Figure 1). Studies have also been carried out to assess the relative toxicity of different types of oils found in PPW to marine biota. Faksness et al. (2015) recently reported higher toxicity to marine copepods and algae from synthetic bunker oil (synthesized from lignite or brown coal) compared to natural diesel (Faksness et al., 2015). The algae (*Skeletonema costatum*) and copepod (*Calanus finmarchicu*) were exposed to classic bunker oil from two British wrecks (the frigate *HMS "Bittern*", and the carrier tanker *RFA "Boardale*", Figure 1) and to synthetic oil from two German wrecks (the destroyer "*Erich Giese*" and "*Nordvard*"). The copepods and algae showed increased growth inhibition and higher mortality when exposed to coal-based oils (e.g. from German shipwrecks *Nordvard* and ''*Erich Giese*, (Faksness et al., 2015)) compared to mineral oils (e.g. British HMS Bittern) (Bergstrøm 2014; Faksness et al., 2015) . The authors attributed the enhanced toxicity of synthetic oils to the higher concentration of phenolic compounds and naphthalenes, which they measured in water accommodated fractions of the coal-based oils compared to natural oils (Faksness et al., 2015) .

*Petroleum inputs to the sea*

The US NRC estimates that about 1.3 million t of oil end up in the sea from natural seeps, petroleum extraction, petroleum transportation, and petroleum consumption annually (NRC, 2003). As the NRC report points out, these inputs represent thousands or tens of thousands of individual releases whose combined effect on the environment is difficult to clearly establish. Regional or worldwide estimates of petroleum entering the environment are useful only as a first order approximation of need for concern (NRC, 2003). Thus, although natural seeps represent the highest input category (estimated at 600 000 t of oil annually), other sources with smaller inputs might have higher ecological impact to the environment depending on location and volume (NRC, 2003). Polycyclic aromatic hydrocarbons are the most toxic class of compounds present in petroleum oil and the concentration of PAH in crude oil ranges from 0.2-7% (NRC, 2003). Oil spills are estimated to contribute about 4900 t of PAH to the North American waters annually (NRC, 2003). Similarly to Hg, quality criteria guidelines in use for PAH levels in marine sediment vary around the world. (Burton, 2002). The Norwegian Environment Agency classifies marine sediments with a total $PAH_{16}$ (i.e. sum of 16 priority

PAH, see methods section) concentration of less than 0.3 mg/kg as background, while sediment with a concentration above 20 mg/kg is categorized as highly contaminated (Bakke et al., 2010). The Canadian and US NOAA have a threshold effect guideline for total PAH concentration in marine sediment of 1.7 mg/kg (Burton, 2002)

*Conclusions*

Although some shipwrecks play an important role (such as recreational diving sites) in the cultural tourism industry (Jeffery, 1990), there is growing concern on the potential environmental impacts from eventual release of fuel and other potentially pollutant cargo held in some of the wrecks. There has been a concerted effort in cataloging the location of these PPW (e.g. (Michel et al., 2005, Girin 2004, Monfils et al., 2006, NOAA 2013)), but there is no matching effort directed at assessing and quantifying the environmental damage caused by PPW. The large number of PPW implies that pertinent national authorities have to prioritize remediation resources mainly based on cargo type, integrity of the wreck and vicinity (Bergstrøm 2014, NOAA 2013). Our study focused on two of the 30 (from a total of 2100) priority wrecks on the Norwegian coast that are deemed by the NCA to pose a pollution risk to the environment. Petroleum oil leakage, mostly from WWII wrecks, poses the highest pollution risk in Norway and also globally. Unlike other pollution risks (such as contaminated seabed sediment) that might diminish with time (e.g. via continuous deposition of fresh uncontaminated sediment), the risk posed by PPW oil (or any other pollutant cargo) leakage increases with time. This is because a wreck`s ability to hold the cargo deteriorates with age, owing to the highly corrosive seabed environment. Unlike WWII wrecks, pollution risk from more recent shipwrecks can be mitigated by removal of dangerous cargo before or soon after vessel sinking combined with a thorough environmental review (e.g. case of MS Server (Norderhaug et al., 2015)). The results from the extensive studies carried out to assess and quantify pollution from the U-864 and *Nordvard* wrecks, show extensive but localized Hg and oil pollution, respectively. The Hg-contaminated sediment area (about 0.03 km$^2$ with THg above 1 mg/kg d.w.) surrounding the U-864 is relatively small, despite the large amount of elemental Hg (about 65 t) presumed to have been part of the submarine`s cargo prior to sinking. The two studies documented here highlight the need for, i) a prioritization of high risk PPW that need continuous assessment and monitoring, ii) complimentary studies to explore and better understand the potential environmental risk and take preemptive measures to alleviate them. Such measures include i) experiments using site sediment to investigate the possibility of toxic methylmercury formation from elemental Hg, and, ii) testing of the relative toxicity to marine biota from the different types of bunker oils in the WWII PPW to aid prioritization of oil removal from the remaining PPW.

*Author Contributions*

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

*Funding Sources*

This research was funded in part by The Norwegian Coastal Administration (Kystverket).

ACKNOWLEDGMENT

We thank the Captain, officers and crew of all the vessels and many workers at NIVA who have been involved in sampling during numerous occupations of the U-864 site over the years.  We are grateful to Kine Baek for help with PAH and TPH analysis.

REFERENCES

Bakke, T., Källqvist, T., Ruus, A., Breedveld, G. D., Hylland, K., 2010. Development of sediment quality criteria in Norway. J. Soils Sed. 10 (2), 172-178.

Becker, R., Buge, H-G.,Bremser, W., Nehls, I., 2006. Mineral oil content in sediments and soils: comparability, traceability and a certified reference material for quality assurance. Anal. Bioanal. Chem. 385, 645-651.

Burton, G. A., 2002. Sediment quality criteria in use around the world, Limnol. 3, 65-76.

Berge, J.A., Schøyen, M., Øxnevad, S., 2009. Undersøkelser av miljøgifter i sedimenter fra Mossesundet (In Norwegian). NIVA Report No. 5805-2009 .

Bergstrøm, R., 2014. Lessons learned from Offloading Oil from Potentially Polluting Ship Wrecks from World War II in Norwegian Waters. International Oil Spill Conference Proceedings. 804-813 (doi:10.7901/2169-3358-2014.1.804)

Black, F. Conaway, C.H., Flegal, A.R., 2012. Mercury in the Marine Environment, in: Banks, M. S. (Ed.), Mercury in the Environment: Pattern and Process. University of California Press, Berkeley and Los Angeles , pp 167-197

National Research Council,, 2003. Oil in the sea III: inputs, fates, and effects : national academies Press, 2003

Chaerun, S.K., Tazaki, K., Asada, R., Kogure, K., 2004. Bioremediation of coastal areas 5 years after the Nakhodka oil spill in the Sea of Japan: isolation and characterization of hydrocarbon-degrading bacteria. Environ. Intern. 30, 911-922.

Champ, M.A., Gomez, L.S., Makeyev, V.M., Brooks, J.M., Palmer, H.D., Betz, F., 2001. Ocean storage of nuclear wastes? Experiences from the Russian Arctic. Mar. Poll. Bull. 43, 1-7.

European Commission (EC), 2006. Setting maximum levels for certain contaminants in foodstuffs. Commission Regulation (EC) No 1881/2006. (https://www.fsai.ie/uploadedFiles/Consol_Reg1881_2006.pdf)

Faksness, L.G., Daling, P., Altin, D., Dolva, H., Fosbaek, B., Bergstrom, R., 2015. Relative bioavailability and toxicity of fuel oils leaking from World War II shipwrecks. Mar. Poll. Bull. 94, 123-130.

Gilmour, C.C., Elias, D.A., Kucken, A.M., Brown, S.D., Palumbo, A.V., Schadt, C.W., Wall, J.D., 2011. Sulfate-Reducing Bacterium Desulfovibrio desulfuricans ND132 as a Model for Understanding Bacterial Mercury Methylation. Appl. Environ. Microbiol. 77, 3938-3951.

Gilmour, C.C., Podar, M., Bullock, A.L., Graham, A.M., Brown, S.D., Somenahally, A.C., Johs, A., Hurt, R.A., Bailey, K.L., Elias, D.A., 2013. Mercury Methylation by Novel Microorganisms from New Environments. Environ. Sci. Technol. 47, 11810-11820.

Girin, M., 2004. European experience in response to potentially polluting shipwrecks. Mar. Technol. Soc. J. 38, 21-25.

Hahladakis, J.N., Stylianos, M., Gidarakos, E., 2013. Assessment of released heavy metals from electrical and electronic equipment (EEE) existing in shipwrecks through laboratory-scale simulation reactor. J. Hazard. Mat. 250, 256-264.

ISO., 2012. International Organization for Standardization-ISO 8217:2012: Petroleum products — Fuels (class F) — Specifications of marine fuels.

Jaccard, P., Staalstrøm, A., Skogan, O.A., 2015. Long term current monitoring at U-864 location outside Fedje. NIVA Report No. 6876-2015.

Jeffery, B., 1990. Realising the cultural tourism potential of South Australian shipwrecks. Historic Environ. 7 (3/4), 72.

Johnson, N.W., Reible, D.D., Katz, L.E., 2010. Biogeochemical Changes and Mercury Methylation beneath an In-Situ Sediment Cap. Environ. Sci. Technol. 44, 7280-7286.

Kerin E. J., Gilmour, C. C., Roden, E., Suzuki, M. T., Coates, J. D., Mason, R. P., 2006. Mercury methylation by dissimilatory iron-reducing bacteria. Appl. Environ. Microbiol. 72, 7919-7921.

Kucuksezgin, F., Kontas, A., Altay, O., Uluturhan, E., Darılmaz, E., 2006. Assessment of marine pollution in Izmir Bay: Nutrient, heavy metal and total hydrocarbon concentrations. Environ. Int. 32, 41-51.

Kvangarsnes, K., Frantzen, S., Julshamn, K., Sæthre, L.J., Nedreaas, K., Maage, A., 2012. Distribution of mercury in a gadoid fish species, tusk (Brosme brosme), and its implication for food safety. J. Food Sci. Eng. 2, 603-615.

Kystverket (Norwegian Coastal Administration), 2006. Status for tidligere undersøkte vrak med potensiell olje langs norskekysten (in Norwegian) http://www.kystverket.no/Documents/Beredskap/Vrak/Vrakrapport_2006.pdf.

Kystverket (The Norwegian Coastal Administration), 2016a. Undersea Images of submarine U-864: http://www.flickr.com/photos/kystverket/sets/72157638343710506/.

Kystverket (The Norwegian Coastal Administration), 2016b. U-864:Timeline-of-work-on-surveys-and-studies/ (http://kystverket.no/en/EN_Preparedness-against-acute-pollution/U-864/U-864-Timeline-of-work-on-surveys-and-studies/).

Laffon, B., Rabade, T., Pasaro, E., Mendez, J., 2006. Monitoring of the impact of Prestige oil spill on Mytilus galloprovincialis from Galician coast. Environ. Int. 32, 342-348.

Malik, S., Beer, M., Megharaj, M., Naidu, R., 2008. The use of molecular techniques to characterize the microbial communities in contaminated soil and water. Environ. Int. 34, 265-276.

Michel, J., Gilbert, T., Etkin, D.S., Urban, R., Waldron, J., Blocksidge, C.T., 2005. Potentially Polluting Wrecks in Marine Waters: An Issue Paper Prepared for the 2005 International Oil Spill Conference. International Oil Spill Conference Proceedings.

Monfils, R., Gilbert, T., Nawadra, S., 2006. Sunken WWII shipwrecks of the Pacific and East Asia: The need for regional collaboration to address the potential marine pollution threat. Ocean & Coast. Manag. 49, 779-788.

Ndungu, K., Schaanning, M., Braaten, H.F.V., 2016. Effects of organic matter addition on methylmercury formation in capped and uncapped marine sediment. Water Res. 103, 401-407.

NOAA (National Oceanic and Atmospheric Administration), 2013. Risk Assessment for Potential Polluting Wrecks in U.S. (127 pp + appendices). National Oceanic and Atmospheric Administration, Silver Spring, MD.

Norderhaug, K.M., Bakke, T.H., Tveiten, L.A., Gitmark, J.K., Walday, M.G., 2015. Miljøundersøkelser rundt vraket av MS Server (in Norwegian) NIVA Report Nr. 6916-2015.

Olsvik, P. A., Brattas, M., Lie, K. K., Goksoyr, A., 2011. Transcriptional responses in juvenile Atlantic cod (Gadus morhua) after exposure to mercury-contaminated sediment obtained near the wreck of the German WW2 submarine U-864, and from Bergen Harbor, Western Norway. Chemosphere, 83, 552-563.

OSPAR Commission, 2006. Agreement on background concentrations for contaminants in seawater, biota and sediment (OSPAR agreement 2005–6).

Øxnevad, S., Beylich, B., 2013. Investigations of mercury during a survey near submarine U-864 outside Fedje in 2013. NIVA Report No. 6499-2013.

Perez-Cadahia, B., Lafuente, A., Cabaleiro, T., Pasaro, E., Mendez, J., Laffon, B., 2011. Initial study on the effects of Prestige oil on human health. Environ. Int. 33, 176-185.

Raban, A., 1973. The mercury carrier from the Red Sea. Int. J. Naut. Arch. 2, 179-183. DOI: 10.1111/j.1095-9270.1973.tb00503.x.

Randall, P.M., Chattopadhyay, S., 2013. Mercury contaminated sediment sites-An evaluation of remedial options. Environ. Res. 125, 131-149.

Readman, J., Fillmann, G., Tolosa, I., Bartocci, J., Villeneuve, J.-P., Catinni, C., Mee, L., 2002. Petroleum and PAH contamination of the Black Sea. Mar. Poll. Bull. 44, 48-62.

Rogowska, J., Kudlak, B., Tsakovski, S., Galuszka, A., Bajger-Nowak, G., Simeonov, V., Konieczka, P., Wolska, L., Namiesnik, J., 2015. Surface sediment pollution due to shipwreck s/s "Stuttgart": a multidisciplinary approach. Stoch. Environ. Res. Risk A. 29, 1797-1807.

Rogowska, J., Wolska, L., Namiesnik, J., 2010. Impacts of pollution derived from ship wrecks on the marine environment on the basis of s/s "Stuttgart" (Polish coast, Europe). Sci. Total Environ,. 408, 5775-5783.

Rua-Ibarz, A., Bolea-Fernandez, E., Maage, A., Frantzen, S., Valdersnes, S., Vanhaecke, F., 2016. Assessment of Hg Pollution Released from a WWII Submarine Wreck (U-864) by Hg Isotopic Analysis of Sediment and Cancer pagurus Tissues. Environ. Sci. Technol. 50, 10361-10369.

Ruus, A., Schaanning, M., Øxnevad, S., Hylland, K. 2005. Experimental results on bioaccumulation of metals and organic contaminants from marine sediments. Aquat. Toxcol. (72), 273-292.

Sanderson, H., Fauser, P., Thomsen, M., Sørensen, P.B., 2007. PBT screening profile of chemical warfare agents (CWAs). J. Hazard. Mater. 148, 210-215.

Sanderson, H., Fauser, P., Thomsen, M., Vanninen, P., Soderstrom, M., Savin, Y., Khalikov, I., Hirvonen, A., Niiranen, S., Missiaen, T., Gress, A., Borodin, P., Medvedeva, N., Polyak, Y., Paka, V., Zhurbas, V., Feller, P., 2010. Environmental Hazards of Sea-Dumped Chemical Weapons. Environ. Sci. Technol. 44, 4389-4394.

Schiel, D.R., Ross, P.M., Battershill, C.N., 2016. Environmental effects of the MV Rena shipwreck: cross-disciplinary investigations of oil and debris impacts on a coastal ecosystem. New Zealand J. Mar. Freshwater Res. 50, 1-9.

Skei, J., 2003. Analyse av sedimentprøver rundt vrak av ubåt (U-864) utenfor Fedje, Hordaland. NIVA-notat 2003.(In Norwegian).

Uriansrud, F., Dahl, I., Skei, J., Wehde, H., Mortensen, T., 2006. Miljøovervåkning, strømundersøkelser, sedimentkartlegging og vurdering av sedimenttildekking - Fase 2 kartlegging ved U-864 høsten. (in Norwegian). NIVA Report No. 5279/2006.

Uriansrud, F., Skei, J., Schøyen, M., 2005. Miljøkonsekvensvurdering av kvikksølv ved sunket ubåt U-864, Fedje i Hordaland. Fase 1. Kvikksølvkartlegging (In Norwegian). NIVA Report No. 5022.

Van Oord., 2016. Stabilising the wreck of the U-864 submarine in Norway (https://vimeo.com/181012972). https://vimeo.com/181012972:

Ventikos, N.P., Louzis, K., Koimtzoglou, A., 2013. The Shipwrecks in Greece are Going Fuzzy: A Study for the Potential of Oil Pollution from Shipwrecks in Greek Waters. Human Ecol. Risk Assess. 19, 462-491.

Viarengo, A., Dondero, F., Pampanin, D.M., Fabbri, R., Poggi, E., Malizia, M., Bolognesi, C., Perrone, E., Gollo, E., Cossa, G.P., 2007. A biomonitoring study assessing the residual biological effects of pollution caused by the HAVEN wreck on marine organisms in the Ligurian sea (Italy). Arch. Environ. Contamin. Toxicol. 3, 607-616.

Volkman, J.K., Holdsworth, D.G., Neill, G.P., Bavor, H., 1992. Identification of natural, anthropogenic and petroleum hydrocarbons in aquatic sediment. Sci. Total Environ. 112, 203-219.

Yablokov, A.V., 2001. Radioactive waste disposal in seas adjacent to the territory of the Russian Federation. Mar. Poll. Bull. 43, 8-18.

Yu, R.Q., Flanders, J.R., Mack, E.E., Turner, R., Mirza, M.B., Barkay, T., 2012. Contribution of Coexisting Sulfate and Iron Reducing Bacteria to Methylmercury Production in Freshwater River Sediment. Environ. Sci. Technol. 46, 2684-2691.

Supporting information

## U-864 samples

Sample site location and year for Mercury concentration in bottom surface sediment sampled at the site of the U-864 submarine wreckage between 2003 and 2013

| Station | year sampled | longitude | latitude | UTMZone | E | N | Hg conc. (mg/kg dry weight) |
|---|---|---|---|---|---|---|---|
| 28 | 2013 | 4,6183 | 60,7709 | 32North | 261428 | 6745232 | 0,28 |
| 31 | 2013 | 4,6176 | 60,7701 | 32North | 261382 | 6745145 | 0,05 |
| 32 | 2013 | 4,6205 | 60,7717 | 32North | 261557 | 6745314 | 0,11 |
| 34 | 2013 | 4,6194 | 60,7712 | 32North | 261491 | 6745267 | 0,26 |
| 35 | 2013 | 4,6190 | 60,7710 | 32North | 261470 | 6745240 | 1,23 |
| 36 | 2013 | 4,6186 | 60,7707 | 32North | 261445 | 6745213 | 0,33 |
| 38 | 2013 | 4,6183 | 60,7700 | 32North | 261423 | 6745135 | 0,41 |
| 83 | 2013 | 4,6176 | 60,7698 | 32North | 261383 | 6745112 | 0,04 |
| 87 | 2013 | 4,6184 | 60,7698 | 32North | 261428 | 6745113 | 0,33 |
| 88 | 2013 | 4,6192 | 60,7698 | 32North | 261470 | 6745107 | 0,89 |
| 142 | 2013 | 4,6230 | 60,7712 | 32North | 261686 | 6745250 | 0,07 |
| 146 | 2013 | 4,6209 | 60,7711 | 32North | 261574 | 6745250 | 1,62 |
| 155 | 2013 | 4,6220 | 60,7701 | 32North | 261625 | 6745133 | 0,03 |
| 204 | 2013 | 4,6231 | 60,7697 | 32North | 261683 | 6745090 | 0,07 |
| 206 | 2013 | 4,6225 | 60,7692 | 32North | 261647 | 6745035 | 0,08 |
| 210 | 2013 | 4,6224 | 60,7695 | 32North | 261640 | 6745064 | 0,03 |
| 211 | 2013 | 4,6219 | 60,7694 | 32North | 261615 | 6745057 | 0,06 |
| 213 | 2013 | 4,6217 | 60,7696 | 32North | 261607 | 6745084 | 0,12 |
| 301 | 2013 | 4,6197 | 60,7710 | 32North | 261507 | 6745240 | 0,89 |
| 302 | 2013 | 4,6203 | 60,7713 | 32North | 261543 | 6745276 | 0,60 |
| 306 | 2013 | 4,6232 | 60,7714 | 32North | 261698 | 6745276 | 0,04 |
| 308 | 2013 | 4,6213 | 60,7717 | 32North | 261597 | 6745315 | 0,07 |
| 312 | 2013 | 4,6183 | 60,7715 | 32North | 261432 | 6745308 | 0,70 |

Hg concentration in sediment cores sampled close to U-864 wreckage. Red numbers indacate samples possibly contaminated during core slicing

| Station | Depth (cm) | Hg mg/kg dry weight |
|---|---|---|
| 401 | 0-10 | 3,6 |
| 401 | 10-20cm | 0,4 |
| 401 | 50-60 | 0,4 |
| 401 | 100-110 | 0,2 |
| 401 | 110-120 | 0,1 |
| 401 | 200-210 | 0,1 |
| 401 | 210-220 | 0,1 |
| 402 | 0-10 | 1,5 |
| 402 | 10-20cm | 0,0 |
| 402 | 50-60 | 0,1 |
| 402 | 100-110 | 0,1 |
| 402 | 110-120 | 0,0 |
| 402 | 200-210 | 0,0 |
| 402 | 210-220 | 0,0 |
| 403 | 0-10 | 0,1 |
| 403 | 10-20cm | 0,0 |
| 403 | 50-60 | 0,0 |
| 403 | 100-110 | 0,0 |
| 403 | 110-120 | 0,0 |
| 404 | 0-10 | 0,2 |
| 404 | 10-20cm | 0,2 |
| 404 | 80-90 | 0,0 |
| 404 | 90-100 | 0,0 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 313 | 2013 | 4,6170 | 60,7713 | 32North | 261359 | 6745280 | 0,06 |
| 315 | 2013 | 4,6168 | 60,7704 | 32North | 261345 | 6745184 | 0,11 |
| 316 | 2013 | 4,6168 | 60,7699 | 32North | 261341 | 6745135 | 0,09 |
| 317 | 2013 | 4,6191 | 60,7702 | 32North | 261465 | 6745153 | 0,58 |
| 320 | 2013 | 4,6170 | 60,7708 | 32North | 261357 | 6745232 | 0,08 |
| 324 | 2013 | 4,6229 | 60,7699 | 32North | 261672 | 6745112 | 0,11 |
| 331 | 2013 | 4,6217 | 60,7692 | 32North | 261600 | 6745037 | 0,18 |
| 332 | 2013 | 4,6221 | 60,7689 | 32North | 261622 | 6744999 | 0,08 |
| 333 | 2013 | 4,6227 | 60,7688 | 32North | 261654 | 6744988 | 0,15 |
| 334 | 2013 | 4,6236 | 60,7689 | 32North | 261701 | 6744999 | 0,05 |
| 30B | 2013 | 4,6172 | 60,7704 | 32North | 261366 | 6745184 | 0,08 |
| Sed-8 | 2013 | 4,6180 | 60,7712 | 32North | 261413 | 6745271 | 0,25 |
| 28 | 2006 | 4,6181 | 60,7708 | 32North | 261415 | 6745227 | 0,44 |
| 30 | 2006 | 4,6177 | 60,7704 | 32North | 261394 | 6745187 | 0,15 |
| 31 | 2006 | 4,6176 | 60,7700 | 32North | 261383 | 6745144 | |
| 32 | 2006 | 4,6205 | 60,7717 | 32North | 261557 | 6745317 | 0,07 |
| 33 | 2006 | 4,6200 | 60,7715 | 32North | 261524 | 6745302 | 0,23 |
| 34 | 2006 | 4,6194 | 60,7712 | 32North | 261492 | 6745268 | 0,22 |
| 35 | 2006 | 4,6190 | 60,7709 | 32North | 261470 | 6745239 | 1,30 |
| 36 | 2006 | 4,6187 | 60,7707 | 32North | 261447 | 6745211 | |
| 37 | 2006 | 4,6185 | 60,7703 | 32North | 261438 | 6745173 | |
| 38 | 2006 | 4,6183 | 60,7700 | 32North | 261424 | 6745135 | 0,07 |
| 41 | 2006 | 4,6197 | 60,7708 | 32North | 261507 | 6745225 | 0,70 |
| 42 | 2006 | 4,6193 | 60,7707 | 32North | 261480 | 6745207 | 0,70 |
| 43 | 2006 | 4,6194 | 60,7702 | 32North | 261485 | 6745152 | 0,60 |
| 44 | 2006 | 4,6190 | 60,7700 | 32North | 261459 | 6745132 | |
| 45 | 2006 | 4,6206 | 60,7707 | 32North | 261551 | 6745206 | 1,00 |
| 46 | 2006 | 4,6202 | 60,7708 | 32North | 261532 | 6745223 | 0,80 |
| 47 | 2006 | 4,6200 | 60,7706 | 32North | 261518 | 6745194 | 1,50 |
| 48 | 2006 | 4,6194 | 60,7704 | 32North | 261487 | 6745175 | 0,80 |
| 49 | 2006 | 4,6199 | 60,7701 | 32North | 261508 | 6745136 | 2,50 |
| 68 | 2006 | 4,6164 | 60,7689 | 32North | 261311 | 6745021 | 0,05 |
| 69 | 2006 | 4,6169 | 60,7685 | 32North | 261333 | 6744980 | 0,02 |

| | | |
|---|---|---|
| 405 | 0-10 | 88 |
| 405 | 50-60 | 0,8 |
| 405 | 100-110 | 0,1 |
| 405 | 110-120 | 0,1 |
| 405 | 200-210 | 0,1 |
| 405 | 210-220 | 0,1 |
| 405 | 300-310 | 0,1 |
| 405 | 310-320 | 8,2 |
| 406 | 0-10 | 3,0 |
| 406 | 10-20cm | 34 |
| 406 | 210-220 | 24 |
| 407 | 0-10 | 37 |
| 407 | 10-20cm | 18 |
| 407 | 50-60 | 1,8 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 70 | 2006 | 4,6175 | 60,7682 | 32North | 261365 | 6744939 | |
| 71 | 2006 | 4,6183 | 60,7679 | 32North | 261405 | 6744902 | |
| 72 | 2006 | 4,6190 | 60,7677 | 32North | 261444 | 6744878 | 0,01 |
| 73 | 2006 | 4,6199 | 60,7675 | 32North | 261492 | 6744855 | |
| 74 | 2006 | 4,6208 | 60,7675 | 32North | 261540 | 6744846 | 0,04 |
| 76 | 2006 | 4,6170 | 60,7693 | 32North | 261347 | 6745067 | 0,04 |
| 77 | 2006 | 4,6173 | 60,7690 | 32North | 261361 | 6745033 | 0,02 |
| 78 | 2006 | 4,6180 | 60,7686 | 32North | 261397 | 6744985 | 0,03 |
| 79 | 2006 | 4,6185 | 60,7684 | 32North | 261419 | 6744962 | |
| 80 | 2006 | 4,6192 | 60,7682 | 32North | 261456 | 6744933 | |
| 81 | 2006 | 4,6198 | 60,7680 | 32North | 261491 | 6744907 | 0,07 |
| 82 | 2006 | 4,6208 | 60,7678 | 32North | 261540 | 6744882 | 0,04 |
| 83 | 2006 | 4,6176 | 60,7698 | 32North | 261381 | 6745112 | |
| 84 | 2006 | 4,6179 | 60,7695 | 32North | 261395 | 6745079 | |
| 85 | 2006 | 4,6183 | 60,7691 | 32North | 261418 | 6745039 | |
| 86 | 2006 | 4,6187 | 60,7695 | 32North | 261442 | 6745079 | 0,08 |
| 87 | 2006 | 4,6184 | 60,7698 | 32North | 261426 | 6745113 | 0,07 |
| 88 | 2006 | 4,6192 | 60,7698 | 32North | 261468 | 6745108 | 0,35 |
| 90 | 2006 | 4,6195 | 60,7685 | 32North | 261475 | 6744963 | 0,03 |
| 92 | 2006 | 4,6208 | 60,7691 | 32North | 261552 | 6745029 | 0,08 |
| 93 | 2006 | 4,6199 | 60,7694 | 32North | 261507 | 6745064 | 0,21 |
| 94 | 2006 | 4,6194 | 60,7693 | 32North | 261479 | 6745053 | 0,08 |
| 95 | 2006 | 4,6200 | 60,7691 | 32North | 261506 | 6745027 | 0,02 |
| 96 | 2006 | 4,6193 | 60,7693 | 32North | 261469 | 6745051 | |
| 97 | 2006 | 4,6195 | 60,7690 | 32North | 261480 | 6745020 | |
| 98 | 2006 | 4,6202 | 60,7688 | 32North | 261514 | 6744992 | |
| 99 | 2006 | 4,6207 | 60,7688 | 32North | 261545 | 6744989 | 0,06 |
| 100 | 2006 | 4,6203 | 60,7685 | 32North | 261519 | 6744967 | 0,04 |
| 142 | 2006 | 4,6230 | 60,7712 | 32North | 261689 | 6745250 | 0,02 |
| 143 | 2006 | 4,6237 | 60,7710 | 32North | 261721 | 6745227 | 0,04 |
| 144 | 2006 | 4,6237 | 60,7706 | 32North | 261721 | 6745188 | |
| 145 | 2006 | 4,6238 | 60,7703 | 32North | 261726 | 6745152 | 0,05 |
| 146 | 2006 | 4,6209 | 60,7711 | 32North | 261573 | 6745250 | 0,20 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 147 | 2006 | 4,6210 | 60,7708 | 32North | 261576 | 6745220 | 0,50 |
| 148 | 2006 | 4,6216 | 60,7711 | 32North | 261609 | 6745250 | |
| 149 | 2006 | 4,6223 | 60,7708 | 32North | 261647 | 6745209 | 0,05 |
| 150 | 2006 | 4,6227 | 60,7708 | 32North | 261666 | 6745213 | 0,10 |
| 151 | 2006 | 4,6229 | 60,7706 | 32North | 261675 | 6745189 | 0,04 |
| 152 | 2006 | 4,6231 | 60,7703 | 32North | 261686 | 6745156 | 0,10 |
| 153 | 2006 | 4,6223 | 60,7705 | 32North | 261645 | 6745172 | 0,10 |
| 154 | 2006 | 4,6216 | 60,7706 | 32North | 261604 | 6745193 | 0,90 |
| 155 | 2006 | 4,6220 | 60,7701 | 32North | 261624 | 6745133 | |
| 156 | 2006 | 4,6228 | 60,7701 | 32North | 261667 | 6745133 | 0,05 |
| 157 | 2006 | 4,6224 | 60,7703 | 32North | 261645 | 6745155 | 0,06 |
| 200 | 2006 | 4,6230 | 60,7689 | 32North | 261670 | 6745000 | 0,05 |
| 201 | 2006 | 4,6224 | 60,7688 | 32North | 261638 | 6744989 | |
| 202 | 2006 | 4,6218 | 60,7688 | 32North | 261606 | 6744988 | 0,05 |
| 203 | 2006 | 4,6233 | 60,7700 | 32North | 261693 | 6745121 | 0,03 |
| 204 | 2006 | 4,6232 | 60,7697 | 32North | 261684 | 6745086 | 0,04 |
| 205 | 2006 | 4,6230 | 60,7693 | 32North | 261674 | 6745042 | 0,02 |
| 206 | 2006 | 4,6226 | 60,7692 | 32North | 261648 | 6745035 | 0,04 |
| 207 | 2006 | 4,6220 | 60,7691 | 32North | 261619 | 6745021 | 0,07 |
| 208 | 2006 | 4,6213 | 60,7690 | 32North | 261581 | 6745018 | 0,04 |
| 209 | 2006 | 4,6227 | 60,7698 | 32North | 261661 | 6745095 | 0,05 |
| 210 | 2006 | 4,6223 | 60,7695 | 32North | 261638 | 6745064 | 0,03 |
| 211 | 2006 | 4,6219 | 60,7694 | 32North | 261615 | 6745056 | 0,20 |
| 212 | 2006 | 4,6220 | 60,7699 | 32North | 261623 | 6745114 | 0,01 |
| 213 | 2006 | 4,6218 | 60,7697 | 32North | 261608 | 6745087 | 0,25 |
| 214 | 2006 | 4,6215 | 60,7698 | 32North | 261596 | 6745106 | 0,22 |
| 215 | 2006 | 4,6212 | 60,7696 | 32North | 261578 | 6745077 | 0,40 |
| 01 FS | 2005 | 4,6216 | 60,7692 | 32North | 261594 | 6745032 | 134,50 |
| 02 FS | 2005 | 4,6218 | 60,7695 | 32North | 261608 | 6745065 | 13,60 |
| 03 FS | 2005 | 4,6211 | 60,7698 | 32North | 261573 | 6745107 | 33,30 |
| 04 FS | 2005 | 4,6215 | 60,7700 | 32North | 261597 | 6745130 | 66,50 |
| 05 FS | 2005 | 4,6225 | 60,7702 | 32North | 261652 | 6745148 | 14,00 |
| 06 FS | 2005 | 4,6216 | 60,7702 | 32North | 261606 | 6745150 | 49,70 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 07 FS | 2005 | 4,6219 | 60,7705 | 32North | 261622 | 6745174 | 0,72 |
| 08 FS | 2005 | 4,6221 | 60,7707 | 32North | 261637 | 6745203 | 0,90 |
| 09 FS | 2005 | 4,6211 | 60,7706 | 32North | 261581 | 6745195 | 4,32 |
| 10 FS | 2005 | 4,6204 | 60,7692 | 32North | 261528 | 6745039 | 7,25 |
| 11 FS | 2005 | 4,6206 | 60,7710 | 32North | 261555 | 6745238 | 2,61 |
| 12 FS | 2005 | 4,6206 | 60,7704 | 32North | 261550 | 6745175 | 5,75 |
| 13 FS | 2005 | 4,6215 | 60,7708 | 32North | 261603 | 6745218 | 4,78 |
| 14 FS | 2005 | 4,6208 | 60,7703 | 32North | 261561 | 6745156 | 58,00 |
| 15 FS | 2005 | 4,6210 | 60,7702 | 32North | 261571 | 6745150 | 185,50 |
| 16 FS | 2005 | 4,6209 | 60,7701 | 32North | 261565 | 6745140 | 194,00 |
| 16 FS | 2005 | 4,6209 | 60,7701 | 32North | 261565 | 6745140 | 181,00 |
| 17 FS | 2005 | 4,6207 | 60,7702 | 32North | 261555 | 6745144 | 28,30 |
| 18 FS | 2005 | 4,6205 | 60,7702 | 32North | 261542 | 6745148 | 21,30 |
| 19 FS | 2005 | 4,6203 | 60,7700 | 32North | 261533 | 6745125 | 21,80 |
| 20 FS | 2005 | 4,6216 | 60,7697 | 32North | 261598 | 6745086 | 1,76 |
| 21 FS | 2005 | 4,6204 | 60,7698 | 32North | 261535 | 6745103 | 29,40 |
| 22 FS | 2005 | 4,6200 | 60,7697 | 32North | 261514 | 6745096 | 21,10 |
| 23 FS | 2005 | 4,6207 | 60,7698 | 32North | 261554 | 6745109 | 24,00 |
| 24 FS | 2005 | 4,6203 | 60,7696 | 32North | 261527 | 6745080 | 60,70 |
| 25 FS | 2005 | 4,6206 | 60,7696 | 32North | 261542 | 6745085 | 107800,00 |
| 26 FS | 2005 | 4,6207 | 60,7697 | 32North | 261549 | 6745090 | 17,70 |
| 27 FS | 2005 | 4,6209 | 60,7696 | 32North | 261561 | 6745077 | 8,05 |
| 28 FS | 2005 | 4,6208 | 60,7695 | 32North | 261552 | 6745070 | 62,30 |
| 29 FS | 2005 | 4,6206 | 60,7694 | 32North | 261542 | 6745066 | 134,40 |
| 30 FS | 2005 | 4,6210 | 60,7694 | 32North | 261567 | 6745060 | 25,20 |
| 31 FS | 2005 | 4,6195 | 60,7696 | 32North | 261486 | 6745086 | 7,65 |
| 32 FS | 2005 | 4,6211 | 60,7703 | 32North | 261575 | 6745163 | 268,60 |
| 33 FS | 2005 | 4,6212 | 60,7702 | 32North | 261579 | 6745148 | 949,50 |
| 34 FS | 2005 | 4,6207 | 60,7700 | 32North | 261554 | 6745125 | 130,10 |
| 35 FS | 2005 | 4,6211 | 60,7703 | 32North | 261575 | 6745154 | 89,20 |
| Sed-1 | 2005 | 4,6271 | 60,7693 | 32North | 261898 | 6745027 | 0,02 |
| Sed-2 | 2005 | 4,6321 | 60,7733 | 32North | 262195 | 6745450 | 0,03 |
| Sed-3 | 2005 | 4,6234 | 60,7764 | 32North | 261745 | 6745836 | 0,02 |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| Sed-4 | 2005 | 4,6064 | 60,7695 | 32North | 260770 | 6745128 | 0,02 |
| Sed-5 | 2005 | 4,6127 | 60,7677 | 32North | 261101 | 6744903 | 0,02 |
| Sed-6 | 2005 | 4,6199 | 60,7650 | 32North | 261473 | 6744569 | 0,02 |
| Sed-7 | 2005 | 4,6207 | 60,7710 | 32North | 261561 | 6745235 | 0,03 |
| Sed-8 | 2005 | 4,6180 | 60,7712 | 32North | 261415 | 6745271 | 0,02 |
| Sed-9 | 2005 | 4,6364 | 60,7657 | 32North | 262375 | 6744587 | 0,02 |
| Sed-10 | 2005 | 4,6459 | 60,7635 | 32North | 262873 | 6744314 | 0,03 |
| Sed-11 | 2005 | 4,6479 | 60,7761 | 32North | 263075 | 6745708 | 0,03 |
| Sed-12 | 2005 | 4,6430 | 60,7808 | 32North | 262848 | 6746246 | 0,03 |
| Sed-13 | 2005 | 4,6211 | 60,7856 | 32North | 261688 | 6746858 | 0,04 |
| Sed-14 | 2005 | 4,6077 | 60,7803 | 32North | 260921 | 6746319 | 0,02 |
| Sed-15 | 2005 | 4,6096 | 60,7723 | 32North | 260966 | 6745424 | 0,10 |
| Sed-16 | 2005 | 4,5958 | 60,7741 | 32North | 260229 | 6745677 | 0,02 |
| Sed-17 | 2005 | 4,6020 | 60,7658 | 32North | 260502 | 6744727 | 0,02 |
| Sed-18 | 2005 | 4,6124 | 60,7629 | 32North | 261047 | 6744367 | 0,01 |
| Sed-19 | 2005 | 4,6233 | 60,7604 | 32North | 261621 | 6744053 | 0,02 |
| Sed-20 | 2005 | 4,6606 | 60,7571 | 32North | 263627 | 6743549 | 0,04 |
| Sed-21 | 2005 | 4,6669 | 60,7696 | 32North | 264065 | 6744914 | 0,03 |
| Sed-22 | 2005 | 4,6751 | 60,7721 | 32North | 264525 | 6745163 | 0,02 |
| Sed-23 | 2005 | 4,6642 | 60,7761 | 32North | 263962 | 6745644 | 0,03 |
| Sed-24 | 2005 | 4,6540 | 60,7885 | 32North | 263500 | 6747069 | 0,02 |
| Sed-25 | 2005 | 4,6373 | 60,7924 | 32North | 262624 | 6747553 | 0,03 |
| Sed-26 | 2005 | 4,6187 | 60,7910 | 32North | 261598 | 6747469 | 0,02 |
| Sed-27 | 2005 | 4,6114 | 60,7973 | 32North | 261250 | 6748202 | 0,02 |
| Sed-28 | 2005 | 4,5881 | 60,7833 | 32North | 259877 | 6746722 | 0,03 |
| Sed-29 | 2005 | 4,5663 | 60,7707 | 32North | 258601 | 6745399 | 0,03 |
| Sed-30 | 2005 | 4,5964 | 60,7571 | 32North | 260135 | 6743780 | 0,02 |
| 1 | 2003 | 4,6208 | 60,7694 | 32North | 261554 | 6745057 | 1,94 |
| 2 | 2003 | 4,6211 | 60,7696 | 32North | 261571 | 6745084 | 0,56 |
| 3 | 2003 | 4,6213 | 60,7695 | 32North | 261579 | 6745067 | 0,41 |
| 4 | 2003 | 4,6210 | 60,7700 | 32North | 261567 | 6745133 | 96,50 |
| 5 | 2003 | 4,6212 | 60,7702 | 32North | 261579 | 6745149 | 1653,00 |
| 6 | 2003 | 4,6213 | 60,7703 | 32North | 261588 | 6745157 | 139,00 |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| 7 | 2003 | 4,6213 | 60,7705 | 32North | 261591 | 6745179 | 10,20 |
| 8 | 2003 | 4,6210 | 60,7703 | 32North | 261570 | 6745164 | 3,23 |
| 9 | 2003 | 4,6206 | 60,7700 | 32North | 261549 | 6745132 | 2,96 |
| 10 | 2003 | 4,6206 | 60,7706 | 32North | 261551 | 6745195 | 2,11 |

Nordvard samples

Sample site location, depth, distance from wreck, PAH and TPH concentration in bottom surface sediment sampled at the site of the Norvard wreckage in Moss Channel in Southern Norway

| Station | Degrees N | Degrees E | Depth (m) | Distance from Nordvard (km) | TPH conc. (g/kg-dw) | PAH-16 conc. (mg/kg) |
|---|---|---|---|---|---|---|
| MS-1 | 59,4367 | 10,6549 | 20 | 0,4 | 1,8 | 3,5 |
| MS-2 | 59,4382 | 10,6539 | 33 | 0,2 | 2,3 | 3,6 |
| MS-3 | 59,4391 | 10,6485 | 15 | 0,5 | 2,3 | 27,6 |
| MS-4 | 59,4396 | 10,6582 | 16 | 0,1 | 2,9 | 10,4 |
| MS-5 | 59,4433 | 10,6526 | 5,9 | 0,5 | 1,0 | 8,7 |
| MS-6 | 59,4422 | 10,6644 | 29 | 0,6 | 7,8 | 11,6 |
| MS-7 | 59,4483 | 10,6647 | 51 | 1,1 | 1,0 | 3,29 |
| MS-8 | 59,4582 | 10,6680 | 56 | 2,1 | 0,6 | 2,8 |
| MS-9 | 59,4611 | 10,6598 | 7,9 | 2,3 | 0,4 | 2,2 |
| MS-10 | 59,4783 | 10,6826 | 51 | 4,5 | 0,1 | 2,2 |
| MS-11 | 59,4728 | 10,6795 | 27 | 3,9 | 0,3 | 1,9 |
| MS-12 | 59,4752 | 10,6853 | 16 | 4,3 | 0,8 | 1,3 |
| MS-13 | 59,4764 | 10,6881 | 5,6 | 4,5 | 0,5 | 0,6 |
| MS-14 | 59,4824 | 10,6774 | 92 | 4,9 | 0,2 | 2,7 |
| MS-15 | 59,4900 | 10,6863 | 1,4 | 5,9 | 0,6 | 1,7 |
| MS-16 | 59,4945 | 10,6779 | 100 | 6,5 | 0,1 | 1,2 |
| MS-17 | 59,4948 | 10,6654 | 2,8 | 7,1 | 0,0 | 1,9 |