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The growth of benthic organisms in a dumping ground for military bombs and munitions

John Kjeken

Marine Coastal Development
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Supervisor: Geir Johnsen, IBI
Co-supervisor: Martin Ludvigsen, IMT
Terje Thorsnes, NGU
Petter Lagstå, FFI

Norwegian University of Science and Technology
Department of Biology

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# Abstract

Dumping sites for WWII-era bombs and munitions are widespread in the North-East Atlantic. The dumped materiel in such sites pose risks to people and environment through the release of toxic chemicals and accidental detonation. One such dumping ground is in the Outer Fjord Basin in the Trondheimsfjord. The dumped materiel in this area provide hard substrate in an otherwise soft-bottomed location. The goal of this thesis is to survey the community and dumped materiel in this area using an ROV-mounted videocamera. The area was found to contain a high number of man-made objects, estimated to be >100,000. Of these, 1,500 were estimated to be 250 kg type bombs. 32 different taxa of organisms were observed, with a higher diversity among sessile than motile organisms. The common species of horny coral in the community, *Paramuricea macandrewi*, *Duva florida*, *Primnoa resedaeformis* and *Paragorgia arborea*, were found to have notably different preferences for substrate. Based on the objects that could be identified and what they were likely to contain, the risk to the environment in the event of a leak was judged to be low and the main risk was judged to be detonation. The potential for bioturbation in sediment, horny corals and macroalgea to serve as bio-indicators was investigated and macroalgae was judged to have potential to yield the most information.

Sammendrag

Dumpeplasser for bomber og ammunisjon fra andre verdenskrig er tallrike i det nordøstlige Atlanterhavet. Militært materiell dumpet på slike steder er farlig for omgivelsene som kilde til giftige kjemikalier og fordi det kan detonere. En slik dumpeplass finnes i Ytterfjorden i Trondheimsfjorden. Det dumpede materiellet i området danner her hardt substrat i en ellers bløtbunnet lokalitet. Målet for denne oppgaven er å undersøke det biologiske samfunnet og de dumpede bombene i dette området ved hjelp av ROV med videokamera. I området ble det funnet mange dumpede objekter og utfra funnene ble det estimert at totalt over 100.000 menneskeskapte objekter ligger i dumpeplassen. Av disse var om lag 1.500 estimert å være flybomber. 32 forskjellige taxa organismer ble observert, med større mangfold blant sessile enn blant motile dyr. De forskjellige artene hornkoraller i området, *Paramuricea macandrewi*, *Duva florida*, *Primnoa resedaeformis* og *Paragorgia arborea*, viste seg å foretrekke forskjellige substrat. Basert på de bombene som kunne identifiseres, ble risikoen mot miljøet om bombene skulle lekke vurdert som lav og hovedrisikoen vurdert å være at bombene skal detonere. Potensialet for bioturbasjon i sedimentet, hornkorallene og makroalger som bioindikatorer ble undersøkt og makroalger ble vurdert som kandidaten som vil gi mest informasjon.

1 Introduction

After the conclusions of the World Wars of the previous century, millions of tons of bombs, grenades and ammunition remained in stockpile, surplus to peacetime requirements (Nixon, 2009). Storing explosives such as these is expensive and dangerous, so it was decided many places to get rid of them by dumping them in the sea (Nixon, 2009). One such dumping ground for explosives is in a deep basin in the Trondheimsfjord(Kartverket, 2017). The dumping in Norway was done immediately after the liberation of the country and was a chaotic affair (Steinbakken et al, 2000; Ribsskog, 1998). For this reason, there is little knowledge of what has been dumped where, and in what quantities (Voie and Mariussen, 2017).

War materiel dumped in the sea carries high risk, both to people and environment (Rossland et al, 2010; Voie and Mariussen, 2017; Nixon, 2009; OSPAR, 2017a). These risks are chiefly pollution as a result of leaks and damage as a result of inadvertent detonation (Rossland et al, 2010; Voie and Mariussen, 2017; Nixon, 2009; OSPAR, 2017a; Bydal et al, 2012).

Soft and hard bottoms play host to different biological communities. This is because sessile organisms need to prevent the movement of surrounding water from re-positioning them somewhere less favorable. Soft substrates are colonized by organisms that use burrowing as their strategy to escape the currents. In the Trondheimsfjord, these are often polychaete worms or crustaceans (Sakshaug et al, 2000). The dominant strategy on hard substrates is to attach firmly with a holdfast. This is favored by corals, sponges, bivalves and others in the Trondheimsfjord (Sakshaug et al, 2000).

The dumping of military bombs and grenades add hard substrate to an area that would otherwise be soft-bottomed. The explosives dumping ground in the Trondheimsfjord has been subject to scientific interest (Ludvigsen et al, 2014; Håpnes, 2016), and was found to host such a community of hard-bottom organisms using the dumped explosives as substrate. This paper aims to investigate the risks associated with the dumped war materiel in the area and the dynamics of this community.

1.1 Aims

The main aims for the study were to

- Investigate the community of organisms living on and around the dumped man-made objects in the dumping ground
- Investigate the types and numbers of dumped man-made objects
- Assess the risks associated with the objects
- Investigate the potential for organisms to serve as bioindicators, providing information on the state of dumped bombs and the surrounding environment

2 Background

2.1 Historical Background

During the Second World War in Norway (1940-1945), there was an ongoing effort by the German occupying forces to fortify and arm the Norwegian coast as a first line of defence against the Allied powers of the Atlantic. After the surrender of German forces, it became important to classify the materiel involved in this fortification in order to identify and obtain what could be put to use in the war in the Pacific and to secure the rest to prevent it from falling into the wrong hands. There was also a worry that the general populace might investigate or plunder arms depots and bunkers, if they were left too long (Steinbakken et al, 2000; Ribsskog, 1998).

The Allies did not have large forces in Norway and there was no time to ascertain the integrity of local organizations, such as the police force. These were considered compromised after five years of occupation. What manpower was available was tied up with securing the peaceful demobilisation of the 400.000 German soldiers still in the country. For these reasons, it was decided that most of the materiel would be dumped in fjords, lakes and the ocean (Steinbakken et al, 2000).

The precise volume of dumped munitions is not known, but the ”status for dumping of ex-German ammunition as of 15. September 1945” states that approximately 100,000 metric tons have been dumped and that a similar mass was waiting to be dumped (Steinbakken et al, 2000). This estimate does not include Finnmark and Troms counties and inclusion of these might double again the total mass of dumped materiel, for a total mass of upwards of 400,000 metric tons. As of today, there are 47 known deep-water dumping grounds (Rossland et al, 2010).

The haphazard nature of the operation means there are few records of exactly what was dumped where, and as of 2012 there was little knowledge of what kinds of ammunition and explosives have been dumped in any particular location. Records that exist are kept classified with the justification that were they public knowledge, curious members of the populace might try and access the materiel, endangering themselves and others (Bydal et al, 2012).

2.2 Dumped munitions in the North-East Atlantic Ocean

The use of the deep sea as a dumping ground of munitions is a concern that reaches beyond Norway and the Trondheimsfjord. Dumping of WWII munitions after the end of the war was done on a large scale by many countries bordering the North-East Atlantic Ocean, and the total mass of munitions dumped in the era is thought to be a minimum of 1,500,000 tons. Most of the total mass is made up by conventional munitions, but there are also several known repositories of chemical warfare agents, particularly mustard gas. The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) lists Dumped Chemical and Conventional Munitions as one of the human activities causing concern in the area (OSPAR, 2017a). It reports 4600 encounters with dumped explosives in the period from 1999-2013, including three deaths caused by an explosion on a fishing vessel in 2005 (Nixon, 2009; OSPAR, 2017a) after one such explosive had been brought aboard. The organization also notes that such encounters are increasingly common (OSPAR, 2017a). These encounters are mapped and can be seen in Figure 1.

2.3 The Trondheimsfjord

The dumping ground that has been surveyed in this project is located in the Trondheimsfjord. Located (Figure 2) in Sør-Trøndelag, Norway, it is the third longest fjord in the country with its 126 km. The total surface area is 1420 km^2 and the mean depth of the fjord is 165 m (Sakshaug et al, 2000).

The fjord is divided into three basins: the Outer fjord, the Middle fjord and an inner basin, Beistadfjorden (Sakshaug et al, 2000). The Outer fjord is separated from the Norwegian sea by the Agdenes ridge and from the Middle fjord by the Tautra ridge. The middle fjord is framed by the Tautra ridge and Skarnsundet. Fjords are characterized by sheer cliffs from land to deep water, and the Trondheimsfjord is no exeption. In the Middle and Outer fjord, the depth increases rapidly from the shore towards the middle of the respective basins. The Middle fjord basin has a depth of 450 m, while the depth of the Outer fjord basin is around 500 m outside of Trondheim, lowering to 625 m at the maximum, which is reached between Agdenes and Rissa (Sakshaug et al, 2000). It is this deep area that has been used as a dumping ground for explosives and is the subject of this study.

The relatively sheer drops from land to depth provide hard-bottom substrates for a diverse host of sessile species. The fjord is famed for its variety of horny coral, including the large *Paragorgia arborea* (Sakshaug et al, 2000). Furthermore, the reef-building cold-water coral *Lophelia pertusa* is present on

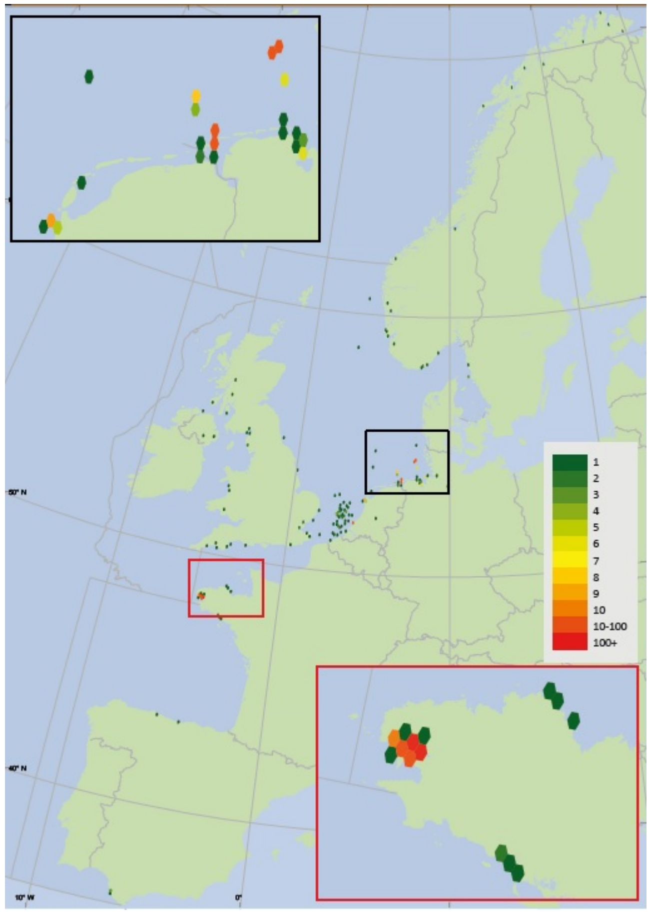

Figure 1: Encounters with dumped chemical and conventional munitions. (OSPAR, 2017a)

several locations. This species forms coral reefs that make up the substrate for an assemblage of other species. The most famous of these reefs in the Trondheimsfjord is along the Tautra sill, a marine protected area (Sakshaug et al, 2000).

While these shallow areas and areas of high biodiversity have been studied in a fair amount of detail, the dynamics of life in the deep basins are much less well understood. This is to a large degree a product of convenience. Greater depths make these areas much more difficult and expensive to reach and study, limiting the possibilities for in-depth classification. Important species in these areas are crustaceans and polychaetes (Sakshaug et al, 2000).

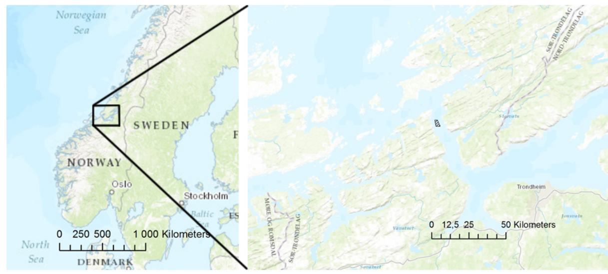

Figure 2: The location of the Trondheimsfjord in Norway.

Recent innovations in robotics and sensor technologies have made expeditions to the deep water considerably more affordable (Sakshaug et al, 2000; Ludvigsen et al, 2014, 2015; Ludvigsen and Sørensen, 2016) and the footage used in this thesis is the result of such an expedition.

2.4 The Agdenes site

The dumping ground is located in the deep basin of the outer fjord, close to the mouth of the Trondheimsfjord. The area is marked by the Norwegian Mapping Authority as "Explosives dumping ground" and is a 1.9 km^2 square. It lies between Agdenes and Rissa in the deepest part of the basin, at 600-625m depth. The coordinates of the corners framing the area are shown in Table 1.

Table 1: Coordinates for the corners of the dumping ground (Kartverket, 2017).

Corner	Longitude (°)	Latitude (°)
North-west	9.76624514 E	63.62018607 N
North-east	9.78228628 E	63.6201998 N
South-west	9.77247143 E	63.60380547 N
South-east	9.79838517 E	63.60355887 N

The depth of the area and the difficulty in reaching and interacting with objects on the seafloor was likely the main reason this area was chosen for the dumping of materiel. The marking of "explosives dumping ground" on official maps has been present from August 1969 and onwards, according to Anita Sunde at Kartverket per correspondence. While it is the focus of this study, war materiel is by no means the only trash that has been dumped in the area. The use of the sea as a convenient deposit for refuse both small and, as the study would find, big, has a long history (OSPAR, 2017b).

When the decision was made to use the area for dumping, there was little reason to believe that the materiel would remain exposed for a long period of time. It was likely either assumed that the bombs and munitions would be buried in sediment, or simply not offered much thought at the time. The continued presence of the bombs on top of the seafloor is testament in itself that any thoughts of them being buried in sediment were wrong. This continued exposure could be explained by what is likely an ongoing process of erosion in the area, which removes sediment at a rate similar to that of deposition. The strong currents in the area, which were also observed during the survey, can be assumed to be a driving factor in this erosion (Bøe et al, 2000).

2.4.1 Currents

As a part of the larger current system in Trondheimsfjord, the area is subject to large movements of water. One of the main drivers of this movement is the tide. The average difference between high and low tide is 1.8 (Carstens, 1975). An estimate of the resulting surface current is 0.21 m/s (Carstens, 1975). Strong currents in the deeper layers have been experienced in the aforementioned previous studies in the area (Ludvigsen et al, 2015).

2.5 Bombs and munitions in the dumping ground

The majority of materiel found in the dumping ground was expected to be various bombs and munitions. The only safe assumption to make about these bombs and their origin is that they were of German manufacture. Throughout the war, the German military used a great number of different compounds to make bombs. These fit in two broad categories: Conventional explosives and specialized payloads, such as smoke bombs. Of these, the most common type was the explosive. This category includes both bombs made to fracture and scatter shrapnel over larger areas and bombs designed to target more armoured targets with more focused explosive power. The explosive power of these munitions comes from one or several energetic compounds, substances or mixes which, on ignition, react rapidly to release large amounts of energy (Bergin et al, 1953). The second category includes different incendiary and smoke-producing compounds. Unlike the explosives, these were often meant to burn over a period of time to cause the intended effect. Bombs in this category contained a range of different compounds (Bergin et al, 1953).

The German Military employed a variety of energetic compounds and mixes according to performance requirements and availability. The simplest way of subdividing these compounds is by chemical classification. The most common classes were nitroaromatics such as TNT, nitramines, chiefly RDX, nitrate esters, like nitroglycerine, and nitroguanine (Voie and Mariussen, 2017). Several mixes used aluminium powder as fuel (Bergin et al, 1953). Of the specialised payloads in service the most notable are incendiary and smoke-producing compounds like phosphorous, chlorosulfuric acid, and sulfur trioxide (Bergin et al, 1953). In addition to payloads, a potential source of toxic compounds are the initiators, a part of the bomb meant to start the explosive reaction. Bombs from this era use different heavy-metal compounds, including lead azide, lead styphnate and mercury fulminate as parts of their initiators (Voie and Mariussen, 2017). The toxicity of lead and mercury is well-established (i.e. (Folkehelseinstituttet, 2016))

Cases for the bombs were mostly made of steel, although parts were made of concrete, cast iron and aluminium. The tails of some bombs were made of magnesium alloy (Bergin et al, 1953). Some types of bomb contain aluminium powder as a fuel.

2.5.1 Toxicity of dumped munitions, general overview

In open bodies of water, the risk of toxicity from leakage of energetic compounds is fairly low (Voie and Mariussen, 2017). Energetic compounds are not toxic at low concentrations and are metabolised quickly when absorbed or ingested by heterotrophic organisms. Combined with an expected high rate of dilution, contamination is likely to be limited to immediately exposed areas where acute toxicity is a possibility at high concentrations (Voie and Mariussen, 2017). Because they are broken down rapidly, the risk of accumulation in the food-web is probably quite low. The risk appears higher for contamination of sediments. Efforts by the Norwegian Defence Research Establishment (FFI) to measure contamination in marine areas where dumped ammunition had been located and disposed of revealed concentrations in the water mass uniformly below their stated critical values, but found concentrations far exceeding said critical values in sediment samples (Rossland et al, 2010). Residues in sediment have a very heterogeneous distribution (Voie and Mariussen, 2017), which makes sampling and estimation of risk difficult.

2.6 ROVs

A remotely operated underwater vehicle (ROV) is a submarine on a tether. This tether, called an umbilical, houses different cables, transferring power down to the vehicle and transmitting video, sonar and other data back to the surface. The umbilical also transmits instructions down to the vehicle, allowing the pilot to remain safe and dry on the surface. ROVs have been in use for over 50 years, but recent advancements in video and robotics have greatly expanded the precision of operations and opened up many new applications for the technology. (Remotely Operated Vehicles Committee of the Marine Technology Society, 2017)

3 Materials and methods

The study was performed by using ROV to capture video of the objects and seafloor on the dumping site. This was done during three cruises: 14. February 2014, and 18. and 21. April 2016.

3.1 Cruises

The ROV cruises were performed using R/V Gunnerus, the research vessel of the Norwegian University of Science and Technology (NTNU). Three separate cruises involved visits to the dumping ground. The first took place on February 14 2014. This first voyage discovered several bombs, boxes and other objects of military origin with an associated rich community of organisms. In order to further investigate this community, the second and a third cruises were scheduled for April, 2016.

The first cruise took up position at 63.61525N 09.77352E while the second and third cruises both took up the same position, 63.61487N 09.77592E. From there, the ROV Sperre was lowered to the bottom and piloted along the seafloor. The ROV logs from Cruise 2 and 3 can be seen in Figure 3

3.1.1 Survey of the seafloor

Lowering the ROV to 620 m depth took some time (approximately 20 mins). A significant limitation during these surveys was the length of the ROV umbilical. The depths at which the survey took place was at the very limit of the operating range, and the drag imposed by the current further limited the operating capabilities of the ROV. In order to maximize the time on the seafloor and ease navigation, dives were scheduled to coincide with low tide. This made it easier to stay close to the bottom and limited exposure to tidal currents, as water-flow through the mouth of the fjord during tidal change was expected to worsen current conditions.

In the first two cruises, the path of the ROV was determined using a short-range sonar to identify objects of interest. This minimized travelling time between objects and served to maximize the number of objects investigated. On the third cruise, the ROV was piloted along two lines of approximately 100 m with a swath width of around 20 m in order to lay a foundation for estimating the density of dumped objects. Figure 3 shows the ROV logs from both cruises, with the two lines as a part of cruise 3 highlighted.

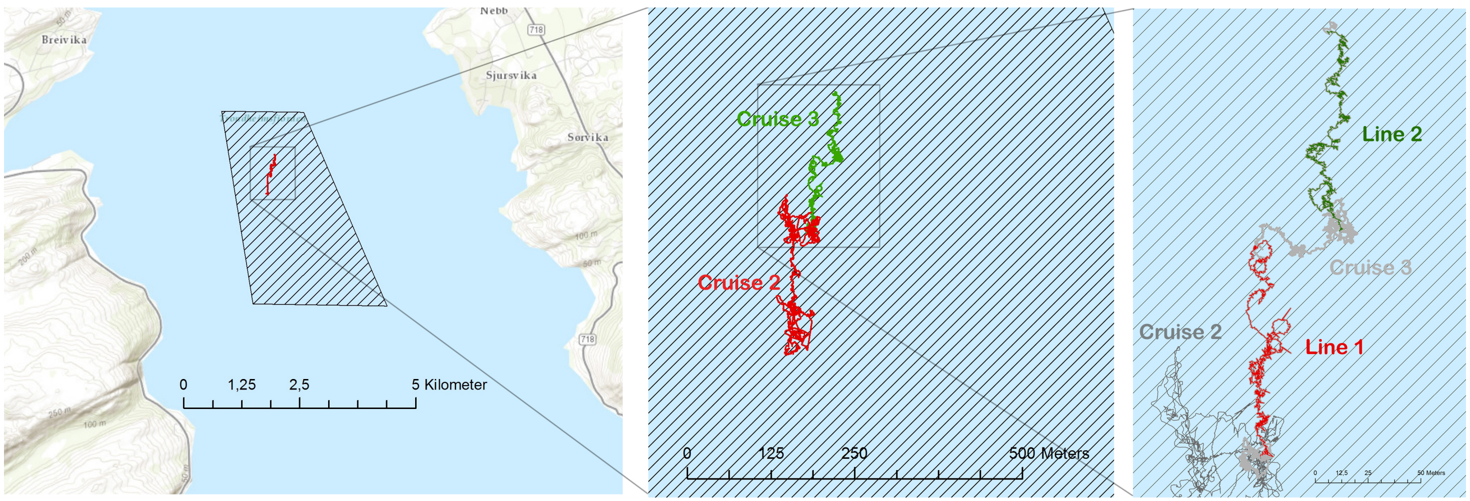

Figure 3: The ROV logs from Cruise 2 and 3. The first image shows the position of the cruises in the dumping ground. The second image shows the two cruises. The third shows the two lines that were piloted as a part of the third cruise.

The data from these surveys was in the shape of video footage taken along the path of the ROV. Physical sampling was considered but ultimately not performed as the explosive nature of the objects in the area and the risk to the environment and equipment was judged as too high if the objects were handled, as inadvertent detonation could not be ruled out.

On the third cruise, one of the two ROV illumination lamps malfunctioned and as a consequence, the illumination in the video from that cruise is substantially poorer. Identification of organisms proved significantly more difficult as a result. Because of this, only the first two cruises were used in the detailed biological survey. The footage from Cruise 3 was used to investigate object types and densities.

3.1.2 ROV Sperre

The ROV used for this survey is NTNUs Sperre sub-fighter 30k (Sperre ROV Technology, 2017). This is a large model, weighing in at approximately two metric tons. Video was captured with a Sony FCB-SE600 HD camera (Sony, 2017). Two HMI halogen lamps were used to illuminate the immediate surroundings of the ROV for the video. Additionally, the ROV was equipped with several auxiliary systems to provide additional information during the survey. These were a short-range Kongsberg MesoTech type 1071 sonar (Kongsberg Maritime, 2017) which was used for orientation and to find objects of interest, a laser ruler made with two parallel SeaLaser® 100s (DeepSea Power & Light, 2017) positioned 10 cm apart, used as a reference to estimate the size of objects in the video footage, the research vessels HiPAP (Kongsberg Maritime, 2016) GPS navigation system providing references of the ROV both in map coordinates and relative to the research vessel, and video-cameras affixed to the front, back and sides of the vehicle to provide a fuller view of the ROVs immediate surroundings and ease navigation (Sperre ROV Technology, 2017).

3.2 Video

The main data from the field was video frame grabs from the ROV-mounted HD video camera. The video data from cruise 1 was 35 minutes, cruise 2 totaled 70 minutes and the third cruise yielded a further 90 minutes, for a total of 3.5 hours.

In the first video, 11 objects were captured with sufficient quality to identify the large species associated with them. For the second cruise, the number was 38. These objects were the basis for the detailed survey of species distributions.

Figure 4: ROV Sperre. The first image shows the Sperre sub-fighter 30k ROV. The second image shows affixed lamps and cameras.

Because of the lamp malfunction, identification based on the third video was much more difficult than in the previous two, and it came to serve as a tool for estimating object density and types rather than species distribution.

3.3 Data

Data on both man-made dumped objects and the biological community was obtained through rigorous study of the videos taken during the cruises and compiled into several sets.

The first effort at compiling data was a list of all the species and groups that had been identified. Not all of the different types of organism could be identified on species level, so several are grouped by higher level taxonomic classification. This list is presented in the next section as Figure 5.

The second dataset was the result of a detailed survey of the most common organism groups. All objects with at least two different identifiable organisms were included. As in the species list, organisms were classified to the lowest taxonomic level at which they could be verifiably identified. In total, 13 different taxa were used, although some, like the ”Squat lobster” and ”Anemone” groups, aggregated observations of several species or sub-groups. Generally, only fairly large individuals could be assigned to species level, as the features of smaller organisms were not captured in enough detail to make a precise identification. Video from Cruise 3 was not used in the detailed survey out of fear that the difference in lighting caused by lantern malfunction would skew the results towards large and colorful organisms. Later in the process, this footage was revisited to investigate and corroborate observed trends in the growth patterns of horny coral.

In addition to biological data, data concerning the types and densities of man-made objects were collected. The first of these sets was concerned with the general shape and type of the dumped objects, and was limited to objects larger than approximately 30 cm. The second set of objects was compiled from the two transect lines that were recorded cruise 3 and was used to estimate the density of objects in the dumping ground.

3.4 R software

The R software (R Development Core Team, 2008) was the main software tool used to manage and analyze data during the project. Most of these analyses were inconclusive and have not been included in this document. The analysis that was included was of the estimates for the correlation of colonized substrates between the horny corals, *P. macandrewi* and *D. florida*, which is presented as a part of the discussion of those species' distributions.

A function was written using the software package to smooth out the GPS logs of the ROV from the survey. The function did this by examining for each point in the log the length from the previous point and eliminating all points for which this was unrealistically high. After running several passes using this function, the paths seen in Figure 3 were produced.

4 Results

4.1 Dumped objects

4.1.1 Object types

As expected, most of the dumped objects that made up the hard substrate in the dumping ground were of clear, human origin. The most striking of these were large bombs, shown on the top right of Figure 5. Several smaller cylindrical objects were also found. These are also likely military in origin. These were perhaps the most obviously worn of the observed man-made objects. The range of different man-made objects was quite a bit wider, including ropes, cables, a ladle, cups, and glasses, not all of which could be precisely identified. Examples of the most common types of man-made, dumped object, the big bombs, smaller cylinders, boxes and other human objects, are shown in Figure 5. A very prominent, big object was the chassis and bodywork of a bus.

To get an overview of the makeup of man-made objects in the dumping ground, a list was compiled of objects classified generally by their shape. The distribution of dumped objects by type in this list can be seen in Figure 6. Of the 229 dumped objects examined, 77 were cylindrical (Category 1), 41 were box-shaped (Category 2), and 58 were not identified (Category 4). The last 53 of the hard substrate objects (Category 3) were recognizably of human origin, but were not further categorized due to the variety of types and shapes in the sample.

4.1.2 State of dumped objects

The dumped objects encountered were generally degraded. The cylindrical, bomb-shaped objects of Category 1 showed signs of degradation but all examined objects appeared to be whole. The Category 2 man-made objects were much more degraded. The examined objects of this type were open to the environment. Several man-made objects in this category, such as the object on the bottom left in Figure 5 had degraded to a point where the casings had fractured, leaving the contents completely open. The broad Category 3 included dumped objects both solid and degraded to the point where the case was no longer intact, such as in Figure 7. High levels of degradation also hampered classification.

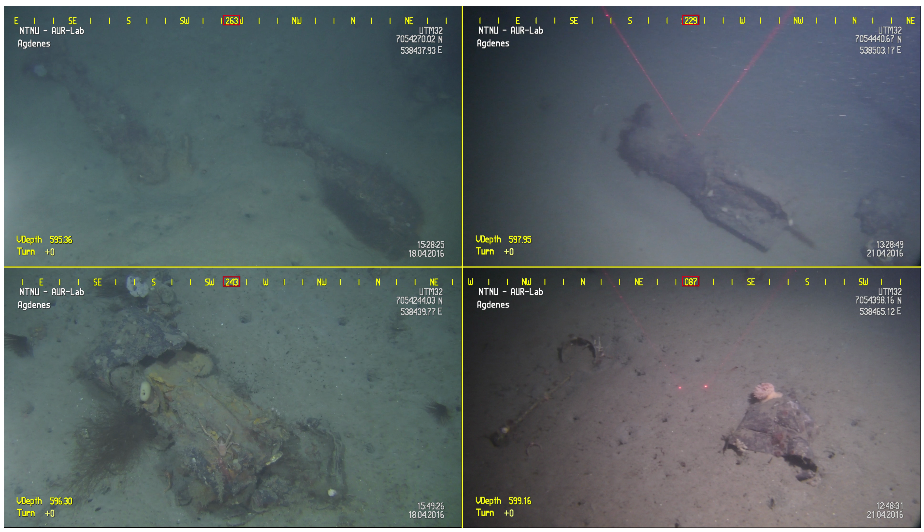

Figure 5: The most common types of objects encountered. Upper left: Two of the smaller bomb-like cylindrical objects. Upper right: One of the large bombs, note the control fins clearly visible on the tail. Lower left: the typical state of the box-like objects. Note the degradation of the case exposing the contents to the current and the detached "lid" partly buried on the left side of the object. Lower right: Two examples to illustrate variety of miscellaneous, identifiable objects of non-military origin (NTNU AUR-lab, 2014, 2016).

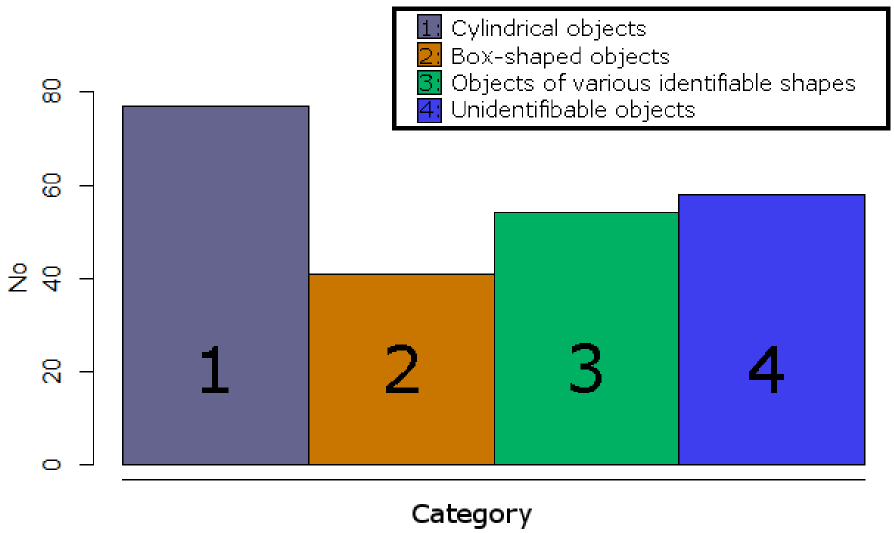

Figure 6: Histogram of object types. The first three categories are objects that appear to be of human origin. The last category contains objects that could not be identified. All objects from all 3 cruises were examined to produce this graph.

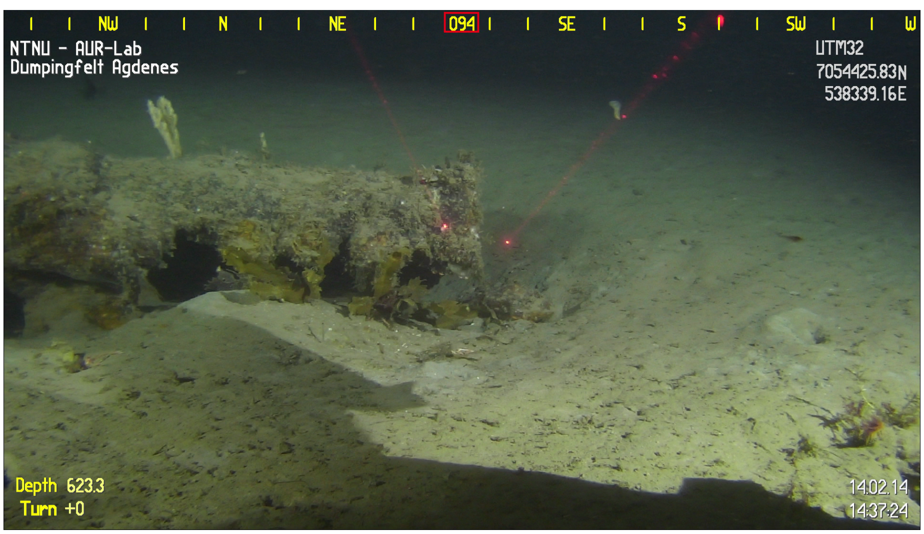

Figure 7: Example of a degraded object. The jagged edges show where this cylindrical object has fractured (NTNU AUR-lab, 2014, 2016).

4.1.3 Density of dumped, man-made objects

The number of objects is the second important characteristic to asses the impact of dumping on the area. In order to yield an estimate of object numbers, two ROV transect lines, approximately 100 m in length and 20 m in width, were performed as a part of the third cruise. The count and density estimate of dumped, man-made objects from these lines is showed in table 2. The mean density of both lines was 56 per 1000 m^2. This would, as shown in Table 4 indicate an approximate total of approximately 100.000 dumped objects in the area. Notably, the difference between the two ROV transect lines is made up entirely by >30cm objects, the count of <30cm objects being the same. 4 of the Category 1 big bombs were found in the transect footage. On the assumption that this figure is representative for the dumping ground as a whole, that would place the total number of bombs at approximately 1500.

A second estimate for the numbers and densities was made using black and white photomosaic camera images obtained with the HUGIN AUV. These images were collected by Håpnes (2016) in the same area and obtained from NTNU AUR-lab for the purpose of this count. The table for all counts can be seen in Appendix D. Averages and estimates can be seen in Table 3. The total estimate from these images can be seen in Table 4. This estimate was higher, at 136,000.

Table 2: Density estimates based on ROV transect lines. The areal coverage of the lines was obtained by multiplying the approximate swath width (20 m) with the exact length of the line, obtained from ROV logs (124 m for line 1, 109 m for line 2).

Line	Large objects count (>35 cm)	Small objects count (<35 cm)	Total area (1000 m^2)	Density (Objects per 1000 m^2)
1	47	65	2.5	47
2	79	65	2.2	66
Both	126	134	4,7	56

Table 3: Density estimate from black and white photmosaic images (Håpnes, 2016).

Images examined	Mean count	Mean area (m^2)	Mean density (Dumped objects per 1000 m^2)
20	2.05	27	74

Table 4: Total object estimates (Data courtesy of (Håpnes, 2016; NTNU AUR-lab, 2014, 2016)).

Source	Density estimate (per 1000 m^2)	Total area (km^2)	Total object estimate
ROV lines	56	1.83	101,889
HUGIN AUV images	74	1.83	136,269

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4.2 Community of organisms

Due to the nature of video footage as a source of data, the survey of the community in the dumping ground is limited to species and groups that can be seen and identified from frame grabs. The most common sessile taxa in the study area were horny corals, anemones, sponges and brachiopods. Decapod crustaceans were the most common taxa of motile animals. A total of 32 different organisms were identified based on video footage, listed in Table 5.

A detailed survey of 49 substrate objects was performed using images from screen grabs. The results of this survey was a list of the numbers and species of all the identified individuals or colonies of 14 common groups in the survey, arranged by the objects they were found on. This detailed list can be seen in Appendix B. Histograms of the most prominent taxa in this data have been collected in Figure 9. The footage from Cruise 3 has not been used for this, as the difference in lighting as a result of a lamp malfunction made identification much more difficult in images from this cruise. Including it would skew the results in favor of larger, more easily identified species.

What follows is an overview of the groups in the dumping ground. The species seen on the body of the dumped bus appeared sufficiently distinct to be treated separately, and are described at the bottom of this section. A few groups accounted for most of the individuals found in the survey, and will be listed first.

4.2.1 Common sessile taxa

Of the sessile organisms, the horny corals *Paramuricea macandrewi* and *Duva florida* were prominent. Both were found in high numbers and one of the two was present on most of the larger objects in the study area. Their distributions can be seen in Figure 9. As the figure shows, 21 colonies *Paramuricea macandrewi* were found on 17 objects and 66 colonies of *Duva florida* were found on 25 objects. In total, 36 of the 49 objects hosted one or both the two species. *Swiftia pallida* was less common, but could be found on several objects. The latter species manifested with two different structures. Some colonies had a single attachment point supporting a larger, branched colony, but in other cases there appeared to be several, unbranched colonies growing in close proximity. The last horny corals identified were *Primnoa resedaeformis* and *Paragorgia arborea*. These were rare on most of the objects, with only a single observation of *P. resedaeformis*, but proved to be very more common growing on the bus, as outlined below.

Sponges were also very common. They were often difficult to identify, but at least four separate types were observed. These were *Geodia* sp., *Mycale* sp., *Phakellia* sp. and an unidentified yellow encrusting sponge. Anemones were very widespread, both on hard substrate and inhabiting tubes on the soft bottom in-between objects. Last of the sessile groups common in the survey area was Brachiopoda, with *Hemithiris psittacea* being present on many objects, often in very high numbers. Only a single individual of a different brachiopod clade, namely *Terebratullina sp.*, was found.

4.2.2 Common motile taxa

Decapod crustaceans were dominant among the motile groups in the study area. Squat lobsters were observed in high numbers associated with almost every object. Two species were found to be present: the larger ($\tilde{7}$5mm)(Moen and Svensen, 1999) long fingered *Munida sarsi*, and the smaller ($\tilde{2}$5mm)(Moen and Svensen, 1999), pale *Munidopsis serricornis.* These were found in great numbers (152 in the detailed survey) associated with the various dumped objects. The latter species featured prominently also on the bus. *Calocaris macandreae* were seen in the sediment occasionally peeking out of characteristic burrows and the presence of the species was seen indirectly in the form of burrows. Shrimp, most likely *Atlantopandalus propinqvus*, were associated with most of the surveyed objects. They were most often observed in stationary positions on top of the objects.

4.2.3 Other taxa

Taxa on the smaller end (Approxmately 20 mm) of the spatial scale that could be detected were likely present in much higher numbers than seen in the video. This category includes the chalk tube-building polychaete *Filograna sp.*, brittle stars (Ophiura) and goose barnacle (*Scalpellum sp.*). The first two of these appeared to be distributed throughout the study area and the last appeared to colonize particularly exposed parts of some objects, such as protruding wires.

Other species found in small numbers were the echinoderm *Stichopus tremulus*, which was found both on the soft bottom and in association with the dumped objects, sea pens (*Virgularia mirabilis*), bivalves (*Acesta excavata*), hermit crabs (*Pagurus. sp.*) and goose barnacles (*Scalpellum sp.*)

Several fish were observed on different occasions. The observed species were rabbit fish (*Chimaera monstrosa*), saithe (*Pollachius virens*), cusk (*Brosme brosme*) and a ray (Superorder Batoidae).

4.2.4 Soft bottom fauna

The focus of the study is the organisms associated with the dumped objects. Still, the surrounding soft-bottomed areas feature prominently in the source footage. Generally, the fauna in the soft-bottom is not seen directly, but rather observed through the presence of bio-turbation, holes in the sediment. These holes form the entries and exits to the burrows of the soft-bottom fauna. A single of these burrowing species was observed directly: the aforementioned large (5cm) (Moen and Svensen, 1999), burrowing, decapod crustacean *Calocaris macandreae*. The burrows made by this species was easily distinguished from others due to their greater (5 cm) size. Smaller holes were present throughout. These were likely the burrows of different species of polychaete worms. One of the anemones was also part of the soft-bottom assemblage. The disc and tentacles of this anemone was observed emerging from a sandy tube sticking out of the bottom. The red sea cucumber *Stichopus tremulus* was found on the soft-bottom as well.

4.2.5 The Bus Assemblage

The assembly of organisms associated with the dumped bus chassis and bodywork was different than that of the other dumped objects in many ways. Like the smaller objects, the bus was colonized by horny coral. The species composition, however, was different from that found on the other objects and on the soft bottom. On the bus chassis, the most prominent species were bubblegum coral, *Paragorgia arborea* and *Primnoa resedaeformis*, the first of which was not found on other objects at all, and the second of which only a single other colony was attested. In addition, the basket star *Gorgonocephalus caputmedusae*, commonly associated with the mentioned horny corals, was observed. All three species can be seen in Figure 8. Another echinoderm taxon, *Henricia* sp., was also observed on the bus.

4.3 Other findings

The water in the area was dense with particulate matter, seen by ROV video. A lot of these were in the form of marine snow, unidentifiable particles, but it was possible to briefly discern larger planktonic lifeforms in the video. Somewhat surprisingly, benthic macroalgae were common in the study area. Several man-made objects had pieces of macroalgae of the class Phaeophyceae (brown algae) attached to the underside. Additionally, large specimens of *Desmarestia* sp. and whole specimens of the kelp *Saccharina latissima* were observed sliding along the seafloor.

Table 5: The organisms detected with ROV in the dumping ground by class. Names are down to the lowest taxonomic level. The criteria used to grade "Rarity" were: Rare: organisms present on <5 dumped objects or <10 observed specimens, Common: present on >5 dumped objects and <50 observed specimens, Very Common: >50 observed specimens. Fish were not graded (N/A)

Name	Rarity	Environment	Notes
Demospongiae			
Mycale sp.	Common	Dumped objects	
Geodia sp.	Common	Dumped objects	
Phakellia sp.	Rare	Dumped objects	
Yellow encrusting sponge	Common	Dumped objects	See Appedix A
Anthozoa			
Duva florida	Very common	Dumped objects	
Paramuricea macandrewi	Common	Dumped objects	
Swiftia pallida	Common	Dumped objects	
Primnoa resedaeformis	Rare	Bus	Also rarely on dumped objects
Paragorgia arborea	Rare	Bus	
Virgularia mirabilis	Rare	Soft bottom	
Anemone A	Very common	Dumped objects	See Appedix A
Anemone B	Common	Dumped objects & bus	See Appedix A
Anemone C	Common	Soft bottom	See Appedix A
Anemone D	Rare	Specific object	See Appedix A
Anemone E	Rare	Dumped objects	See Appedix A
Rhynchonellata			
Hemithiris psittacea	Common	Dumped objects	
Terebratullina sp.	Rare	Dumped objects	
Malacostraca			
Munida sarsi	Very common	Dumped objects	
Munidopsis serricornis	Common	Dumped objects & Bus	
Calocaris macandreae	Common	Soft bottom	Also observed indirectly by holes in the seafloor
Atlantopandalus propinqvus	Very common	Dumped objects & Bus	
Pagurus sp.	Rare	Dumped objects	
Scalpellum sp.	Rare	Specific object	
Bivalvia			
Acesta excavata	Rare	Dumped objects	
Holothuroidea			
Stichopus tremulus	Rare	Dumped objects & soft bottom	
Asterozoa			
Unid. Ophiuroid	Common	Dumped objects	
Gorgonocephalus caputmedusae	Rare	Bus	
Henricia sp.	Rare	Bus	
Polychaeta			
Filograna sp.	Common	Dumped objects & bus	
Actinopterygii			
Brosme brosme	N/A	Under objects	
Chondrichthyes			
Chimaera monstrosa	N/A	Water column	
Rajidae	N/A	Along seafloor	

Figure 8: The species associated with the bus. Several specimens of *Paragorgia arborea* can be seen lining the windows. *Primnoa resedaeformis* can be seen to the right. The Basket star *Gorgonocephalus caputmedusae* can be seen attached to the bar between the windows in the center (NTNU AUR-lab, 2014, 2016).

The presence of strong currents as a defining feature of the area was reaffirmed during the cruises. The currents were observed and experienced in several ways. The influence on the ROV was observed directly, as constant side-currents made piloting difficult, at times to the point where the survey had to be put on hold to regain control of the vehicle. Directional movement in the upper layers of the water column were detected as drag on the ROV umbilical. The effect of currents on suspended objects could also be observed on the marine snow at the site, which was in constant high movement. Several large macroalgae were observed "gliding" along the seafloor in the survey area, their presence a strong indication of transport from surface areas to the seafloor, and their movement a testament to the activity at the seafloor.

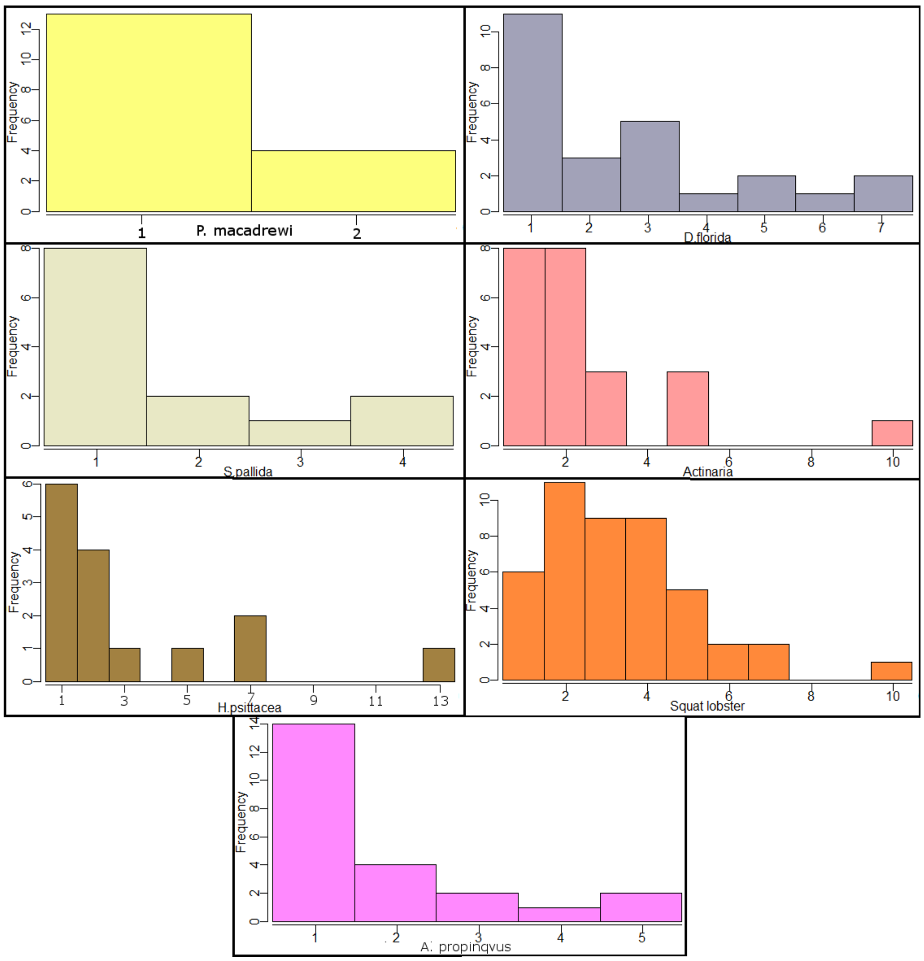

Figure 9: Histograms of the distributions for different taxa in the detailed survey of 49 substrate objects. Due to uncertainty in classification, counts for anemones and squat lobsters have been grouped by category.

5 Discussion

5.1 Types of man-made objects

As shown earlier, the makeup of objects of human origin in the dumping ground was found to be quite varied. One of the aims of this thesis is to properly characterize the bombs and other dumped man-made objects in the area and the possible risks associated with them. This will start with a discussion on the types of dumped objects that were found.

5.1.1 Large bomb

Because of their size and distinctive feature, the large bombs were easy to boradly classify. The length of the large bombs was estimated using frame grabs from video with the ROV laser ruler. This was performed by using a image-processing program to measure the number of pixels between the nose and tail of the bomb and the number of pixels between the two reference dots of the ruler, known to be 10 cm apart. The length of the measured bombs was determined to be approximately 140 cm. This length would place the bombs in one of several classes of 250 kg munitions (Bergin et al, 1953). The presence of braces on the tail-fins of many bombs would further indicate they belong in these classes of munitions. The classes and their known fillings are listed in Table 6. Figure 10 shows a picture of a SC250 bomb next to one of the objects found in the dumping ground.

Table 6: The different classes of German bombs which match the dimensions of those in the dumping ground and their fillings (Bergin et al, 1953)

Type	Known filling
SC250	60/40 Amatol/TNT, TNT, TNT and wax, TNT and woodmeal and aluminium powder and naphthalene and ammonium nitrate
SD250	TNT
SBe250	Ammonium nitrate with small amounts of woodmeal and aluminium and a column of TNT pellets
C250	Oil incendiary mixture and TNT
CE250	Oil incendiary mixture and TNT

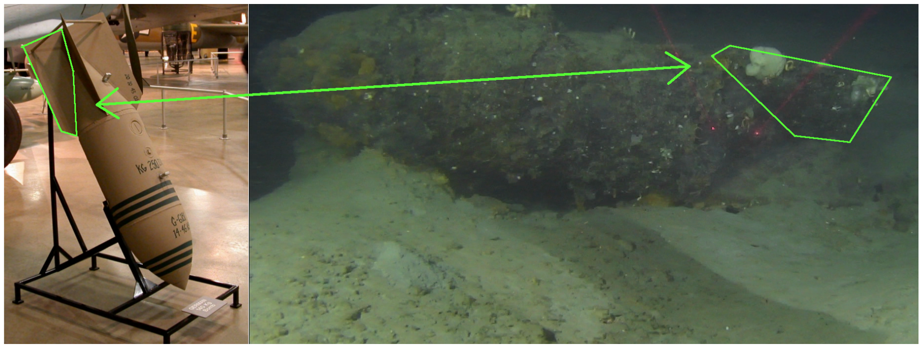

Figure 10: German SC 250 bomb (Goebels, 2004) next to an image of one of the bombs in the dumping site (NTNU AUR-lab, 2014, 2016). Note the general shape of the tail fins.

5.1.2 Small bomb

The smaller bomb-like objects shown in Figure 5 are more difficult to identify. The shape and overall appearance indicates artillery or mortar shells. The length of one such object was estimated with the same method as the large bombs to approximately 50 cm. This is much larger than a mortal grenade, which means artillery shells are the best estimate. There is a very high degree of uncertainty attached to this classification. If correct, the fillings would likely be TNT or amatol (Bergin et al, 1953).

5.1.3 Other objects

Compared to the large bombs, other man-made objects are either less common or less distinctive in their shape. This is a result of most objects being smaller. This both makes their shape harder to distinguish and magnifies the distortion caused by corrosion and wear. Many square objects were found. These are likely boxes, but any statement on their contents would be speculation.

5.1.4 The Bus

At the end of cruise 2, an object was discovered at 63.5061°N, 9.2009°E that was larger than even the big, 250kg bombs by an order of magnitude. This object turned out to be the chassis and body of a bus. This bus played a large part in the media interest in this project, expanded upon later in this chapter. As a result, its origin and the story of how it came to be dumped in the fjord was explored by Addresseavisa, a local newspaper (Lervik, 2016). The bus, a Volvo B57 1970, was dumped in the early 1980s by Fosen Trafikklag, a transportation company, after being stripped of its engines and window panes (Lervik, 2016).

5.2 Species composition of the community

The most striking result of the dumping activity and the presence of these objects in the area is perhaps the abundant presence of life using these hard objects as substrate.

A considerably higher diversity of species was observed among sessile organisms than among motile. Of the 32 observed organisms, 21 were sessile and these were distributed among 7 classes, with many species of sponges, and horny corals and anemones. Furthermore, species from these groups and the brachiopod *Hemithiris psittacea* were all, as can be seen in Figure 9 and Table 5, fairly common. In comparison, the motile fauna was found to be dominated, at the scale of this survey, by decapod crustaceans. Two species of squat lobster and one of shrimp, *Munida sarsi*, *Munidopsis serricornis* and *Atlantopandalus propinqvus*, accounted for almost all the observed individuals in this category. On larger and smaller spatial scales, the picture is a little more varied, however. On the smaller end, a yellow ophiuroid was one of the smallest species recorded, and likely under-counted as it was at the very low bounds of what could be detected. At the larger end of the scale, several fish species were recorded. These likely play an important role in the ecology of the community.

One way to account for this disparity in diversity is in the inherent difference between the two categories. Because they don't move, sessile organisms are more dependent on specific properties in their immediate surroundings, such as current strength and the roughness and angle of the substrate. This means there is room for different species which prefer slightly different conditions. For motile groups, these differences are less pronounced, leading a few strong competitors to dominate.

5.2.1 The detailed survey and species distributions

Of the 32 different species or groups found, most were either too difficult to identify or too rare to be included in the detailed survey, which focused on the most common and conspicuous species and groups. In order to discuss the community and its constituents beyond simply presence/absence, quantitative data is crucial. The detailed survey and the histograms presented in Figure 9 are the best quantitative information on species distributions and provide the best basis for understanding the distributions and dynamics in the area.

As Figure 9 shows, the distributions of individuals on substrate objects is fairly similar for the most numerous groups. This is a result of the method used to produce them. As stated, these histograms were produced using data from species counts. The species counts were made by counting the individuals or colonies present of each species on each substrate object. Counts like this one fit the definition of a Poisson process (Løvås, 2013). Because of this, it is expected that the resulting counts follow the Poisson distribution. The histograms in Figure 9 appear to be consistent with this distribution. This indicates that the count can be considered sound.

Looking at the species distributions in the histograms of Figure 9, an obvious feature is the dominant presence by number of individuals of squat lobsters in the survey. This taxon has the most observations and is the only taxon where the most common count of individuals on a substrate object wasn't 1. Notably, for this species the counts are grouped quite tightly around the mean compared to other, less numerous groups. This might be explained by the squat lobsters seeking to avoid overcrowding, putting an effective upper limit to their numbers on any one object. Another notable species distribution is that of the horny coral *Paramuricea macandrewi*. This species is widespread, but never numerous on any single substrate object. This is different from the other distributions, which are fairly similar and have patchy distributions with strong presences on a limited number of substrate objects and a low presence on many. The lower patchiness of *P. macandrewi* will be further examined below.

5.2.2 The bus assemblage

The community of organisms found on the bus was different from that found on the bombs. This was most prominent for the sessile groups, and horny corals in particular. The bus was overgrown with the large bubblegum coral (*Paragorgia arborea*) along with the associated basket star, *Gorgonochephalus caputmedusae*, and the smaller *Primnoa resedaeformis*. The latter horny coral was found only on one other dumped object, making it very rare except for on the bus. *P. arborea* and the echinoderms *Henricia* sp. and *G. caputmedusae* were not observed at all except attached to the bus. In addition to hosting new species, some otherwise common organisms were absent on the bus. These were the horny corals that were common on the other objects, *D. florida* and *P. macandrewi*, which were completely absent on the bus chassis, and *Munida sarsi*, the largest of the squat lobster species.

With the difference in species compositions firmly established, the next question that needs to be addressed is what distinguishes the bus as substrate. One possible difference was the material it was made of, because different materials might differ in their textures as substrate. Interviews with businesses which had produced the bodywork for such buses confirmed that the chassis of bus is likely made of the same material as bombs casings, steel, but that the bodywork of the bus, which is where most of the organisms were found, is aluminium. There might be a difference in their properties as substrates which could explain the difference in coral communities between man-made object types.

A distinctive feature of the bus is the great size. This has effects on its properties as a substrate by giving it a more elevated position from the seafloor. This likely entails a difference in current conditions. The growth of organisms on the bus is most prominent around what used to be the windows. The corridors provided by the windows can be assumed to be areas of high water flow, which would explain their status as the "hotspots" for colonies. Previous studies on the horny coral species in the community growing on the bus, *P. arborea* and *P. resedaeformis*, have found that the former prefers the top of rocks and the latter the sides (Mortensen and Buhl-Mortensen, 2005). On the chassis of the bus, however, these coral species grow side by side in what appears to be similar areas. This discrepancy is likely a result of their common preference for these window areas.

There are other factors to consider of remoteness from the seafloor. It is possible that there is a higher load of inedible sediment, whirled up by currents or the movement of animals, in the water flow closer to the bottom. An elevated position like that provided by the bus would avoid these inedible particles.

The last factor to consider is possible biological control. For this to be responsible for the difference in horny coral species would require both a predator that suppresses *P. macandrewi* and *D. florida* on the bus and a predator that suppresses *P. arborea* and *P. resedaeformis* on the other dumped objects. Since neither of these predators were found, this can be considered an unlikely explanation.

5.2.3 *P. macandrewi* and *D. florida*

The makeups of the community on the bus and the community on the rest of the dumped objects were not the only cause of difference between the distributions of horny coral species. The two most common species of gorgonian coral, *D. florida* and *P. macadrewi*, also showed differences in their patterns of distribution. Both were fairly common, with *P. macandrewi* found on 17 man-made objects and *D. florida* on 25. The big difference was in how many specimens could be found on a single dumped object. As can be seen in Figure 9, no object in the detailed survey was found to have more than 2 colonies of *P. macandrewi* attached. *D. florida*, on the other hand, was frequently found many times on the same object. Compared the distributions of other species seen in the figure, that of *P. macandrewi* seemed to differ the most.

The perhaps simplest idea to explain the lack of more objects with many colonies of *P. macandrewi* would be that the species showed a preference for small objects, and that the substrate simply wasn't large enough to accommodate more colonies than two. This explanation was dismissed after looking at the colonies in the source footage found no such relationship. Other findings were uncovered by that survey, however. The species appeared to have a very strict preference for vertical orientation of colonies, with all the specimens except for one found growing in such a pattern. It also seemed to strongly favor the highest points of the substrate, 18/21 colonies in the detailed survey being on top of the dumped objbect they were found on. There was a notably low incidence of *P. macandrewi* and *D. florida* in association with the same substrate. In fact, only 6 of the 49 man-made objects included in the detailed survey were found to host both species. The low coincidence of the species was judged to be worth exploring further.

In order to investigate this low coindcidence, a subset was made from the detailed species data using the counts for the species in question and the substrate objects with at least one colony from one of the species attached. Using the subset as data, a correlation coefficient was estimated by the R Software. This coefficient can be seen in Table 7. The printout from R software can be seen in Appendix C. If there was no relationship between the species, a weak positive correlation would be the expected outcome. This positive correlation would be the result of the unaccounted for difference in size between objects. If there are no other forces in play, the size of an object should be expected to weakly predict the average number of both *D. florida* and *P. macandrewi* colonizing it. This was not what was found. Instead, the estimate was a negative correlation between the two species. This means that the species occur together less frequently than expected.

In order to further corroborate these observations, the video from Cruise 3, which was not included in the detailed survey used as a basis for the correlation estimate and the histograms in Figure 9, was used to make a second dataset containing observations of *D. florida* and *P. macandrewi* only. This second set, attached as Appendix C, was used first on its own and then together with the first set to make histograms of the distributions of species and to produce new correlation estimates. A collection of the histograms for both datasets and a consolidated set can be seen in Figure 11. The results of the three correlation tests run with the same sets can be seen in Table 7.

Table 7 shows that the data from Cruise 3 generated an estimate similar to that of the original data. The two sets combined yielded an estimate very close to that of the original data. For the correlation estimate, at least, the newly collected data seems to confirm the original conclusion that *P. macandrewi* and *D. florida* prefer different substrate objects.

Table 7: The results of estimates for the correlation between *P. macandrewi* and *D. florida* on surveyed objects. The table shows estimates from the detailed survey data collected Cruises 1 & 2, new collection of data from Cruise 3 and a consolidated set. Both sets provided negative estimates, indicating that the species prefer different substrate objects. The estimate from the consolidated dataset is much closer to that from Cruise 1 & 2 than Cruise 3, which might indicate that this data is more representative.

Source data	Correlation estimate
Cruise 1 & 2	-0.3123673
Cruise 3	-0.3755713
All cruises	-0.3125104

There are two likely explanations for this relationship. Either the species prefer different substrate textures or current conditions and colonize different objects as a result, or there is some form of competitive exclusion. The cover of coral on the objects in the survey does not appear dense to the point of preventing new colonies from establishing, so exclusion does not appear likely. That leaves different preference as the best explanation for the negative relationship between the presence of *D. florida* and *P. macandrewi*.

Moving on to the distributions seen in the Figure 11, the impact of more data seem to have different effects on the apparent distributions of the two species. *P. macandrewi* seems to have similar distributions in both samples. Although a single object hosting three colonies has appeared, the overall distribution is relatively unchanged. *D. florida*, however, has very different distributions in the two samples. In the original data, this species has a long-tailed distribution, with two objects hosting seven colonies. In the new dataset, it has a distribution much closer to that of *P. macandrewi*, tapering off very quickly and ending at 4 observed colonies. This is likely a result of of the difference in lighting in the videos used as source material and the slight transparency of the species. Small colonies can be difficult to see clearly, and may not have been observed in the darker video.

Returning to the question which prompted this investigation, what can explain the lack of dense groups of *P. macandrewi*? One explanation could be very strict habitat preference, but this would limit more severely the total number of colonies as well as the numbers on each object. Another explanation could be a very strong preference for a position on top of objects. This is where the species was most often found. This was also the case for *D. florida*, however, and that

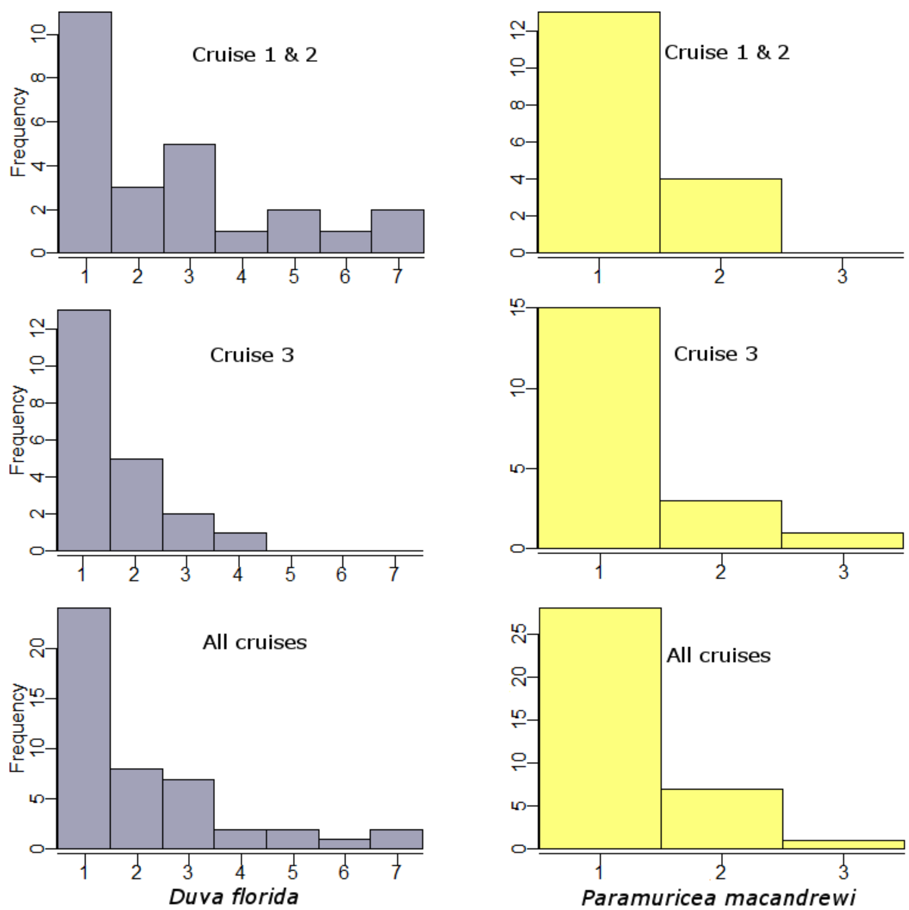

Figure 11: Histograms of the distributions of *D. florida* and *P. macandrewi* specimens on 49 substrate objects in Cruises 1 & 2, new collection of data from 37 substrate objects in Cruise 3 and a consolidated set. Specimen numbers on the X axis and frequency of observations on the Y axis.

species did not have the same short-tailed distribution. Another possibility is mis-identification of small colonies as *S. pallida*. The species were at times difficult to distinguish in the images from Cruise 3. In cruise 1 & 2, however, the difference in colour and growth form was much easier to spot, and there were no noticeable difference in distribution on this cruise, so this can be considered a fairly small source of uncertainty.

5.3 The basis for the community

In order to thrive, the species in the community found on man-made objects need two basic necessities to be present in the environment: A hard substrate to attach to and an adequate supply of food. The hard substrate is, as revealed by the survey and illustrated in Figures 5, 7 and 10, provided by the man-made objects dumped in the area. The missing piece, then, is to account for the food source, and as the next step to understanding the dynamics of the habitat, the food supply to the benthic organisms on the site will be the next point addressed.

5.3.1 Food supply

Throughout all cruises, frequent observations were made of brown macroalgae (Phaeophyta). Large pieces or whole specimens of the kelp species *Saccharina latissima* and *Laminaria digitata* and of others, such as *Desmarestia sp.*, a thread algae, were found. These specimens were observed both sliding along the seafloor and attached to the objects. The dumping ground, at 600 m depth, is far below the photic zone where photosynthesis could sustain these organisms. In fact, according to Geir Johnsen, professor at NTNU, kelp forests are rarely found below 10 m in this area. Because they can not sustain themselves, one would not expect find algae in the area under normal conditions.

Strong currents were expected and observed during the cruises, and is theorized to be the eroding force that prevents dumped objects from being buried in sediment, as the next section will show. These currents, particularly the vertical system, also explain the presence of macroalgae in the dumping ground, as they cause transport from upper layers of the water column down into the deep. Macroalgae were likely the most easily seen of the matter transported in this fashion due to the size of individuals. With their presence as evidence of the transport of large organisms, it can be assumed that transportation of smaller organisms takes place as well.

There also appear to be strong horizontal currents, likely driven by tidal forces (Carstens, 1975), in the dumping ground. These currents keep food particles suspended and in motion, preventing sedimentation. This means food particles are available for filter feeding organisms like anemones and coral, further ensuring their food supply.

5.3.2 Substrate and erosion

The defining feature of the surveyed hard-bottom benthic community in an otherwise soft-bottomed habitat in the dumping ground is the hard substrate that is provided by dumped, man-made objects. Hard substrate is a basic necessity for the horny corals, sponges and other species that constitute this community. While the presence of hard substrate has been shown, it is worth investigating what mechanisms work to prevent this hard substrate from being buried in sediment. The expectation when these objects were dumped was likely that sedimentation would happen, that the dumped objects would be buried, and that the bombs and munitions could be ignored thereafter. Evidently, this has not occurred. Because of the geographic location of the dumping ground, at the bottom of a soft-bottomed basin, we can assume that sedimentation is ongoing in the area. What remains to be explained is why that process has not led to the dumped objects being buried. The continued presence is evident from the images that form the basis for this project, so one can infer that something is removing sediment at the same rate it is being deposited, and that this erosion is the reason the dumped objects are still exposed 70 years after deposition (Bøe et al, 2000). The Norwegian Geologic Survey (NGU) makes several notes of erosion as a force that shapes this part of the fjord (Bøe et al, 2000).

The most likely force behind this erosion is the currents in the area. The presence and strength of currents have been described. The transport of other food from the surface has also been seen, and it is a reasonable inference that a similar transport of sediment could occur. This transport would explain the erosion.

5.4 Risk assessment

With the most likely candidate classes for the bombs in the dumping ground determined, the list of contaminants they may contain becomes significantly shorter. The bombs listed in Table 6 are known to contain the following explosives: 2,4,6-Trinitrotoluene (TNT), Amatol (a mixture between TNT and ammonium nitrate), ammonium nitrate and possibly naphthalene and aluminium. Additionally, the possibility of incendiary bombs was not ruled out. These devices contain an oil-mixture as well as TNT. The initiators of the bombs may contain mercury and lead (Bergin et al, 1953; Bydal et al, 2012).

Ammonium nitrate is commonly used as a fertilizer (Olsen et al, 2014). High runoffs of fertilizers like ammonium nitrate can cause eutrophication, runaway growth of microalgae. The size of the Outer fjord basin means it would take tens of thousands of tons to cause such growth. The volumes that might be present in bombs are many orders of magnitude too low to have that sort of impact (Smith et al, 1999; Carstens, 1975), which means leaks of this compound are not a hazard. The health and environmental effects of TNT are also well-studied. The toxicity of TNT to humans is well-established, mostly in cases of accidental ingestion in production facilities. After ingestion, the compound damages the liver and blood (EPA, 2014). It also has carcinogenic properties (EPA, 2014). As a pollutant, the potential harm caused by TNT is limited by the high rate of absorption in soils and biota. The compound is broken down rapidly in the livers of animals and as a result, it does not accumulate in the food-web (EPA, 2014; Bydal et al, 2012). The last compound that might be present in quantity is the "oil-mixture". The toxicity of this component depends on what the unnamed constituent oils are. Many hydrocarbons are quite toxic and there is potential for these to pose a threat to the environment (Schmidt et al, 2000). Experience from releases of hydrocarbons on larger scales have shown that these compounds usually degrade rapidly, the exception being if they form dense accumulations (Atlas, 1995). The formation of an accumulation is judged to be very unlikely given the relative difference between the volumes of bomb contents and the volume of water in the basin. The last compounds listed in Table 6 are likely present in small amounts if at all. These are wax and aluminium, both of which are inert and pose no risks to the environment (Frank et al, 2000; Krendlinger et al, 2000), and naphthalene. Naphthalene is similar to TNT as a possible pollutant; it has toxic effects if ingested in high concentrations, but is broken down quickly in the tissues of organisms and does not accumulate in food webs (Collin et al, 2000). Because volumes are almost certainly very small, the potential damage due to toxicity from a small leak is low.

Because of the relative volumes of the bomb contents and the fjord basin, the potential toxicity in the event of a leak appears to be very limited. The added factor of strong currents ensures that any leaking substance, be it TNT, oil-mixture or ammonium nitrate, will be diluted quickly into the very large volume of the basin. The threat of toxicity would then be limited to organisms located in the direct path of the leak or attached to the leaking object. This, along with the potential of these lifeforms to help detect such leaks, is discussed in more detail in the next section.

The larger danger is the risk of an inadvertent or accidental detonation. There is no reason to assume that the bombs are not still capable of detonation. The effect of wear and corrosion is varied and unpredictable, which means the bombs have to be considered highly unstable and dangerous. Fortunately, the great depth makes the risk of injury to humans exceedingly unlikely, unless the bombs are brought up to the surface and handled. The risk is present for any equipment used to study the area (for instance in this project) and to the biota associated with the bombs, particularly if techniques that involve direct contact with the objects are employed and the bombs are disturbed.

5.5 Bioindicators

One way to detect a change of state in the dumping ground and the potential risks it might involve is to use the organisms in the associated community as bioindicators, organisms that are used as sources of information on their environment.

5.5.1 Horny coral as bioindicators

Horny corals have been found to grow to great ages (>250 years for *P. resedaeformis* (Watling et al, 2011)). Specimens of species found as a part of this survey, *Paramuricea* spp. and *Primnoa resadaeformis*, have been found that were over 100 years old (Watling et al, 2011). It is a sessile group, and has several common species in the dumping ground. These characteristics make the group a potential source of bioindicators. The sessile nature of the organisms mean that their environment is fixed, and their passive mode of feeding means that they are ”forced” to consume whatever is available in the water column, including, if present, pollutants. The long lifespans of colonies could provide a view into the past, and the ages of large colonies can possibly provide minimum estimates for the age of the community.

There are also several challenges with using these organisms. Because they are attached to the bombs, sampling will be very difficult without disturbing the potentially volatile explosives within. Unless this challenge can be solved it will be unfeasible to detect pollutants directly. This would limit the observer to passive modes of observation which limits information to what can be inferred from visual observation. Still, looking at the sizes and potentially the deaths of colonies could provide some information. The second challenge is the organisms metabolizing pollutants. As the risk-assessment revealed, the most potent possible pollutant, TNT, is broken down rapidly in animal tissue. This means that an organism that was present during a leak will not contain the compound if tested after the leak has passed.

5.5.2 Bioturbation as bioindicator

The video shows a high incidence of holes in the sediment. These holes are the homes of burrowing organisms. Burrows of organisms evidenced by holes in the seabed are called bioturbation. The high incidence of these organisms is explained by the same factors outlined above, the transport of organic matter by strong vertical and horizontal currents.

Investigations by the Norwegian Defence Research Establishment (FFI) (Rossland et al, 2010) found that concentrations of energetic compounds in sediments can exceed threshold values by an order of magnitude in areas where the levels in surrounding waters are below the threshold. The presence or abscense of burrowing organisms, given their high grade of exposure to any pollutants in the sediment, can therefore be an important indication of a leak.

It is difficult to gauge the sensitivity of such an approach without precise data on the impact on sediment dwellers of leaks. What speaks for this method is the ease of performing it. Compared with methods involving physical sampling and lab analysis, going through video footage to look for areas with less or no bioturbation is much less time and resource-intensive.

5.5.3 Algae as bioindicators

One of the findings in the survey was widespread presence of brown algae, kelp in particular, in spite of the depth of the location. Brown algae are dependent on photosynthesis for energy and are generally found in the lower tidal and subtidal zone. Kelp species are, however, known to survive and even grow in dark periods for several months, for instance during the arctic polar night (Berge et al, 2015).

Lacking the root systems of land plants, algae absorb nutrients directly from the surrounding seawater. Because of this mode of absorption, algae tend to absorb is available in the surrounding water, whatever compound that may be (Kleiven, 2014). In the case of heavy metal contamination, for instance, the presence of trace metals in algal tissues increases over time, old tissue contains much more trace metal than young tissue, and algae has been shown to remove heavy metals from solution (Volesky and Holan, 1995). This tendency was confirmed to apply to energetic compounds by the Norwegian Defence Research Establishment (FFI) during the disposal of a mine from Tælavågen near Bergen. Seaweed growing on the mine was found to have concentrations of HMX, RDX and TNT considerable higher than surrounding seawater (Rossland et al, 2010).

Sampling of macroalgae, then, might be more effective than sampling the surrounding water as the higher concentrations in algal tissues will make testing more sensitive. Furthermore, testing of water masses will need to precisely coincide with a leak in order to detect it, since the released compounds will be immediately diluted by the strong currents on the site. The compounds will persist, however, in algal tissues. This means algal sampling has the potential to detect past or intermittent leaks, as well as ongoing ones. This might make sampling of algae more sensitive than sampling of water, because concentrations are higher and less reliant on the leak and survey coinciding in time. Lab analysis such as mass spectroscopy may be used to obtain further information about the composition of inorganic compounds such as heavy metals, using data gathered by Kleiven (2014) on the background concentrations in the Trondheimsfjord as a baseline.

Using the algae already present in the area has several downsides. Firstly, obtaining samples would involve getting perilously close to explosives. If an explosive was to go off, that would destroy the organisms attached to it, endanger expensive equipment and release in one burst every potentially hazardous compound it contained. Secondly, the deposition of these algae is random in nature, and there is no reason to assume they will be present to a sufficient degree in places of interest. A way to address both of these concerns is to instead introduce new algae along with a scaffold to keep them in place, possibly as imagined in Figure 12. This avoids contact with potentially dangerous materiel and enables placement of algae in the positions judged most useful. In addition to reducing risks associated with the bombs, this would allow placement of samples to be systematic, rather than reliant on finding already-present algae in sampling areas.

5.5.4 Comparison of candidate groups

Of the three groups, using bioturbation as a proxy for the viability of an area is the least involved and least sensitive, essentially coming down to presence or absence of the feature. Using horny coral would also be limited to visually gauging the state of specimens, as the compounds of interest are broken down very quickly in their tissues. Only algae can provide information on the leak of explosives. Brown algae do not metabolize TNT and instead store it in higher concentrations than the surrounding water masses (Rossland et al, 2010). Furthermore, the compound likely remains in tissues after the leak ends. This means sampling of algae can provide information on leaks in the recent past as well as present.

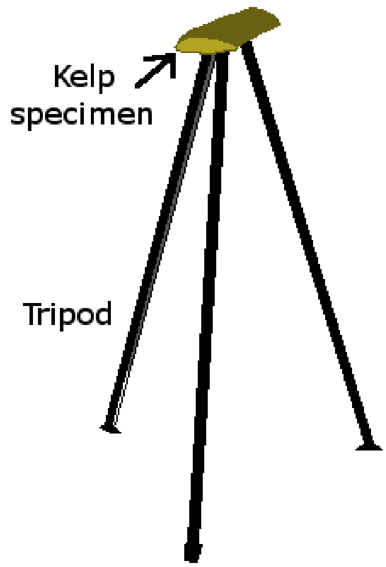

Figure 12: A possible design to introduce algea for use as bioindicators

5.6 Future perspectives

The risk posed to the wider environment of the Trondheimsfjord has been shown to be fairly low. There is also little risk that humans will be adversely impacted by any events in the dumping ground as long as the explosive munitions are not disturbed. In fact, the unexploded ordnance in the area has been judged likely to pose risks only to the community their presence sustains. Should continued surveillance of the dumping ground then be prioritized?

While the ordnance in this particular location does not pose great environmental risks, that is not the case for all dumped explosives in all dumping grounds. As was shown in the introduction, such dumping grounds are widespread throughout the North Atlantic and encounters between people and dumped explosives are anything but rare. If knowledge gleaned both through this project and as parts of potential future surveys transfers to other sites there is still potential to reduce harm to people and environment. Such knowledge will include how long the bombs can remain underwater before corroding to the point that they start leaking and particularly whether and to what degree the use of organisms as bioindicators will be a useful method to detect such leaks.

Furthermore, the community associated with the bombs holds interest both by its presence in an area which, without human interference, would likely be void of hard substrate and as a snapshot of colonization and succession in deep-water locations. The course of this process in the dumping ground might mirror other locations. These are not limited to other munition dump sites. Several offshore economic activities, for example, involve the placement of large, solid installations on the seafloor. Managing the colonization, also known as bio-fouling, of these installations by organisms is an important part of maintenance. It is projected that new ways of exploiting the seas, for instance for power generation, could significantly increase the number of installations like these (OECD, 2016). If this becomes the case, finding safe ways to manage fouling will be even more important. Understanding the processes, seeing the results and having access to a wealth of data will be key in that endeavor.

5.6.1 Media interest

During cruise 2, the project team was accompanied by a journalist from the NTNU online magazine, Gemini (Bazilchuk and Leite, 2016). This journalist took an interest in the dumping ground, and published a feature. After publication, this feature was picked up by the Norwegian Broadcasting Corporation (NRK) (Krüger, 2016), Addresseavisen (Bjørgan, 2016; Lervik, 2016) and the Danish Broadcasting Corporation (DR) (Kokkegård, 2016). This high level of media interest shows that the narrative of dumped war materiel becoming substrate for marine life appeals to the public.

5.7 Evaluation of methods and procedures

5.7.1 Limitations of video as a single source of data

The main strength of non-invasive video as opposed to physical sampling is that it does not rely on the same level of proximity. This is the reason video was chosen for this project and why physical sampling was not performed. The risks to equipment if it was to handle potentially volatile bombs were judged to far outweigh the value of potential discoveries made through sampling. Furthermore, video allows the capture of data from many objects in a relatively short amount of time. Taking multiple physical samples at the depth of the dumping ground involved would have been a time-consuming affair.

The complete reliance of video also came with strong limitations. First and foremost of these was the inability to make definite identification of the different biological species encountered in the dumping ground. This challenge was felt in every aspect of the project. Secondly, using a single source of data meant being locked to a single resolution and spatial scale. The attested presence of a species in the data was more dependent on whether it was of sufficient size to be seen in the video than its actual prominence in the community. This forced single-scale approach with respect to spatial resolution is also a likely source of error, as the population numbers for species on the lower end of the observable size-range are likely underestimated by a significant margin. Species too small to be seen properly in the video have not been surveyed at all. Thirdly, the added variables of random movement in the ROV due to currents and difference in staying time meant that the quality of imaging varied considerably between objects. Loss of quality affected observation at smaller spatial scales more than larger. The resulting lack of comprehensive quantitative data was a big challenge.

The minimum spatial scales for species to be detected by the video can be estimated by looking at the groups which were detected in reasonably high numbers with respect to the sizes of individuals in these groups. Looking back to the species list in Table 5, these would appear to be *M. serricornis*, although the pale color of that species might make it easier to detect than others in the same size range, *H. psittacea*, and the unidentified species of brittle star (Ophiuroid). The shells of the first two and the disc of the last all have maximum sizes of 15-25mm (Thayer, 1975; Moen and Svensen, 1999). This number can be treated as an estimate for the lower end of the spatial scale for organisms to be detected. An important secondary consideration on this issue is visibility. Species with a more cryptic appearance than the mentioned three might be harder to detect, even if it is considerably larger. This might also apply to small specimens of species that are otherwise fairly easy to detect.

This last challenge was experienced directly during the investigations into the relationship between the presence of the two gorgonian corals *D. florida* and *P. macandrewi*. The video from Cruise 3, which had been excluded from the detailed survey due to poor lighting and resulting difficulties in identification, was used to produce a new dataset. In Figure 11, the distributions of these species can be seen for both sets. It is the distribution of *D. florida* that is relevant for this topic. As the figure shows, the distribution of this species is quite different between the two data sets. The set from the cruises with better conditions has a long tail, while the set from Cruise 3 has a much shorter tail, and no observations of more than 4 colonies on a single object. This is likely due to the worse lighting conditions. The colonies of this species are somewhat transparent. This is not really a challenge in the case of larger colonies, because their bulk makes up for this transparency. In the case of smaller colonies, however, it can make them more difficult to see. This is likely what has happened for the new set. Because small colonies are hard to see, these have not been observed. As a result, the counts are skewed towards larger colonies, which are less likely to be numerous for simple reasons of space. This leads to a very different distribution between the two sets and serves as an example of the limitations of the method.

On the larger end of the scale, the method is not limited in what in can detect *per se*, but by the area covered. This was most obvious in the case of the several fishes encountered. The distribution of these fish is far too patchy on the scale of the survey to draw any conclusions beyond acknowledging the presence in the survey area of the species observed. If fish were the subjects of the study, a different set of tools would have to be used, as they were in Håpnes' (2016) study.

5.7.2 Lighting and exclusion of footage from Cruise 3

Illumination proved to be a very important variable. At the depth of this survey, 600 m, there is no natural light. In order to see anything in the recorded video, it is therefore crucial to provide illumination. The ROV used in this survey used two lamps to do this. For one of the three cruises one of these failed. The resulting difference in illumination meant the footage from this cruise had to be treated differently. This reduction in density and evenness of illumination meant that the smaller species in the survey were much harder to distinguish than in the well-lit images, essentially losing resolution on the smaller end of the spatial scale. Because observations of species composition was different and judged to be worse than the images from the other cruises, Cruise 3 was not included in the detailed survey. The later use of the images to corroborate information on *D. florida* appeared to provide a different distribution than that previously found, suggesting a loss of detail also for one of the largest species in the survey.

5.7.3 Diversity indices

There are several ways to quantify the variety within a biological sample. One of these methods are diversity indices. Several exist, and they all aim to give a description of the density of information in sample to provide ecological insights beyond a simple species number(Lande, 1996). The dataset made as a part of the detailed biological survey could have been used to produce a value on such an index. The reason this was not performed was that there is a lot of biological information missing due to lack of resolution on the spatial scale. There is also considerable variation in time spent and quality of imaging between substrate objects, a source of random variation. The result of these limitations is that the ”input” data for a diversity index would be lacking a lot of information. Because the data used for the index would be lacking, the result would severely underestimate diversity in the community. This means the figure would be meaningless at best, misleading at worst.

6 Conclusions

6.1 Main findings

The objects of human origin in the dumping ground were investigated. The total number of dumped object was estimated to be in excess of 100,000. Of these, approximately 1500 were estimated to be bombs. These objects were found to be the substrate for many organisms.

The community associated with dumped objects proved to have higher diversity among sessile organisms, where horny corals, sponges, anemones and brachiopods all were common, than among motile organisms, as decapod crustaceans dominated this group. The different species of horny coral were found to have differences in preferred locations, indicated by the negative correlations between *D. florida* and *P. macandrewi* in the dumping ground, and the different assemblage of species found colonizing the bus. The strong currents in the area were judged crucial for the community, being responsible both for food supply through transport and the maintenance of hard substrate through erosion.

The risks associated with the bombs were considered significant to the local communities, and very high in the inadvisable case that bombs should be pulled up to the surface. The environmental risks posed by the contents of the bombs were judged to be relatively limited.

The potential for different groups of organisms to serve as bioindicators was assessed. Notably, the presence and survival of algae in the area provides opportunities to detect TNT, a compound which is rapidly metabolized by animals.

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Appendix A: Unidentified species

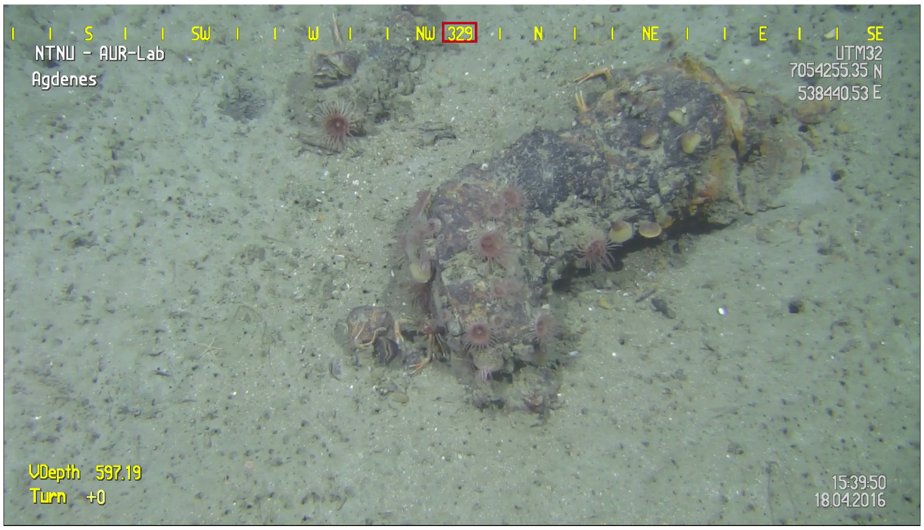

Figure I: Anemone A

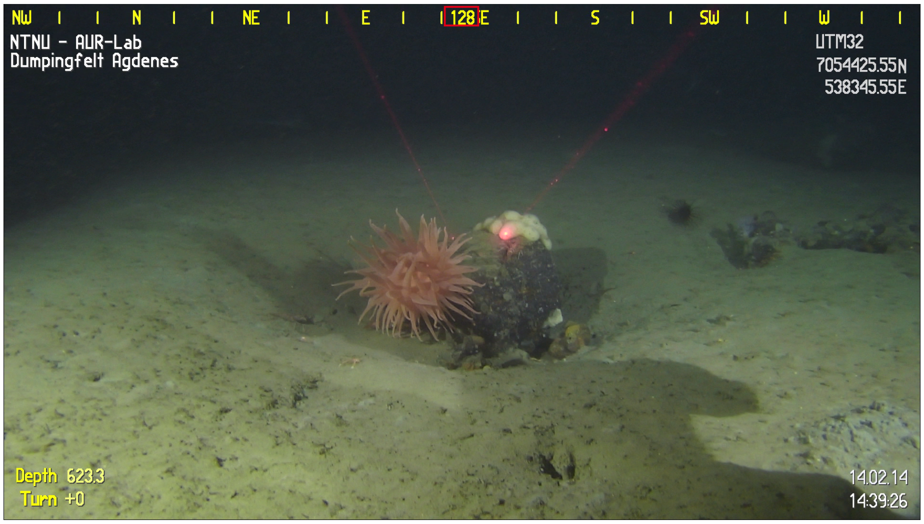

Figure II: Anemone B

Figure III: Anemone C

Appendix A

Figure IV: Anemone D

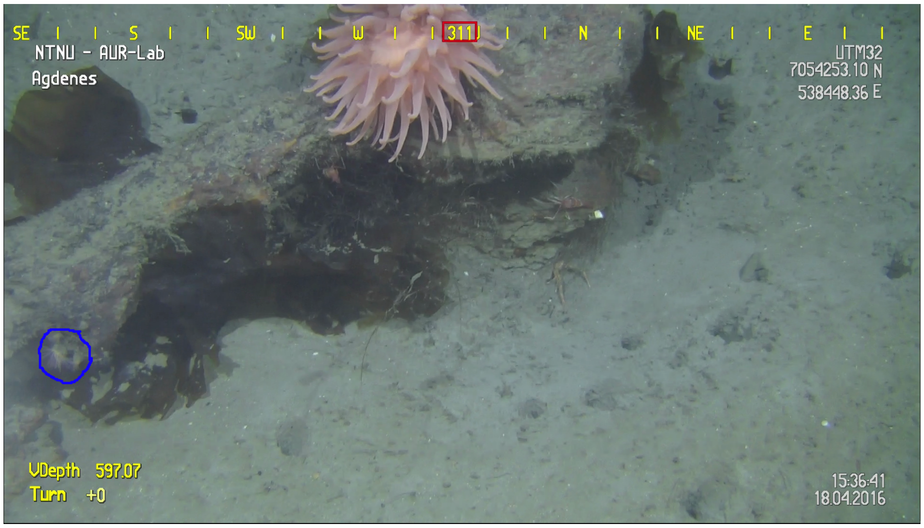

Figure V: Anemone E

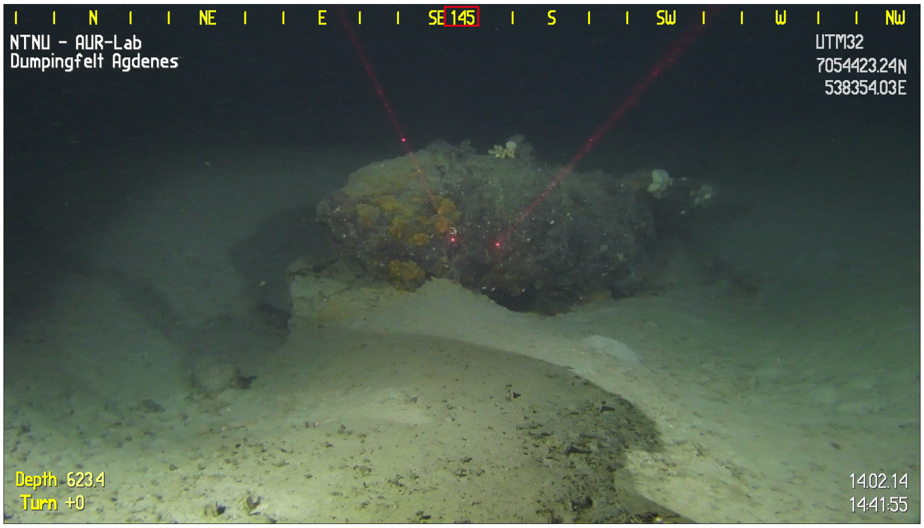

Figure VI: Yellow Encrusting sponge

Appendix B: Detailed Survey

Object	Time	"Squat lobster"	"Shrimp"	*D.florida*	*P.macandrewi*
1.1	14:24:48	3		2	
1.2	14:25:00	1		1	1
1.3	14:28:50	1		1	
1.4	14:32:20	5		7	
1.5	14:33:48	1		1	1
1.6	14:37:35	3			1
1.7	14:39:24	1	1		
1.8	14:40:11			2	1
1.9	14:41:55	5			2
1.10	14:47:01	2		3	
1.11	14:53:04			5	
2.1	14:49:40	7	1	5	
2.2	14:52:40	6	1		1
2.3	14:54:00	2	1	3	
2.4	14:56:13	3			
2.5	14:57:52	5	2	1	
2.6	14:59:13	5		6	2
2.7	15:10:06	2	1		1
2.8	15:13:09	10	3		
2.9	15:17:37				1
2.10	15:18:03	2	1	1	
2.11	15:19:07			3	
2.12	15:22:08	2	1		1
2.13	15:22:45	3		7	
2.14	15:23:49	2			2
2.15	15:25:22	6		3	2
2.16	15:34:36	1	2		
2.17	15:37:48	2			
2.18	15:39:43	3			
2.19	15:45:40	4	2	1	
2.20	15:47:05	1	1	4	
2.21	15:48:00	2		1	
2.22	15:49:15	3	2	1	
2.23	15:53:05	4	1		
2.24	15:55:31	4		2	
2.25	15:56:46	2		1	
2.26	15:57:20	2		1	1
2.27	15:59:21	4	1		1
2.28	16:03:30	4	1		
2.29	16:05:47	4	1	1	
2.30	16:11:00	4	5		
2.31	16:12:46	7			
2.32	16:14:05	3	1	3	
2.33	16:14:33	5			
2.34	16:15:41	2	5		1
2.35	16:20:21	3			1
2.36	16:23:15	3	4		
2.37	16:26:54	4	3		1
2.38	16:31:32	4	1		

Actinaria	*P. resedaeformis*	Sponge	*S.pallida*
			1
2			
		2	
			1
			4
5			
5			
2			
		12	1
5			
1			
1			
			1
			1
1			
2			
10			
1			
2			2
		1	
		1	
3			
		2	
			1
		1	4
1		8	
1			
			3
2			2
3			
2		3	1
3			1
	1		
2			
1			
1			
2			

H.psittacea	*Pagurus* sp.	Ophiorid	*S. tremulus*	*A. excavata*
			1	
	1			
2				
2				
				1
1				
1				
5				
1				
2				
13				
1	1			
2		1		
1				
7				
	1			
7				
3				
1				

Appendix C: Correlation estimates and Cruise 3 Coral data

R Software printout

```
Cruise 1&2 data

> estimate <- cor(newdata$D.florida,newdata$P.macandrewi)
> estimate
[1] -0.3123673
> summary(estimate)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
-0.3124 -0.3124 -0.3124 -0.3124 -0.3124 -0.3124

Cruise 3 data:

> estimate <- cor(newdata$D.florida,newdata$P.macandrewi)
> estimate
[1] -0.3755713
> summary(estimate)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
-0.3756 -0.3756 -0.3756 -0.3756 -0.3756 -0.3756

Consolidated data:

> estimate <- cor(newdata$D.florida,newdata$P.macandrewi)
> estimate
[1] -0.3125104
> summary(test)
   Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
-0.3125 -0.3125 -0.3125 -0.3125 -0.3125 -0.3125
```

Cruise 3 Coral Data

Object no	P.macandr	D.florida
1	1	0
2	1	0
3	0	3
4	2	0
5	1	0
6	1	0
7	0	1
8	0	4
9	1	0
10	0	1
11	1	0
12	0	2
13	0	1
14	1	0
15	1	0
16	2	0
17	3	2
18	0	1
19	0	1
20	0	1
21	1	0
22	0	1
23	0	1
24	1	2
25	0	2
26	2	0
27	0	2
28	1	0
29	0	1
30	0	1
31	0	1
32	0	1
33	1	0
34	0	1
35	1	0
36	1	3
37	1	0

Appendix D: Hugin AUV Object Count

Random Seed	Random Image No	Object Count	Altitude (m)
0.693749389	1391	2	6.4
0.623927262	1252	2	6.5
0.674378236	1353	2	6.3
0.763969261	1531	1	6.5
0.632331629	1269	3	6.5
0.89814906	1798	1	6.5
0.112163514	234	1	6.3
0.891920672	1785	1	6.3
0.058751162	127	4	6.4
0.97521266	1951	4	6.4
0.544137564	1093	3	6.5
0.788308712	1579	1	6.6
0.887780145	1777	3	6.2
0.797975083	1598	0	6.4
0.699037164	1402	4	6.6
0.146376788	302	3	6.5
0.677108978	1358	3	6.5
0.084797518	179	0	6.4
0.476321873	958	1	6.2
0.149030363	307	2	6.3

Area (m^2)	Density (per 1000 m^2)
27.30666667	73.2421875
28.16666667	71.00591716
26.46	75.58578987
28.16666667	35.50295858
28.16666667	106.5088757
28.16666667	35.50295858
26.46	37.79289494
26.46	37.79289494
27.30666667	146.484375
27.30666667	146.484375
28.16666667	106.5088757
29.04	34.43526171
25.62666667	117.0655567
27.30666667	0
29.04	137.7410468
28.16666667	106.5088757
28.16666667	106.5088757
27.30666667	0
25.62666667	39.02185224
26.46	75.58578987
Avg. Density (per m^2)	74.46396809
Total Area (1000 m^2)	1830
Total Objects Estimate	136269