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Impact of trawling on the benthos around oil and gas pipelines

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Abstract

Where fisheries actively target specific areas there may be a disproportionately higher impact on the seabed than in less targeted areas. Previous analysis of VMS data has demonstrated a high level of fishing around oil and gas pipelines in the North Sea. This is thought to be due to a reef effect which attracts fish to the pipeline. We present side scan and photographic imaging which clearly reveals evidence of bottom trawling within an area of 500 m either side of the pipelines. Investigation of individual photographs on transects running over the pipeline, point towards evidence for a reduction in benthic fauna on seabed where there are trawl marks compared to seabed where there are not. This likely effect is also evident on sea pens which were commonly found on the muddier ground in the survey areas. Two of the most frequent biotopes, “burrowed mud” and “sea pens and burrowing megafauna in circalittoral fine mud”, are the focus of conservation efforts through OSPAR and as ‘Priority Marine Features’ in Scottish waters. As the North Sea is a mature basin for exploitation of oil and gas, many pipelines are being considered for decommissioning. We consider the implication of this benthic impact of fisheries on decisions for pipeline decommissioning.

Introduction

Two widespread human activities in the North Sea are commercial fishing and exploitation of oil and gas resources. Where these activities overlap there is potential for interaction. The North Sea is an intensively fished marine ecosystem (Jennings *et al.,* 1999) and fishing gear is known to impact the benthic fauna (Dayton *et al.,* 1995; Tuck *et al.,* 1998; Jennings and Kaiser, 1998; Kaiser and Spencer, 1996). It is reported that there are over 45 000 km of oil and gas pipelines, cables and umbilicals in the North Sea (Oil and Gas UK, 2013). While safety zones (500 m radius) exist around offshore oil and gas infrastructure in which fishing is restricted, there are no such restrictions around pipelines. Some pipelines are installed proud of the seabed and have the potential to interact with commercial fishing gear (Oil and Gas UK, 2013). Where snagging hazards exist, operators will cover the pipeline using rock dump or concrete mattresses. Analysis of Vessel Monitoring System (VMS) data and pipeline position has shown that far from avoiding the pipelines, some fisheries appear to actively target them (Rouse *et al.,* 2017; Osmundsen and Tveteras, 2003). Anecdotally, it is thought that the pipelines create a shelter on a largely featureless seabed and consequently generate localised enhancement of fish caused by a reef effect (Hunter and Sayer, 2009). If these areas surrounding pipelines are favoured by fisheries, as is reported by Rouse *et al*. (2017), this may create a high degree of fishing intensity on the habitats within these grounds. OSPAR Decision 98/3 requires the removal of offshore platforms for re-use, recycling or final disposal on land unless a permit allowing derogation from the terms of the decisions is submitted. However, the decision of whether and how pipelines are decommissioned lies at the discretion of individual Member States. Where pipelines are being considered for *in-situ* decommissioning a comparative assessment approach will be applied taking into consideration safety, environmental, technical, societal and cost components.

The seabed habitats found offshore in the northern North Sea are predicted to be mud, sand, coarse and mixed sediments (EMODnet, 2017). Deep mud habitats in the North Sea (10 to 500 m) are an important habitat for burrowing species such as the prawn *Nephrops norwegicus*, Actiniaria (the anemones), Holothurians (the sea cucumbers) and Pennatulids (the sea pens) (Wilding *et al.,* 2016). The richness of mud habitats has afforded their protection in UK waters. 'Mud habitats in deep water' are priority habitats for UK Biodiversity Action Plans as a part of the Scottish Biodiversity Strategy (Mud Habitats in Deep Water, 2008). The habitat 'burrowed mud' (including all component biotopes and species) has recently been included as a 'Priority Marine Feature' (PMF) (Wilding *et al.,* 2016), a focused list of habitats important in Scottish waters arising from The Marine (Scotland) Act 2010. The habitat "sea pens and burrowing megafauna communities" is also listed as key conservation importance under Annex V of the 1992 Oslo Paris Convention (OSPAR, 1992). Three species of sea pens exist in Scottish waters, *Pennatula phosphorea* (phosphorescent sea pen), *Virgularia miribalis* (slender sea pen) and *Funiculina quadrangularis* (tall sea pen) (Greathead *et al.,* 2007). Being erect and fragile, sea pens are particularly vulnerable to mobile fishing methods (Tuck *et al.,* 1998; Greathead *et al.,* 2005).

Recent VMS data (2009 to 2013) display evidence for high levels of mobile demersal fishing for ground fish, *Nephrops* and scallop in the northern North Sea (NMPI, 2017). Trawling on muddy ground causes a significant level of disturbance to the seabed in an otherwise low energy environment (MacDonald *et al.*, 1996). *Nephrops* trawls, for example, have low head-lines and the mouth of the net skims the seafloor with a heavy grass rope and small bobbins. Dragging the trawl scrapes the seabed and removes or flattens epifauna leaving the seabed highly modified (Magorrian and Service, 1998). Beam trawling was reported to result in a 58% decrease in some taxa on naturally stable sediments which may lead to the long-term changes in benthic community structure (Kaiser and Spencer, 1996). Side scan sonar is a recognised technique for revealing evidence of trawling over wide areas (Smith and Rumohr, 2005; Harris, 2012), while a camera or video towed on a drop frame can provide detailed images of trawl scars and biological communities with minimal disturbance (Smith and Rumohr, 2005).

In May 2015 Marine Scotland Science conducted a survey on board the MRV Scotia at seven stations coincidental with oil and gas pipelines in the northern North Sea. These stations were selected based on a study using VMS data which found an aggregation of fishing around these areas (Rouse *et al.*, *2017*). Side scan sonar was carried out over the pipelines and TV tows were conducted perpendicular to the pipeline. The purpose of this survey was firstly to gain evidence of trawling in the vicinity of the pipelines and secondly to assess the impact on the surrounding seabed. This report firstly details the biotopes classified from the videos and photographs and secondly presents evidence for trawl scars from the side scan and the photographs. The effect of trawling on abundance of benthic invertebrates is investigated using two measures: the total count of organisms recorded on a photograph frame and the total number of sea pens recorded on a frame. Being widespread on muddy ground and vulnerable to trawling, sea pens in particular provide an ideal test case for the benthic impact of trawling in the vicinity of oil and gas pipelines.

Methods

Side scan sonar

Seven stations were surveyed over four pipelines in May 2015 (Table 1, Figure 1). An Edgetech side scan sonar was towed at a speed of approximately 5 knots in lines parallel to the pipelines covering an area 500 m either side of them, over a distance of between 11 and 12.8 kms. The depth of the tow above the seabed (approximately 15 m) was optimised for the speed and stability of the vessel and the bottom topography enabling the visualisation of trawl scars. A Scout USBL system (Sonardyne) recorded the exact position of the side scan. The side scan sonar data were analysed following standard software guidelines using the software Caris Hips and Sips, v. 9. Errors were found in these data at three of the stations when processing the USBL data and a final surface could only be produced for four of the seven stations (Table 1).

Table 1. Stations surveyed using side scan, video and photographs

Station	Pipeline name	Area surveyed by side scan	Date surveyed	Number of video transects
Station 1	Forties C to Cruden Bay (PL8 & PL721)	13.5 km^2	21/05/2015	5
Station 9	Forties C to Cruden Bay (PL8 & PL721)	13.1 km^2	23/05/2015	7
Station 19	Brent A to St Fergus (FLAGS)	11.3 km^2	25/05/2015	6
Station 20	Brent A to St Fergus (FLAGS)	no side scan	25/05/2015	4
Station 21	Nyhamna Sleipner R	no side scan	14/05/2015	3
Station 23	Kollsnes Sleipner R	12.2 km^2	18/05/2015	6
Station 24	Kollsnes Sleipner R	no side scan	17/05/2015	6

Video and camera deployment

A drop-frame TV camera system was towed behind the vessel at ~1 knot. A digital stills camera (Canon) was mounted on the drop-frame together with a high definition and standard definition video (Kongsberg Simrad). The drop-frame was suspended 1 m above the seabed, guided by a steel weight attached by a line to the drop-frame. Maintaining the steel weight (63.5 mm diameter) on or just above the seabed ensured the correct height for accurate focussing of the video and digital camera. Video was recorded continuously together with digital photographs taken at one minute intervals for the duration of the transect including the pipeline feature itself. Two laser pointers set 68 mm apart provided a scale for identifying features.

The TV tows were conducted along a transect perpendicular to the pipeline extending to 500 m either side of it, for a duration of between 30 to 45 minutes. A minimum of three TV tows were carried out at regular intervals along each stretch of pipeline. The location of the drop-frame and the digital stills were recorded directly into ArcView. The substrate and macrobenthos were recorded every minute of the tow.

Photograph and video analysis

The photographs were analysed in Adobe Photoshop Elements 14 for substrate type, species presence, total number of sea pens, total number of all invertebrate species and evidence of trawling. A grid was projected over the photograph to standardise the area (0.65 m^2) in which species were identified and counted and trawl marks were noted. The species were identified to as high a level as possible. Burrows of *N. norwegicus* were distinguished from those of other species by their horse-shoe like shape. A burrow complex was counted as one individual (ICES, 2008). Sea pens were counted when visibly projecting out of their burrow. A trawl mark was distinguished from other marks on the seabed by their straightness (Annex I). Animal tracks, such as those left by decapods, are generally not straight.

Biotopes were allocated based on the substrate and species present according to the Marine Habitat Classification (Connor *et al.,* 2004). As the area covered by the photograph was less than 25 m^2, biotope presence was verified on the corresponding video. Poor quality photographs were not analysed and abundance counts were not carried out on images that were taken too close to the seabed. The videos were analysed qualitatively for substrate type, species presence, evidence of trawling and biotope.

Statistical analysis

Structure of the data

The data comprised counts of individual invertebrates within a total of 783 area-standardised photographic 'frames' (each 0.65 m^2) from between three and seven 'transects' at each of seven 'stations'. Individual frames are categorised as being 'trawled' or 'untrawled' on the presence of indicative markings left by the trawls.

Two observation variables were analysed. These are:

- The abundance of invertebrates on natural substrates (frames with pipelines were excluded). Counts vary between zero (418 frames) to 28 (one frame).
- The abundance of sea pens. A subset of the data comprising counts within a total of 441 frames from one to six transects at each of six stations. Counts used in the analysis exclude the pipeline themselves. Only transects with at least one sea pen present were retained in order to limit the study to stations that contained favourable substrates for sea pen establishment. Counts vary between zero (342 frames) and five (two frames).

Data editing

Zero counts were present for a large number of frames and could generate problems with fitting a satisfactory model. By summing counts across frames categorised as either trawled or untrawled within transects, it is possible to substantially reduce the occurrence of zero counts while retaining all of the explanatory variables structural to the study; these are hereafter referred to as ‘summed frames’. Standardisation of the areas covered by summed frames is facilitated by additionally recording the constituent number of frames. Not all transects or stations contain both trawled and untrawled frames. These have, however, been retained for analysis to improve the estimates of site and transect variation.

Statistical analysis

The analyses undertaken comprise estimating:

1. The association between trawling and the total abundance of invertebrates.

2. The association between trawling and the abundance of sea pens.

Mean abundances were calculated and 95% confidence intervals (CI) estimated using a bootstrap corrected for bias and acceleration (Efron, 1987). Confidence intervals are approximate given that one of the estimations involved end point values.

The CI confounds uncertainty around the estimate of the association between abundance and trawling with variation between stations and transects. Generalised linear mixed models (GLMM) (McCullagh and Nelder, 1989) were used to partition the variation for each of these explanatory variables. The model used for both analyses is:

$$\log(E(y_{ijk} \backslash u_{jk})) - \log(x_{ijk}) = \beta_0 + \beta_1 . x_i + \beta_2 . x_j + u_{jk}$$

where y_{ijk} = abundance of either 1) invertebrates or 2) sea pen in summed frames associated with trawled status *i* in transect *k* within site *j* (0 to 144 or 46) assuming a Poisson distribution; β_o = intercept; β_1 = fixed effect of trawled category *i* (trawled, untrawled); β_2 = fixed effect of site j (1 to 7 or 6); u_{jk} = random effect of transect *k* within site *j*; x_{ijk} = number of constituent frames comprising summed frame for trawled category *i* in transect *k* within site *j*. Models were estimated using penalized least squares. Stations were modelled as fixed rather than random effects because this gave rise to improved model diagnostics. Evidence for an association between the abundance and trawled category was obtained using a likelihood ratio test of nested models including and excluding β_1 for which exploratory probability values (p_{exp}) for a type I error of no greater than 0.05, assuming no difference in abundance between trawled and untrawled frames, were categorised as statistically significant. The coefficient β_1 provides, after exponentiation, an estimate of relative abundance of trawled compared to untrawled areas with the 95% CI calculated from the profile likelihood.

Analyses were performed within the R statistical environment (Ihaka and Gentleman, 1996) version 3.3.3 utilising the supplementary R packages boot 1.3-18 (for the bootstrap) and lme4 1.1-12 (for GLMM) (Bates *et al.*, 2015).

Results

The biotopes identified across the stations are displayed in Figure 1. Photographic examples of these biotopes are given in Annex I. Annex II contains the biotopes allocated for the video. The biotopes of the photographs are available as a dataset at http:doi.org/10.7489/12117-1. Four biotopes were recorded; “offshore circalittoral mud” (SS.SMu.OMu), “sea pens and burrowing megafauna in circalittoral fine mud” (SS.SMu.CFiMu.SpnMeg), “offshore circalittoral mixed sediment” (SS.SMx.OMx) and “circalittoral sand” (SS.SSa.OSa). Evidence of trawling was found at all stations except 9 (Nyhamna Sleipner R pipeline) and 21 (Forties C to Cruden Bay pipeline) (Figure 1).

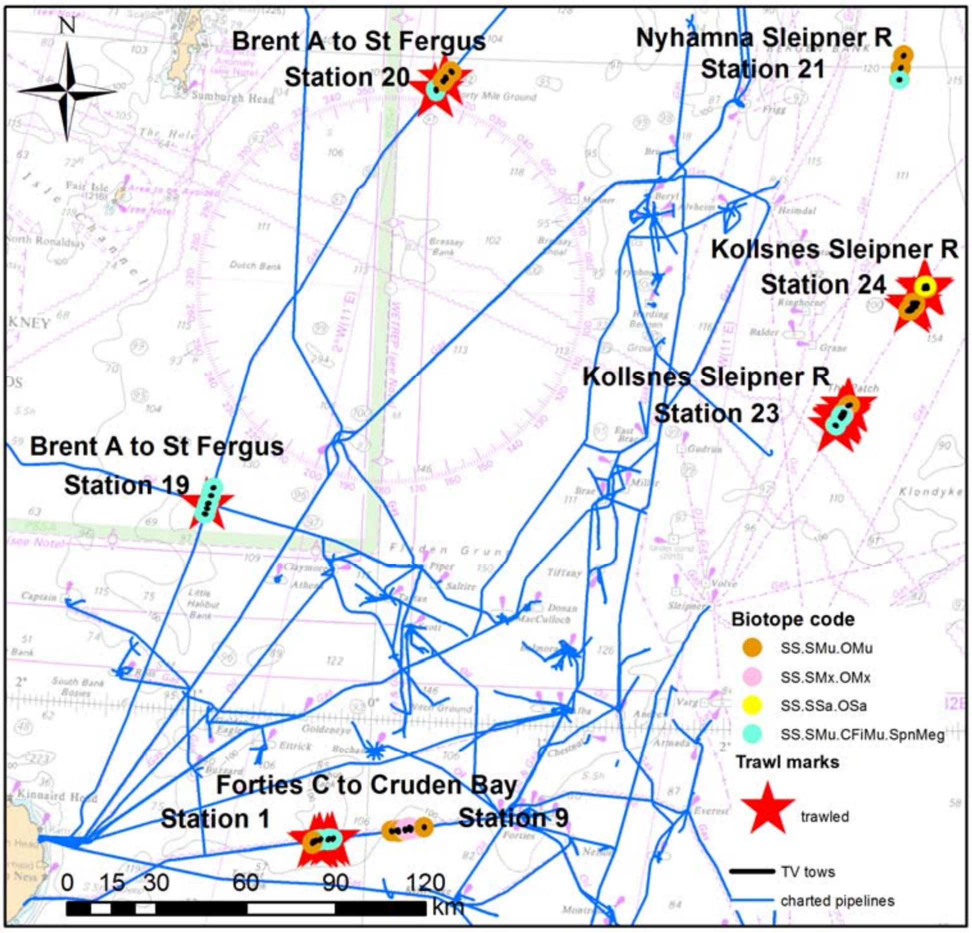

Figure 1. Biotopes and evidence of trawling present in the 7 survey areas.

Forties C to Cruden Bay

Stations 1 and 9 were located on the same pipeline within 20 km of each other and displayed similar biotopes; burrowed mud (SS.SMu.OMu), mud with sea pens and burrowing megafauna (SS.SMu.CFiMu.SpnMeg), mixed sediments (SS.SMx.OMx) and sand (SS.SSa.OSa) (Figure 2). Burrowing species such as *N. norwegicus* inhabited the sand and the sea pen *P. phosphorea* was widespread on the muddier substrate. Other frequent species recorded were *V. miribalis*, *Sabella sp.*, *Urticina sp.* and starfish such as *Stichastrella rosea*. Evidence of trawling is widespread. Large sweeps running diagonally across the pipeline can be seen on the side scan at station 1 and to a lesser extent at station 9. Trawl marks are present in many of the photographs and video at station 1 (TV runs 1 to 4, Annex I and II). The pipeline lies proud of the seabed (darker line running along the centre of the side scan image) and has an accumulation of gravel immediately to the side of it. The pipeline itself harbours a rich covering of hydroid/bryozoan turf together with anemones and hermit crabs.

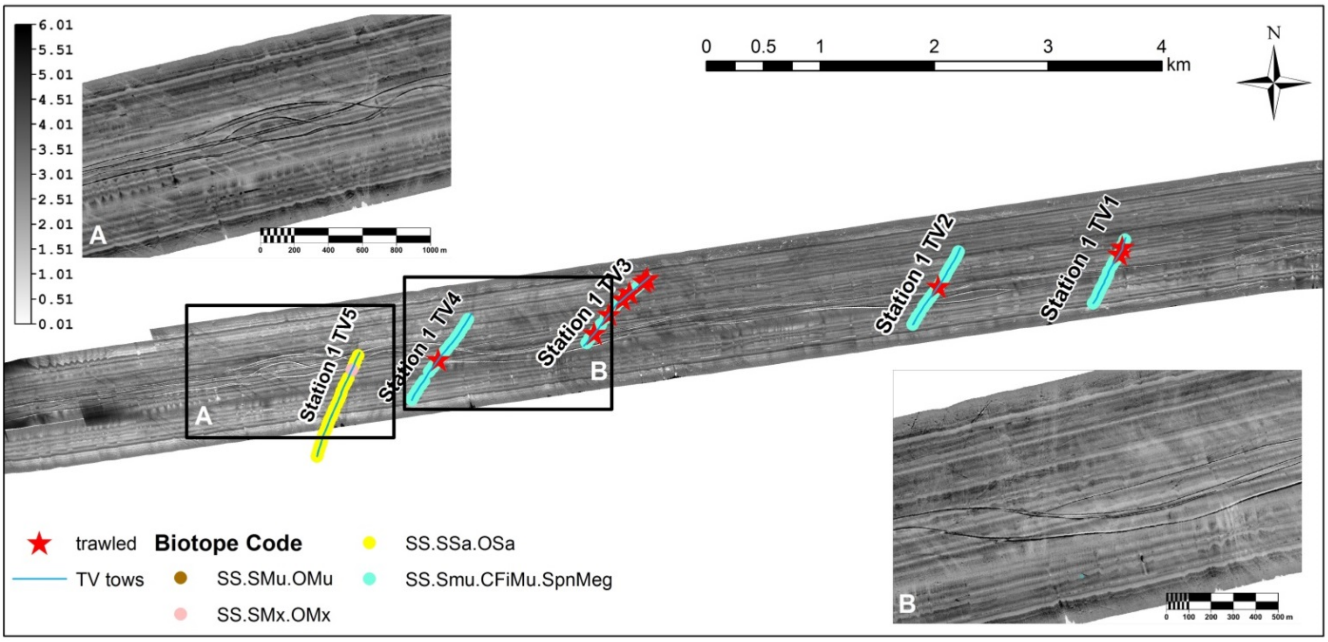

Figure 2. Side scan images of station 1 on the Forties C to Cruden Bay (PL8 & PL721) pipeline

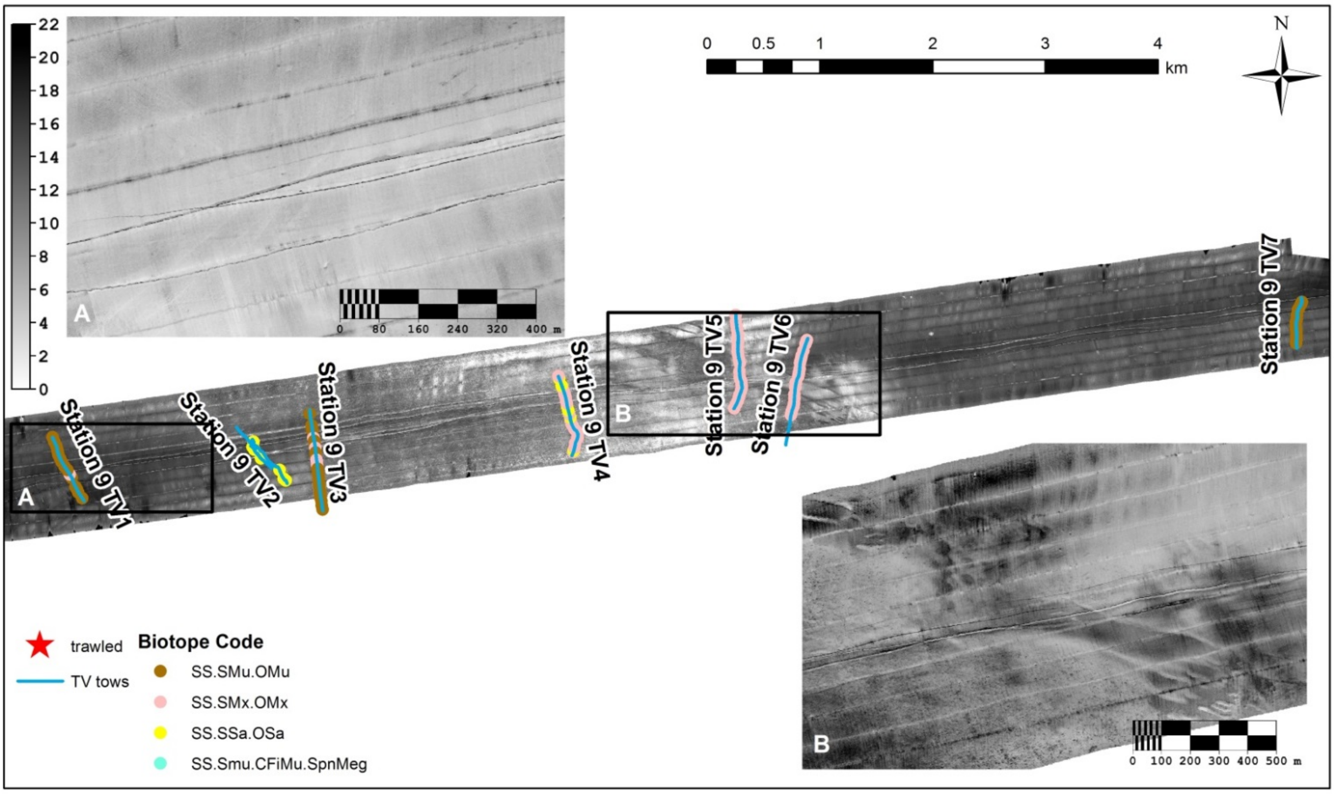

Figure 3. Side scan images of station 9 on the Forties C to Cruden Bay (PL8 & PL721) pipeline

Brent A to St Fergus (FLAGS) pipeline

The predominant biotope identified at Station 19 was mud with sea pens and burrowing megafauna (Figure 4). *P. phosphorea* was widespread with occasional sitings of *V. miribalis*. There were high densities of burrowing fauna particularly *N. norwegicus* but also burrows of worms, anemones and other decapods. Rock dump was found at TV3 close to the pipeline. The community on the rock dump was typical of loose cobbles and pebbles and contained hydroids, starfish and crabs (Annex I). The pipeline itself was rich with *Caryophyllia smithii*, hermit crabs, anemones and hydroids or bryozoans. No photographic or video evidence of trawling was recorded at station 19. Potential trawl scars are visible on the side scan, such as inset B on Figure 4 (TV4).

Due north on the same pipeline at station 20, there was much photographic evidence of trawling but side scan images could not be post-processed. The biotope at TV1 and part of TV2 was mud with sea pens and burrowing megafauna. Both *P. phosphorea* and *V. miribalis* were present and burrows of *N. norwegicus.* TV2 to 4 were characterised by burrowed mud and mixed sediment. A rich community of starfish, urchins, sea cucumbers and sponges were found on the mixed sediment. The sea anemone *Bolocera tuediae* was common as was the calcareous worm *Hyalinoecia tubicola.* The pipeline was covered in a hydroid/bryozoan turf.

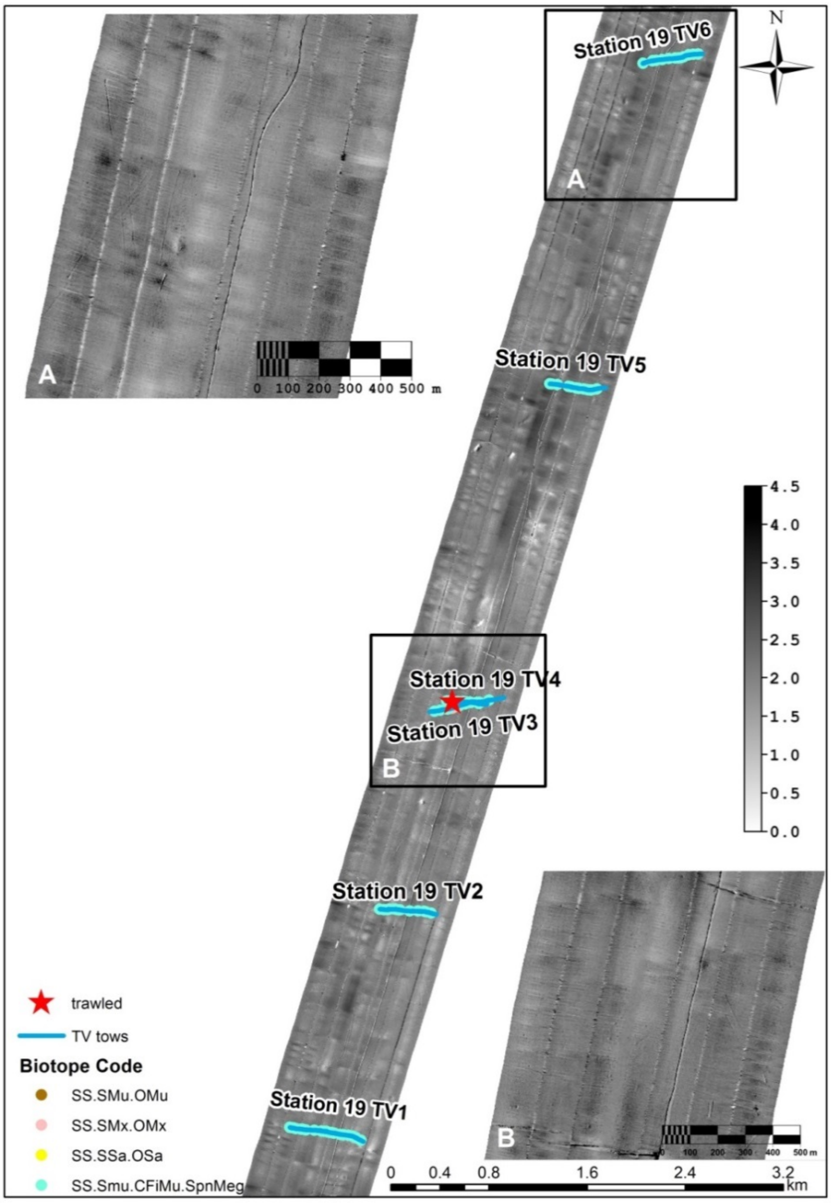

Figure 4. Side scan images of station 19 on the Brent A to St Fergus (FLAGS) pipeline

Kollsnes Sleipner R pipeline

The biotopes found at station 23 on the Kollsnes Sleipner R pipeline are SS.SMu.CFiMu.SpnMeg, SS.SMu.OMu and SS.SMxOMx (Figure 5). Frequent occupants of this habitat are anemones such as *B. tuediae*, urchins, sponges and starfish. Clear trawl tracks crossing over the pipeline were recorded on the side scan on the northern section of the survey area, while the southern section appears less disturbed. However, evidence of trawling can be seen on all TV runs crossing the station. The trawl marks are more visible where the side scan has passed over rougher ground (TV1 to 4). Fauna such as anemones, starfish and calcareous tubeworms were recorded on the pipeline. Fish were sheltering next to or underneath it.

The sea bed substrates at station 24 are more diverse, ranging from mud to sands, gravels and occasional boulders. Consequently, a greater variety of species were occupying these different habitats, such as urchins, starfish, hermit crabs, occasional *V. miribalis* and burrowing species such as anemones, *N. norwegicus* and sea cucumbers*.* The pipeline itself was occupied by anemones and juvenile fish clustering around it. Trawl marks are evident at this site. The bobbins appear to leave a furrowing mark in the sediment (Annex I).

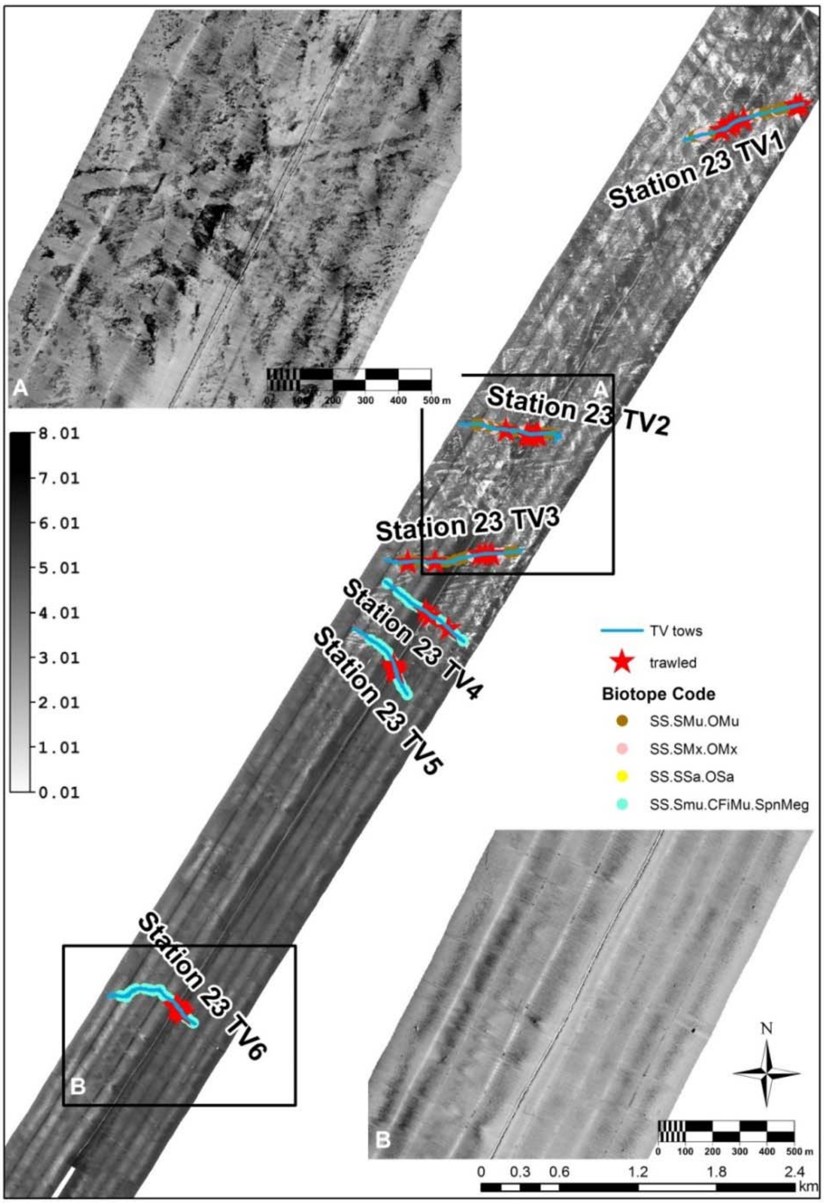

Figure 5. Side scan images of station 23 on the Kollsnes Sleipner R pipeline

Effect of trawling on the total abundance of invertebrates

Mean values and confidence intervals (CI) are presented in Figure 6a. The CI, which includes variation between stations and transects within stations, overlap.

The relative abundance for trawled relative to untrawled summed frames, as estimated by the GLMM, is 0.63 (with 95% CI of 0.44 to 0.87). This difference is categorised as statistically significant (χ^2=8.032 for 1 degree of freedom (df), p_{exp}=0.005).

Model diagnostics are regarded as being satisfactory. There is evidence of an association between trawling and a reduction in the abundance of invertebrates.

Effect of trawling on the abundance of sea pen

Mean abundances and CI are presented in Figure 6b. The CI, which includes variation between stations and transects within stations, overlap.

The relative abundance for trawled relative to untrawled summed frames, as estimated by the GLMM, is 0.32 (0.10 to 0.79). This difference is categorised as being statistically significant (χ^2=6.698 for 1 df, p_{exp} =0.010).

Model diagnostics are not satisfactory with evidence of:

- a high outlying sea pen count from an untrawled summed frame with the potential to exert leverage,
- and under-dispersion (dispersion-ratio = 0.47).

However, deletion of the outlying observation substantially improves the diagnostics of the model and generates similar results.

There is evidence of an association between trawling and a reduction in the abundance of sea pen. It is likely, however, that the number of stations is only just sufficient to detect this association and additional data to confirm the result is desirable.

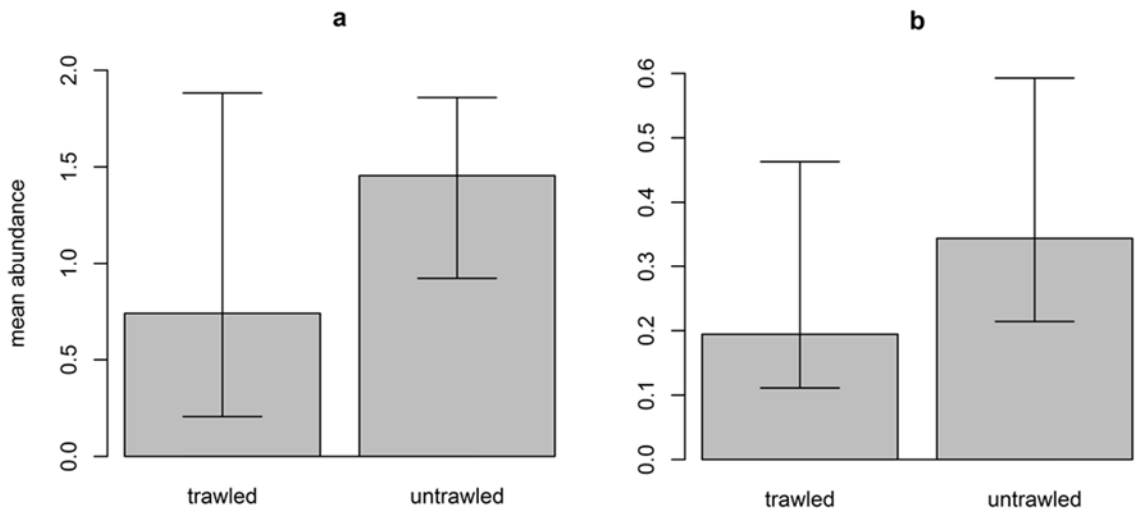

Figure 6. Mean abundances with 95% CI of trawled and untrawled frames in a 0.65 m^2 area for (a) the total abundance of invertebrates and (b) the abundance of sea pens.

Discussion

This study provides evidence of an association between trawling and a reduction in the total abundance of invertebrates and specifically the total abundance of sea pens in the northern North Sea. This strengthens the evidence of the negative effect of bottom trawling on benthic fauna (Kaiser and Spencer, 1996; Dayton *et al.,* 1995; Tuck *et al.,* 1998; Jennings *et al.,* 2001). The side scan imaging coupled with the video and photographs, clearly reveals evidence of trawling around the pipelines. This confirms the finding of Rouse *et al.* (2017) that fisheries do target oil and gas pipelines in the North Sea. The study demonstrates that the elevated fishing effort in the vicinity of the pipelines has a negative effect on sea pens and other benthic invertebrates. These results provide further insights into decisions on decommissioning of such pipelines.

The study also extends knowledge of the known distribution of sea pens in this region. These photographic records confirm that they occur far out into the North Sea where habitat is suitable for them, i.e. on mud or fine sand. This is in keeping with predicted habitat models of sea pen distribution which suggest that the habitat suitability increases with mud content (Greathead *et al.,* 2015). Habitat mapping in this offshore area of the North Sea has been carried out from predicted data (EMODnet, 2017). Records from this study could be incorporated into finer scale habitat maps using actual sampling data.

Although, the analysis of the impact of trawling on sea pens could have benefited from additional sampling stations in which they were present, the study is still able to demonstrate a likely reduction of sea pens in areas where trawling took place. There are several factors that could have affected the results however. Both *P. phosphorea* and *V. miribalis* are able to retract into their burrows in response to predation (Kinnear *et al.,* 1996), which could result in a lower abundance count on the frames. However, the burrows are still visible even if the sea pen has retracted inside it. Further to this, empty burrows were rarely encountered on trawled sediment, so the effect could only lead to an underestimation of the impact of sea pens by trawling.

Another factor that could not be accounted for was the age of the trawl marks and the history of trawling in the study sites. How long it takes for the trawl marks to fade in such a low energy environment is not known, nor do we know the length of time for *P. phosphorea* and *V. miribalis* to re-grow or to re-colonise an area after it has been trawled. Kinnear *et al.* (1996) simulated the effect of static creeling on sea pens. *V. miribalis* retracted into its burrow and *P. phosphorea* was able to re-anchor itself once it touched the mud but static creeling is a much more benign method of fishing than a mobile demersal trawl. If these species are able to re-establish themselves before the trawl marks have faded it would result in an underestimate of the effect of trawling on sea pens. Likewise, we may also see an underestimate in the effect on total abundance of invertebrates but recovery rates after trawling are species-specific. Long-lived gastropods, bivalves and fragile species such as urchins are the most affected by mobile trawling. Scavengers, such as starfish, crabs and small polychaetes may accumulate in large numbers as a result of disturbances (Kaiser *et al.,* 2000; Jennings *et al.,* 2001). Small polychaete worms are present on the trawled areas at station 24 on the Kollsnes Sleipner R pipeline.

Similar to the present study, Greathead *et al.* (2004) report that the population median of *F. quadrangularis* (the tall sea pen) is lower at a more heavily trawled site on the west coast of Scotland than a less trawled one. In the present study it is possible to determine the likely effect of trawling at the scale of an individual photograph (<1 m^2), while the site effect can also be accounted for in the model. This is beneficial as we can account for the variation in trawling within a site. We also recorded other species that were only present in sites where no trawling had taken place such as anemones and sponges. These species are often larger and non-mobile.

Analysis of the side scan imaging coupled with the video and photographs, clearly shows that trawling does take place within 500 m either side of the pipelines. The trawl marks on the side scan appear to sweep over the pipelines and back again (e.g. stations 1 and 23). These marks are likely made by the otter boards used to spread the gear on demersal trawls, such as those used for *Nephrops* fishing or a mixed demersal fishery (Galbraith *et al.,* 2004). Other marks on the side scan imaging appear to be isolated striations (e.g. at station 19). These striations are likely formed when an otter board rides over an obstacle, such as a rock or a pipeline, and rebounds on the seabed with greater force leaving a depression on the seabed. Many of the photographs show repeated horizontal striations indicative of ground gear which creates a furrowed appearance. The ground gear comprises of spacers and different diameters of rubber discs attached to the foot rope of the net (Galbraith *et al.,* 2004). Where such trawl marks are present, there is often just barren sediment with no megafauna at all. As is reported by Maggorian and Service (1998), the ground gear effectively scrapes the top layer of sediment and removes any emergent epifauna. These trawl marks may be present on the seabed for a long time because it is a low energy environment. Understanding the recovery rate of the benthos relative to the intensity of trawling is likely to be key to determining whether the demersal fishery is sustainable.

The study by Rouse *et al.* (2017) analysed VMS data on a North Sea scale and clearly shows that fisheries do target oil and gas pipelines. This study provides evidence directly from the field that fishing is taking place around these pipelines. Trawl marks are clearly visible from the side scan, video and photographs. It is thought that fisheries target oil and gas pipelines because of the reef effect they create which leads to greater numbers of fish and higher catches around the pipeline (Hunter and Sayer, 2009). Although fish were not quantified in this study, they were seen to cluster to the side or underneath the pipelines. Those fish that were recorded were usually the juveniles. The larger individuals, that were big enough to be of commercial value, such as *Gadus morhua* or *Lophius piscatorius*, were typically seen further from the pipeline. It is possible that fish are attracted to the pipeline for shelter and forage in the surrounding area (Sarno *et al.,* 1994). An understanding of the type of fishery taking place at these stations, i.e. whether boats are targeting ground fish or *Nephrops* or both, would help confirm the reasoning for the increased trawl activity close to the pipelines.

The pipelines themselves harboured an assemblage of species typical of a hard substrate, such as Ascidians, *Caryophyllia smithii*, hermit crabs and anemones. There was also an accumulation of gravels next to the pipeline which were occupied by a community of species typical of coarser substrate, such as starfish and decapods. These coarser substrates occurred in the immediate vicinity of the pipeline however, and the substrate quickly reverted to its original composition (usually sand or mud) a few metres away. No non-native species were identified on the pipelines but the communities recorded would not otherwise be present at these stations if the pipelines were not there. Results from these pipelines at the time they were sampled, would suggest that concerns over species of conservation interest or non-native species residing on the pipeline, do not need to be considered in the decision making process over whether the pipelines should be fully removed or not. However, the greater fishing intensity on the area surrounding the pipeline and the impact this is having on the benthos does require consideration.

Conclusion

This study provides evidence that the abundance of benthic fauna is reduced by trawling on burrowed mud and sand. Both burrowed mud and the component species of the habitat are of key conservation importance and recommended for protection. The burrowed mud habitat associated with sea pens is widespread in the North Sea but it is also the focus of the *Nephrops* fishery. Thus conservation efforts must be balanced by fisheries interests. Together with the evidence from VMS studies (Rouse et al., 2017), this study furthers the evidence for elevated fishing around oil and gas pipelines in the North Sea. Where burrowed mud and pipelines coincide, there is potential for a greater impact on the sea pens from fisheries. In order to achieve a clear seabed pipelines would need to be removed during decommissioning. However, if technology for the removal of larger diameter pipelines does not exist or is too costly, an alternative solution may be to trench and bury the pipeline in situ. Trenching and burying a pipeline would have the same effect as removing it by eliminating a surface environment for fish aggregation. This would return the habitat to a condition that would enable the expansion of PMF species and reduce the frequency of future fishing effort for the area.

Future studies might also consider the scale of the impact associated with the elevated fishing intensity around surface laid pipelines, particularly those that coincide with sandy mud and muddy environments typical of *Nephrops* and sea pens. Following on from this, we need to consider the life cycle of pipelines that are likely to be decommissioned. While in operation surface laid pipelines appear to present an acceptable risk to fishers. However, the onset of pipeline degradation post decommissioning will increase the snagging risk significantly. Are there options available to reduce the risk to an acceptable level and what scale of impact will the resulting demersal fishing have on the benthic fauna? We conclude that the operators and the regulators of oil and gas pipelines are advised to consider fishing intensity and presence of sensitive habitats in the decision making process of decommissioning oil and gas pipelines.

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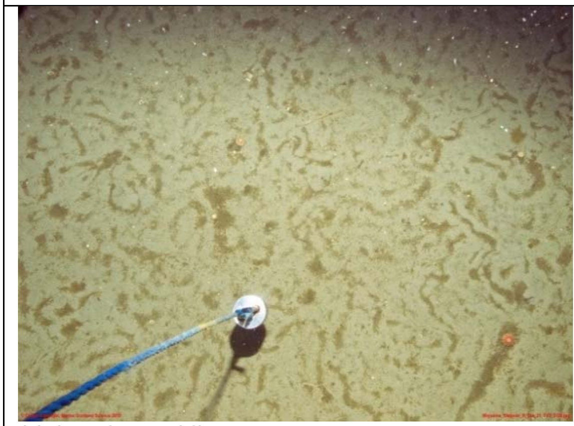
Annex I. Photographs of the biotopes identified in the study. Priority marine features are labelled in red.

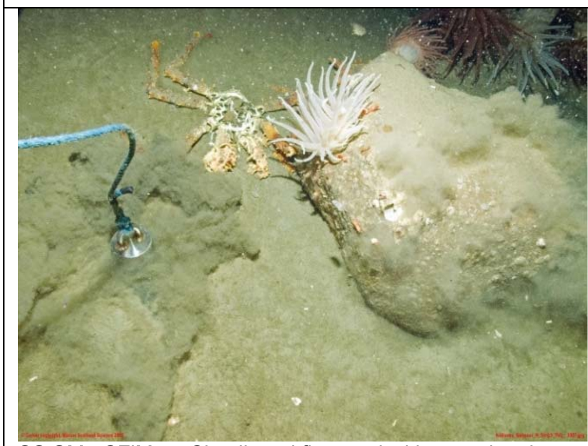
 SS.SMu.CFiMu.SpnMeg – Sea pens and burrowing megafauna in circalittoral fine mud with *Pennatula phosphorea* Forties C to Cruden Bay, Station 1, TV2, 3544	 SS.SMu.CFiMu.SpnMeg – Sea pens and burrowing megafauna in circalittoral fine mud with *P. phosphorea* and *Nephrops norwegicus* Forties C to Cruden Bay, Station 1, TV2, 3520
 SS.SMu.OMu – Offshore circalittoral mud with *Bolocera tuediae* Kollsnes Sleipner R, Station 24, TV4, 3236	 SS.SMu.CFiMu.SpnMeg – Sea pens and burrowing megafauna in circalittoral fine mud with *P. phosphorea* and *Gadus morhua.* Note, the sea pen component of this biotope is evident in the video. Brent A to St Fergus (FLAGS), Station 19, TV3, 3727
 SS.SMu.OMu – Offshore circalittoral mud with *Hyalinoecia tubicola* and *Psammechinus miliaris* Nhyamna Sleipner R, Station 21, TV3, 3129	 SS.Smu.CFiMu.SpnMeg – Sea pens and burrowing megafauna in circalittoral fine mud with burrowing anemone (biotope allocated due to presence of sea pens in corresponding video) Forties C to Cruden Bay (PL8 & PL721), Station 1, TV4, 3595

SS.SMx.OMx - Offshore circalittoral mixed sediment with *Callionymus lyra*
Forties C to Cruden Bay (PL8 & PL721), Station 9, TV6, 3590

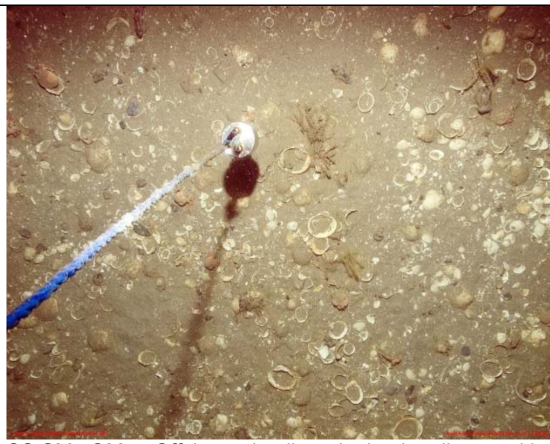
Offshore circalittoral mud with *Hyalinoecia tubicola*
Brent A to St Fergus (FLAGS) Station 20, TV3, 3852

SS.SMx.OMx - Offshore circalittoral mixed sediment
Forties C to Cruden Bay (PL8 & PL721), Station 9, TV3, 3517

SS.SMx.OMx - Offshore circalittoral mixed sediment
Kollsnes Sleipner R, Station 23, TV1, 3327

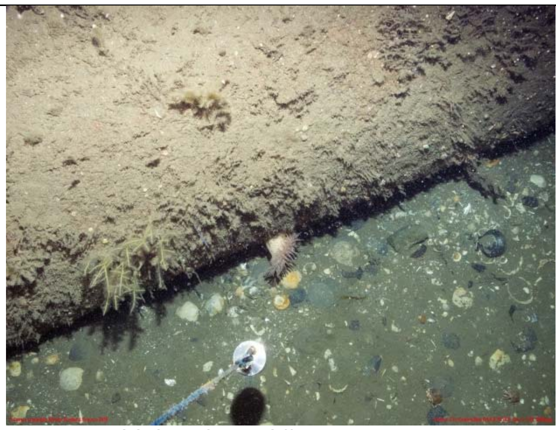


SS.SMu.CFiMu – Circalittoral fine mud with occasional boulders. *Bolocera tuediae* and carapace of *Lithodes maia*
Kollsnes Sleipner R, Station 23, TV2, 3357

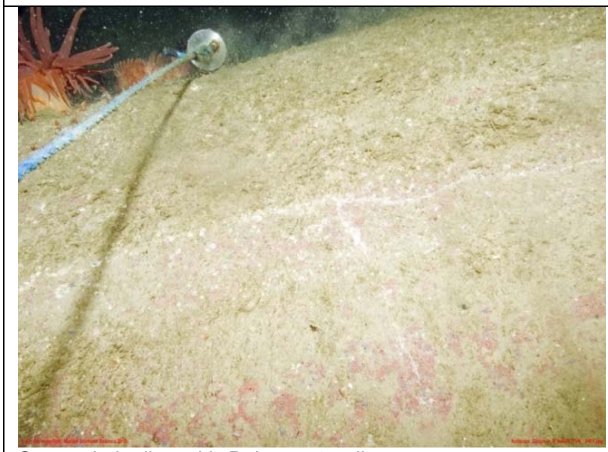


SS.SMx.OMx - Offshore circalittoral mixed sediment with shells, hydroids and Paguridae
Brent A to St Fergus (FLAGS) Station 19, TV3, 3726

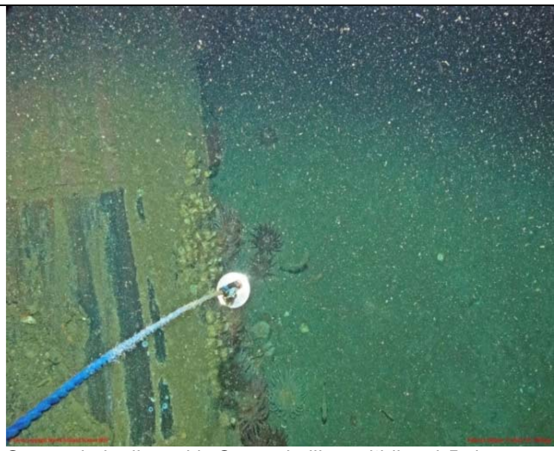
Pipeline on SS.SMx.OMx - Offshore circalittoral mixed sediment
Forties C to Cruden Bay (PL8 & PL721), Station 9, TV3, 3518



Pipeline on SS.SMx.OMx - Offshore circalittoral mixed sediment
Forties C to Cruden Bay (PL8 & PL721), Station 1, TV5, 3598



Scraped pipeline with *Bolocera tuediae*
Kollsnes Sleipner R, Station 23, TV4, 3411

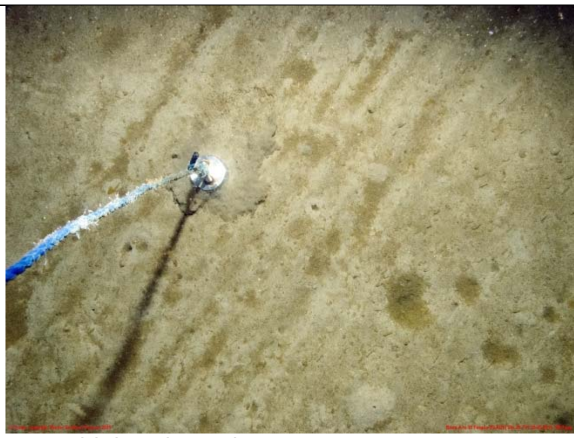


Scraped pipeline with *Caryophyllia smithii* and *Bolocera tuediae* on SS.SMu.OMu - Offshore circalittoral mud
Kollsnes, Sleipner R, Station 23, TV1, 3335

Rock dump with hydroid turf, *Hippasteria phrygiana* and *Stichastrella rosea*
Brent A to St Fergus (FLAGS), Station 19, TV3, 3737

Pipeline with ascidian and hydroid turf. *Bolocera tuediae*, burrowing anemone and juvenile fish on SS.SMu.OMu with occasional gravel
Kollsnes Sleipner R Station 23, TV3, 3387

Barren SS.SMu.OMu with bobbin marks from a trawl
Kollsnes Sleipner R, Station 23, TV3, 3388

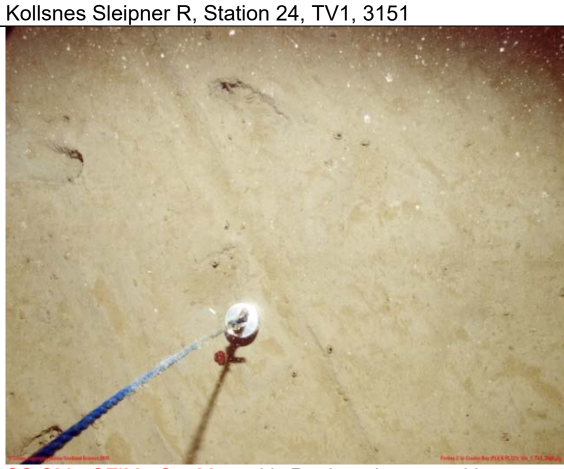


Barren SS.SMu.CFiMu.SpnMeg with bobbin marks. Note, the sea pen component of this biotope is present in the video.
Brent A to St Fergus (FLAGS), Station 20, TV1, 3803

SS.SMu.CFiMu.SpnMeg – offshore circalittoral sand with bobbin marks and *Virgularia miribalis*
Kollsnes Sleipner R, Station 23, TV4, 3409

SS.SMu.OMu with bobbin marks and numerous small worm casts
Kollsnes Sleipner R, Station 24, TV1, 3151

Barren offshore circalittoral mud (SS.SMu.OMu) with trawl marks
Kollsnes Sleipner R, Station 23, TV2, 3355



SS.SMu.CFiMu.SpnMeg with *P. phosphorea* and burrows of *Nephrops norwegicus*. Trawl marks visible on the surface.
Forties C to Cruden Bay, Station 1, TV3, 3560

Annex II. Description of videos, including position, substrate, evidence of trawl marks, depths, pipeline crossing time, biota, interpretation of biotopes and presence of priority marine features

Pipeline, Station, TV run and date	Start latitude	Start longitude	End latitude	End longitude	Substrate	Trawl marks present	Depth at start (m)	Depth at finish (m)	Time of pipeline crossing on video	Biota	Biotope	Priority Marine Feature
Nyhamna Sleipner R Stn 21 TV1 14-05-15	60.03617	3.022232	60.03226	3.015813	fine sand	no	123	123	not present	*Psammechinus miliaris, Asturias rubens*	SS.SMu.CfiMu	none
Nyhamna Sleipner R Stn 21 TV2 14-05-15	59.99952	3.00693	59.99632	3.001575	fine sand	no	123	123	not present	*Psammechinus miliaris, Hyalinoecia tubicola*	SS.SSa.OSa	none
Nyhamna Sleipner R Stn 21 TV3 14-05-15	59.96256	2.997786	59.96212	2.990382	fine sand	no	124	122	not present	*Psammechinus miliaris, Hippasteria phrygiana, Paguridae*	SS.SSa.OSa	none
Kollsnes Sleipner R Stn 24 TV1 17-05-15	59.26792	3.065425	59.26714	3.040857	fine sand, mixed cobbles and pebbles	yes	135	130	not present	*Psammechinus miliaris, Asturias rubens, Epizoanthus incrustatus, Asturias rubens, Paguridae*	SS.SSa.OSa, SS.SMx.OMx	none
Kollsnes Sleipner R Stn 24 TV2 17-05-15	59.27208	3.051767	59.271613	3.07087	fine sand, shells, rock, sand and gravel	no	130	135	03:22:48	*Bolocera tuediae, Psammechinus miliaris, Asturias rubens, Hyalinoecia tubicola, Paguridae, Myxine glutinosa, Lophius piscatorius;* anemones and juvenile fish on side of pipeline	SS.SSa.OSa, SS.SMx.OMx	none
Kollsnes Sleipner R Stn 24 TV3 17-05-15	59.28027	3.09266	59.28013	3.067981	fine sand	yes	137	132	04:14:23	*Asturias rubens, Stichastrella rosea, Psammechinus miliaris, Stichopus tremulus, Hyalinoecia tubicola, Nephrops norwegicus, Myxine glutinosa, Bolocera tuediae* on side of pipeline	SS.SSa.OSa	none
Kollsnes Sleipner R Stn 24 TV4 17-05-15	59.29106	3.068687	59.29092	3.101895	fine sand, rock	yes	134	138	07:05:00	*Psammechinus miliaris, Paguridae, Nephrops* burrows, *Asturias rubens, Pectinidae, Stichopus tremulus,* worm burrows, *Myxine glutinosa*	SS.SSa.OSa	none
Kollsnes Sleipner R Stn 24 TV5 17-05-15	59.33493	3.160858	59.33391	3.137638	fine sand, burrowed sand	yes	142	140	not present	*Nephrops burrows, Psammechinus miliaris, burrowing anemone, Stichopus tremulus, Bolocera tuediae, Myxine glutinosa*	SS.SSa.OSa	none
Kollsnes Sleipner R Stn 24 TV6 17-05-15	59.33973	3.141673	59.34159	3.156045	no video	no video	141	142	no video	no video	no video	no video

Kollsnes Sleipner R Stn 23 TV1 18-05-15	58.97904	2.6935	58.9815	2.709264	fine sand, mixed sand and gravel, fine sand with gravel	yes	120	120	13:15:00	*Bolocera tuediae,* unidentified anemones, *Astropecten irregularis, Asteroidea,* Porifera, juvenile fish*; Bolocera, Metridium sp. and Salmacina sp.* on side of pipeline	SS.SSa.OSa, SS.SMx.OMx	none
Kollsnes Sleipner R Stn 23 TV2 18-05-15	58.95831	2.676523	58.95946	2.663768	fine sand, sand and gravel	yes	120	120	03:27	*Stichastrella rosea, Astropecten irregularis, Metridium sp., Bolocera tuediae, Pennatula phosphorea; Bolocera* on side of pipeline	SS.SSa.OSa, SS.SMx.OMx	*Pennatula phosphorea*
Kollsnes Sleipner R Stn 23 TV3 18-05-15	58.95007	2.653912	58.95086	2.672161	fine sand, sand and gravel, sand and cobbles, angular boulders	yes	121	120	14:33	*Bolocera tuediae, P. phosphorea, Stichastrella rosea, Astropecten irregularis, Echinus sp., Axinella infundibuliformis, Porifera;* anemones on the side of pipeline, fish sheltering underneath pipeline	SS.SSa.OSa, SS.SMx.OMx	*Pennatula phosphorea*
Kollsnes Sleipner R Stn 23 TV4 18-05-15	58.94861	2.653918	58.94455	2.664416	fine sand	yes	121	120	14:20	*Pennatula phosphorea, Bolocera tuediae, Astropectin irregularis, Stichastrella rosea, Asturias rubens, Nephrops* burrow, *tube anemone; Bolocera, Helicolenus dactylopterus* and unidentified teleost fish on or under pipeline	SS.SMu.CFiMu.SpnMeg, SS.SSa.OSa	SS.SMu.CFiMu.SpnMeg
Kollsnes Sleipner R Stn 23 TV5 18-05-15	58.94533	2.649707	58.94084	2.657045	fine sand	yes	122	123	10:34	*Pennatula phosphorea, Virgularia miribalis, Stichastrella rosea, Astropecten irregularis, Asturias rubens, Nephrops norwegicus, Bolocera tuediae,* unidentified anemones on side of pipeline	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Kollsnes Sleipner R Stn 23 TV6 18-05-15	58.92001	2.617477	58.91819	2.629044	fine sand, burrowed sand, fine sand with shells	yes	121	120	22:06, 25:21	*Pennatula phosphorea, Virgularia miribalis, Bolocera tuediae, Asteroidea, Echinoids, Nephrops* burrow, *Hyalinoecia tubicola; Bolocera tuediae* and *Stichastrella rosea* on pipeline	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Forties C to Cruden Bay Stn 1 TV1 21-05-15	57.637308	-0.182621	57.632077	-0.186935	fine sand, shelly sand	yes	104	106	22:52	*Pennatula phosphorea, Virgularia miribalis,* unidentified anemones, *Majoidea, Asturias rubens, Scyliorhinus sp., Pleuronectiformes;* hydroids and Paguridae on pipeline	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Forties C to Cruden Bay Stn 1 TV2 21-05-15	57.635937	-0.206788	57.629881	-0.213053	fine sand, shelly sand	yes	105	108	26:13	*Pennatula phosphorea, Virgularia miribalis,* unidentified anemones, *Asturias rubens, Astropecten irregularis, Stichastrella rosea, Hippasteria phrygiana, Nephrops norwegicus, Myxine glutinosa, Pleuronectiformes, Paguridae* with and without *Hydractinia* associated with pipeline	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Forties C to Cruden Bay Stn 1 TV3 21-05-15	57.632511	-0.252207	57.621927	-0.286242	fine sand, shelly sand	yes	107	106	37:58	*Pennatula phosphorea, Virgularia miribalis, Pleuronectiformes, Nephrops norwegicus, Asturias rubens, Paguridae with Hydractinia, Triglidae,* unidentified anemones and hydroids on pipeline	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Forties C to Cruden Bay Stn 1 TV4 21-05-15	57.625453	-0.294247	57.617129	-0.299769	fine sand, shelly sand, cable	no	100	100	23:03	*Pennatula phosphorea, Virgularia miribalis, Nephrops norwegicus, Paguridae, Hyalinoecia tubicola, Asturias rubens, Holothurian, Sabella pavonina,* bivalve displaying paired siphons, *Myxine glutinosa, Triglidae, Raja sp.,* unidentified teleost fish	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg

Forties C to Cruden Bay Stn 1 TV5 21-05-15	57.625453	-0.294247	58.609551	-0.299769	fine sand	no	99	101	3:06	*Pennatula phosphorea, Actinauge richardi, Epizoanthus incrustans, Sabella sp, Stichastrella rosea, Asturias rubens, Urticina sp., Cancer pagurus,* Paguridae, Brachyura, *Hyalinoecia tubicola, Myxine glutinosa,* unidentified teleost fish	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Forties C to Cruden Bay Stn 9 TV1 22-05-15	57.66252	0.145252	57.6675	0.140185	fine sand	yes	115	117	31:55	*Nephrops* burrows, Paguridae, *Myxine glutinosa*	SS.SSa.OSa	none
Forties C to Cruden Bay Stn 9 TV2 22-05-15	57.66579	0.17286	57.668	0.169865	fine sand, fine sand with shells, shelly sand	no	97	99	not present	Hydroid, *Asturias rubens*, Asteroidea	SS.SSa.OSa, SS.SMx.OMx	none
Forties C to Cruden Bay Stn 9 TV3 22-05-15	57.67056	0.178207	57.66254	0.180801	fine sand, mixed sand, sand with boulders	no	94	94	31:16	*Hyalinoecia tubicola,* tube worms, *Astropecten irregularis, Stichastrella rosea,* Hydroids, *Raja sp.*	SS.SSa.OSa, SS.SMx.OMx	none
Forties C to Cruden Bay Stn 9 TV4 22-05-15	57.66775	0.217449	57.67404 0.217449	0.214948	shelly sand and boulders, mixed sand and gravel, rock dump	no	86	87	1:35:50	Hydroids, *Stichastrella rosea, Astropecten irregularis, Axinella infundibuliformis,* Porifera	SS.SMx.OMx SS.SSa.OSa	none
Forties C to Cruden Bay Stn 9 TV5 22-05-15	57.67951	0.240938	57.67201 0.240938	0.24121 57.67201	mixed sand and gravel, rock dump 0.24121	no	87	86	not present	*Virgularia miribalis, Securiflustra securifrons, Hyalinoecia tubicola, Stichastrella rosea, Porania pulvillus, Asteroidea, Tethya sp.,* Porifera, *Paguridae,* unidentified teleost fish	SS.SMx.OMx	*Virgularia miribalis*
Forties C to Cruden Bay Stn 9 TV6 22-05-15	57.6693	0.249141	57.67785	0.251798	mixed sand and gravel, shelly sand	no	88	89	03:16:42	*Pennatula phosphorea, Asturias rubens, Astropecten irregularis, Porania pulvillus, Axinella infundibuliformis, Tethya sp., Hyalinoecia tubicola, Callionymus lyra; Stichastrella rosea* and hydroids on pipeline	SS.SMx.OMx	*Pennatula phosphorea*
Forties C to Cruden Bay Stn 9 TV7 22-05-15	57.67862	0.324564	57.68268	0.324851	fine sand	no	108	109	4:24:44	*Pennatula phosphorea, Nephrops burrows, Paguridae, Majidae, Asturias rubens, Luidia sarsi, Ophiuroidea, Aphroditidae, Pleuronectidae,* hydroids on side of pipeline	SS.SSa.OSa	*Pennatula phosphorea*
Brent A to St Fergus Stn 19 TV1 24-05-2015	58.592485	-1.005292	58.593207	-1.015719	no video	no video	116	116	no video	no video	no video	no video
Brent A to St Fergus Stn 19 TV2 24-05-2015	58.609408	-0.996931	58.609551	-1.004959	no video	no video	116	116	no video	no video	no video	no video

Brent A to St Fergus Stn 19 TV3 24-05-15	58.625556	-0.989350	58.624197	-0.261394	no video	no video	118	116	no video	no video	no video	no video
Brent A to St Fergus Stn 19 TV4 24-05-15	58.624989	-0.991624	58.625031	-0.997426	no video	no video	117	117	no video	no video	no video	no video
Brent A to St Fergus Stn 19 TV5 24-05-15	58.648627	-0.991624	58.648688	-0.985506	no video	no video	125	125	no video	no video	no video	no video
Brent A to St Fergus Stn 19 TV6 24-05-2015	58.673454	-0.966858	58.672500	-0.975125	no video	no video	120	119	no video	no video	no video	no video
Brent A to St Fergus Stn 20 TV1 25-05-15	59.898785	0.221013	59.90464	0.216687	mud / fine sand	yes	134	134	01:11:04	*Virgularia miribalis, Pennatula phosphorea, burrowing anemones, Hippasteria phrygiana, Hyalinoecia tubicola,* Paguridae, *Nephrops norwegicus, Lophius piscatorius*	SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Brent A to St Fergus Stn 20 TV2 25-05-15	59.93019	0.256007	59.9264	0.262875	mud / fine sand	no	124	124	not present	*Virgularia miribalis, Bolocera tuediae, Epizoanthus incrustans, Psammechinus miliaris, Hippasteria phrygiana, Asturias rubens,* Sabellid worm, *Hyalinoecia tubicola*	SS.SMu.OMu, SS.SMu.CFiMu.SpnMeg	SS.SMu.CFiMu.SpnMeg
Brent A to St Fergus Stn 20 TV3 25-05-15	59.94243	0.271973	59.93661	0.275601	mud / fine sand	no	125	122	03:16:00	*Nephrops norwegicus, Paguridae, Henricia sp., Ophiuroidea, Holothuroidea, Axinella infundibuliformis, Geodia barretti, Hyalinoecia tubicola, Salmacina sp./ Filograna sp., Bolocera tuediae,* burrowing anemones, *Lophius piscatorius*	SS.SMu.OMu, SS.SMx.OMx	burrowed mud
Brent A to St Fergus Stn 20 TV4 25-05-15	59.96091	0.302672	59.9563	0.311059	mud / fine sand	no	121	123	04:09:00	*Psammechinus miliaris, Spatangus purpureus, Echinus esculentus, Hippasteria phrygiana, Ophiuroids,* Holothurians, *Hyalinoecia tubicola, Bolocera tuediae, Nephrops norwegicus* and *Nephrops* burrows, *Brachyura, Glyptocephalus cynoglossus, Raja radiata, Pleuronectiformes;* hydroids on side of pipeline	SS.SMu.OMu, SS.SMx.OMx	burrowed mud