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Deep-sea observations at hydrocarbon drilling locations: contributions from the SERPENT Project after 120 field visits

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Abstract

The SERPENT Project has been running for over ten years. In this time scientists from universities and research institutions have made more than 120 visits to oil rigs, drill ships and survey vessels operated by 16 oil companies, in order to work with the industry's Remotely Operated Vehicles (ROV). Visits have taken place in Europe, North and South America, Africa and Australasia at water depths from 100 m to nearly 3000 m. The project has directly produced >40 peer reviewed publications and data from the project's >2600 entry online image and video archive have been used in many others. The aim of this paper is to highlight examples of how valuable data can be obtained through collaboration with hydrocarbon exploration and production companies to use existing industry infrastructure to increase scientific discovery in unexplored areas and augment environmental monitoring of industrial activity. The large number of industry ROVs operating globally increases chance encounters with large, enigmatic marine organisms. SERPENT video observations include the deepest known records of species previously considered epipelagic such as scalloped hammerhead (*Sphyrna lewini*) and southern sunfish (*Mola ramsayi*) and the first *in situ* observations of pelagic species such as oarfish (*Regalecus glesne*). Such observations enable improvements to distribution records and description of behaviour of poorly understood species. Specimen collection has been used for taxonomic descriptions, functional studies and natural products chemistry research. Anthropogenic effects been assessed at the local scale using *in situ* observations and sample collection at the time of drilling operations and subsequent visits have enabled study of recovery from drilling. Future challenges to be addressed using the SERPENT approach include ensuring unique faunal observations by industry ROV operators are reported, further study of recovery from deep-water drilling activity and to carry out *in situ* studies to improve the understanding of potential future decommissioning of obsolete hydrocarbon infrastructure.

Keywords

120, after, project, serpent, contributions, locations:, drilling, hydrocarbon, observations, deep-sea, visits, field

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Deep-sea observations at hydrocarbon drilling locations: Contributions from the SERPENT Project
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Keywords

Anthropogenic disturbance, Benthic megafauna, Decommissioning, In situ observation, Observatory,
Oil exploration, Remotely Operated Vehicle, Rigs-to-reefs, SERPENT Project

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42

1. Introduction

The world's deep seas provide important services (Thurber et al., 2014) and, increasingly, resources (Levin and Le Bris, 2015). They are subject to anthropogenic disturbance from global change and industrial exploitation (Glover and Smith, 2003; Ramirez-Llodra et al., 2011). For example, hydrocarbon exploration and production is now common in the deep-sea (Pinder, 2001). Despite this, there is limited research and few institutions and even countries in the world have extensive deep-sea research programmes (Ruth, 2006). Even at relatively shallow water depths *in situ* observational studies become more limited as depth increases beyond the reach of divers. Existing deep-sea research programmes are limited, as multi-disciplinary open ocean research requires specialist infrastructure, such as ships, autonomous underwater vehicles and remotely operated vehicles (ROVs), as well as significant financial resources.

The hydrocarbon industry operates in water depths to over 3000 m and has the financial resources to invest in the large scale offshore surveys and the infrastructure required to work in these areas. The industry has hundreds of deep-water ROVs in use globally on a daily basis. During routine operations these vehicles may also be on standby for long periods of time. The SERPENT Project (Scientific and Environmental ROV Partnership using Existing iNdustrial Technology) (www.serpentproject.com) aims to collaborate with hydrocarbon companies to make use of the offshore infrastructure, primarily through access to ROVs in standby time, in order to collect scientific data (Jones, 2009). Formed through collaboration with BP, Transocean and Subsea 7 to facilitate field visits to oil rigs in the North East Atlantic in 2002, the SERPENT Project has since worked with 16 oil companies (Table 1) and numerous ROV contractors and rig operators around the world (Figure 1). The SERPENT project is based in Southampton at the National Oceanography Centre and SERPENT hubs also work independently in Australia, New Zealand and SE Asia (SEA SERPENT) and the USA (Gulf SERPENT) with a focus on the Gulf of Mexico.

The SERPENT Project has proved important to deep-sea scientists, providing a valuable research infrastructure to access water beyond diver depth in hydrocarbon exploration areas. In addition, it has tangible benefits to industry through improvement of environmental management of activity areas. Data collected through SERPENT are primarily marine biological in nature and address scientific questions under two main themes:

- 1) the distribution and behaviour of deep-sea organisms
- 2) the effects of hydrocarbon exploration on deep-sea organisms

This paper aims to highlight examples of how valuable data can be obtained through collaboration with oil and gas companies, increasing scientific discovery in unexplored areas and supplementing environmental monitoring. The paper considers possible future directions using the approach to enhance understanding of deep-sea ecosystems, in particular in areas impacted by industry.

2. The SERPENT approach to deep-sea data collection

There are two main ways industry data can be collected by SERPENT:

- 1) Deep-sea ROV observations provided by industry to SERPENT scientists
- 2) Visits by scientists to offshore infrastructure (oil rigs, drill ships, survey vessels and support vessels)

2.1. Material provided by industry

The SERPENT Project has many links with industry, fostered through a continued presence and clear brand. This has been developed and maintained by promotion at conferences, in trade magazine articles, video material, online presence, lectures and in specific training given to ROV operators by SERPENT staff. These methods, as well as targeted campaigns, have encouraged ROV operators and company staff operating in deep water to look for and record observations of deep-sea species and habitat features, which are sent to the project coordinators. These are identified to the highest taxonomic resolution possible from the imagery and recorded in the SERPENT archive (<http://archive.serpentproject.com>). The SERPENT archive is a publicly available online database of images and video clips sent to the project and collected during offshore fieldwork. At the time of article submission it contains >2600 records from the offshore waters off 22 countries. Each entry shows thumbnail images or video clips with metadata and taxonomic information. Higher resolution versions are available on request. The SERPENT archive spans most areas of active offshore oil industry activity (Figure 1). The archive is compliant with the Open Archives Protocol for Metadata Harvesting so it can be incorporated into other global databases. As an example, the SERPENT archive is harvested by the Encyclopaedia of Life (www.eol.org) (EOL, 2015) providing images for often poorly known deep-sea species (http://eol.org/content_partners/248). Independently the Australian Museum hosts images from Australian waters. (e.g. <http://australianmuseum.net.au/fishes-by-habitat-deepsea-fishes>).

2.2. Visits

At the time of article submission the SERPENT Project had completed 127 visits to drilling rigs, survey vessels and support vessels in 13 countries (study locations are listed in Table 1 and shown in red on

Figure 1). Visits are normally made to exploration drilling rigs during drilling programmes, when ROVs can be accessed in stand-by time, when the ROV is prepared for diving but has no tasked work. Crucially, SERPENT observations are normally carried out at times that do not interfere with industry operations (exceptions are pre-drilling surveys which may delay onset of drilling). At exploration drilling sites ROV dives are used for general visual inspections of risers and blow-out preventers (BOPs) on a near daily basis. SERPENT ROV access is most often provided after this scheduled operational work. As well as enabling the collection of scientific observational data or samples, this provides opportunities for the less experienced ROV team members to increase their piloting experience to the benefit of their professional development.

On several occasions it has also been possible to visit installations before any drilling (and hence seabed disturbance) has taken place. While desirable for scientific investigations, these pre-drilling visits are more challenging because time is limited at this stage in the drilling process. Pre-drilling SERPENT surveys will normally delay the onset of drilling so require additional negotiation or a particular interest from the host company. In such cases, the SERPENT observations can be carried as an enhancement of the ROV 'as found' survey, which is designed to assess the presence of obstacles, munitions or obvious features to avoid, and to create a record of site condition prior to drilling, so the company can 'leave it as they found it' when drilling activity is completed.

Many SERPENT offshore visits have been in relatively well-studied deep-sea areas such as the Gulf of Mexico and the North East Atlantic, but even in these areas novel observations are relatively common. Data collected by SERPENT supplement ongoing studies in these areas and add to environmental monitoring in hydrocarbon exploration areas. In the north east Atlantic, 21 drilling sites have been visited off Norway and UK, covering a range of water depth from 150 m to over 1700 m.

The study of poorly known areas, which have been largely neglected by institutions and expeditions in nationally funded research programmes, can be enhanced by using industry infrastructure. Examples include visits to the Orinoco fan off Venezuela (Jones et al., 2012b), the Gulf of Guinea off Nigeria (Jones et al., 2013); the Nile submarine fan, off Egypt, the deepest SERPENT site visited so far, located at 2720 m depth (Gates et al., 2012); and in the western Indian Ocean off Tanzania (Gates, 2016).

2.3. ROVs and ROV time

In 127 SERPENT visits to offshore installations a variety of types of ROV have been used (Figure 2). The majority have been Oceaneering, Subsea 7 or Fugro systems. Industry ROV systems are

increasingly acquiring HD video (e.g. 1920 × 1080 pixels or more), improving the quality of material collected through SERPENT. For example, Oceaneering International's Millennium ROVs, an important component of the deep-water offshore industry ROV fleet, are now routinely equipped with the Ocean ProHD® camera system (1920 x 1080 pixels). These can be enhanced by addition of digital stills cameras (e.g. Kongsberg OE14-408, DPC-8000). The resolution of images from these cameras, along with HD video provides an improved resource for the identification of species observed compared to the standard definition systems used when the project began. With the addition of specimens collected using a variety of methods, including modified sediment sampling devices, scoops, scrapers and baited traps, material has been used in taxonomic studies and to aid identification of organisms seen in video footage.

A significant amount of ROV time can be made available to SERPENT research in a typical visit. In the series of five visits to the *Deepsea Metro 1* drill ship operating in the Indian Ocean off Tanzania, 44 dives were completed with the aim of carrying out SERPENT activities, equating to over 114 hours of ROV time. Six visits to rigs in the Gulf of Mexico in 2009 yielded 64 hours of ROV time. In addition, in both cases, between scientist visits, the ROV team would regularly record footage of organisms they encountered, adding to the dataset collected during SERPENT visits.

2.4. Techniques

Using techniques such as in situ observations, video transects, specimen collection and deployment of equipment industry ROV can be used to collect integrated multi-disciplinary data (Table 2, Figure 3). It should be noted that it is not possible to carry out all the activities highlighted in Figure 3 in a single visit but parts are accomplished on every visit.

Physical and chemical properties of the environment have been routinely acquired using self-contained dataloggers (e.g. RBR XR-420) with appropriate sensors attached to the ROV or cage (Figure 3.1) or deployed on the seabed. Seabed current data (e.g. from Aanderaa Data Instruments self-recording Seaguard TD 262b current meter) (Figure 3.8) have been collected at the time of drilling to explain the observed distribution of drill cuttings around a well. The time-lapse camera used in SERPENT studies is an Insight Pacific Scorpio Plus digital still camera and strobe light with bespoke frame designed for ROV deployment. It has been used to assess the scavenging fauna at drilling sites when deployed with bait or to observe megafauna behaviour, highlighting fine scale habitat provided by individual coral colonies (Gates et al., 2016). Collection of certain faunal groups has been carried out with a variety of traps. Simple baited traps are used to capture large numbers

of necrophagous amphipods and isopods for taxonomic or morphological study (Figure 3.10) and light traps successfully collect photopositive epibenthic and pelagic fauna, in particular larval fishes.

Sediment sampling can be carried out successfully from industrial ROVs. ROV-operated push corers are used to collect quantitative sediment samples for assessment of sediment physical parameters such as particle size or chemical analysis and biological analyses such as meiofaunal assemblages (Figure 3.5), and Ekman corers modified for ROV deployment, for macrofaunal assessment. The Ekman corers have proved difficult to acquire sufficient replicates as each deployment requires an ROV dive whereas multiple push corers can be deployed per dive (e.g. six held in a bespoke rack attached to a manipulator arm, Figure 2b).

In situ experimentation using ROVs at oil and gas exploration sites has been successfully carried out. Simple experiments include baited time-lapse camera deployments, to compare the scavenging fauna at different locations and bait choice experiments, to investigate food preferences by the scavenging amphipod assemblages. Settlement experiments have been carried out including, as part of the INDEEP project (<http://www.indeep-project.org/wg/population-connectivity>), to deploy standardised settlement frames on deep-sea infrastructure to investigate larval settlement and connectivity in the deep sea. These experiments remain in progress but deployment and recovery of settlement plates attached to subsea structures such as blow-out preventers (BOP) has proved successful at two sites. Other experimental work carried out through SERPENT include the development of a method to present nutritionally defined food sources to deep-sea organisms (Andrews et al., 2008) and the assessment of sub-lethal stress by echinoids exposed to drilling disturbance (Hughes et al., 2010) and measurement of the gut throughput time of holothurians feeding on florescent tracers (Hudson et al., 2004).

3. Project outcomes

3.1 Biodiversity

A large part of data collection by the project is *in situ* observation in the vicinity of the drilling rig, either during scientist visits or ROV operator observations. Indeed, most chance encounters with large marine organisms occur outside SERPENT visits (Figure 3.3). There is still much to learn about most deep-sea species with behaviour, distribution and inter- and intraspecific interactions particularly poorly understood. The presence of a wide network of industry ROVs operating in deep water increases the likelihood of encounters with deep-sea organisms that would probably go unnoticed without a means to report them. Examples include the unique bathypteroiform swimming

200 motion and landing behaviour of the tripodfish *Bathypterois* sp. This was described from fortuitous
201 video footage obtained by the SERPENT Project when a specimen was encountered by ROV
202 operators working at 1440 m depth in the Atlantic off Brazil (Davis and Chakrabarty, 2011).
203 Encounters with large species such as manefish (Benfield et al., 2009), oarfish (Benfield et al. 2013)
204 and sleeper shark (Benfield et al., 2008) in the Gulf of Mexico indicate that even relatively well
205 studied areas of the deep sea reveal new records. The sleeper shark records have since been
206 supplemented by further (unpublished) observations suggesting that they are commonly observed
207 near the bottom within the bathypelagic zone in the Gulf of Mexico.

208 The deep pelagic is the largest but least explored living space on Earth (Robison, 2009) so
209 observations from industry ROVs are valuable. Biological processes there are essential to
210 understanding global biogeochemical cycles (Thurber et al., 2014). It is perhaps the only habitat on
211 Earth where unexpected encounters with large organisms occur and the presence of industry ROVs
212 here can provide notable observations. Such observations may not be attained through pre-planned
213 deep-sea research expeditions. In the Gulf of Mexico the use of mid-water ROV video transects and
214 opportunistic encounters yielded observations of four *Regalecus glesne* (oarfish) along with a fifth
215 observation during a post-oil spill natural resource damage assessment cruise that utilized SERPENT
216 survey methodologies (Benfield et al., 2013). These were the first records of apparently healthy
217 individuals from the Gulf of Mexico and include the deepest confirmed record of the species (463-
218 492 m). The footage also enabled descriptions of the primary means of locomotion (undulations of
219 the dorsal and anal fins; (Curet et al., 2011)) and vigorous escape behaviour (sinusoidal lateral
220 undulation of the entire body). SERPENT *in situ* observations of the deep-sea squid *Grimalditeuthis*
221 *bonplandi* from 914-1981 m depth in the Gulf of Mexico coupled with observations from the
222 Monterey Bay Aquarium Research Institute indicated a previously unknown behaviour in cephalopods
223 in which the tentacle is used as a lure to attract prey (Hoving et al., 2013). Other industry ROV mid-
224 water video surveys have revealed the first records of the large medusa *Stygiomedusa gigantea*
225 (Figure 4 c) (Benfield and Graham, 2010) and described swimming behaviour in manefish (likely
226 *Paracaristius* sp., Figure 4 f) (Benfield et al., 2009). Serendipitous observations of acrocirrid
227 polychaetes known as “squidworms” (*Teuthidodrilus* sp.) (Figure 4 m) from industry ROVs were cited
228 in a description of the species (*T. samae*). The SERPENT observations revealed different posture and
229 swimming behaviour to the specimen described, tantalisingly indicating a potentially unknown
230 species (Osborn et al., 2011).

231 A study of the depth distribution of three species of ocean sunfish using SERPENT archive data and
232 other publicly available online resources reported deep encounters with *Mola mola*, *M. ramsayi* and

Masturus lanceolatus (Phillips et al., 2015). Such data supplement tagging studies that provide more detailed information on the diving behaviour of individuals (Nakamura et al., 2015; Potter and Howell, 2011). Pop-up satellite tagging studies have typically focussed on the more common *M. mola* in preference to other sunfish species. The observations on the SERPENT archive included a new depth record for *M. ramsayi*. Similarly, SERPENT observations of scalloped hammerheads at 500 m and 1040 m in the Indian Ocean include the deepest record of this species (Moore and Gates, 2015), again supplementing the study of this species by tagging methods (Hoffmayer et al., 2013). The accumulation of such observations alongside tagging and other telemetry studies are adding to the growing evidence of species generally considered epipelagic making regular forays into meso- and bathypelagic depths, probably for feeding at the deep scattering layer, thereby providing a direct link between surface waters and the deep sea (Thorrold et al., 2014).

The accumulation of observations of even familiar organisms can reveal new ecological information. At water depths from 150-600 m on the UK and Irish continental slope the asteroid *Porania pulvillus* (Figure 4 l) is one of the most common megabenthic species (SERPENT sites: Cashel, Lancaster, Whirlwind, Schiehallion and Foinaven). Multiple records in the SERPENT archive, among other resources, have been used to demonstrate predatory behaviour in this species, previously considered a suspension feeder (Mah and Foltz, 2014).

In situ observation can provide insights into biological oceanographic processes. Analysis of replicated short sections of SERPENT ROV video data from a depth gradient in the Faroe-Shetland Channel indicated the spatial and temporal extent of diel vertical migrations of zooplankton, demonstrating the link these organisms create between surface and deep waters. The observations demonstrated greatest abundance of *Meganyctiphanes norvegica* at 400-600 m depth (Hirai and Jones, 2011). This food source is accessed by direct predation by benthic organisms such as squat lobster *Munida* sp. The observations of *Munida* sp. accessing krill as a food source was first recorded by SERPENT ROV observations (Hudson and Wigham, 2003) and subsequent photographs from the same approximate area (Figure 4 i) indicate this is may be a common behaviour that likely provides a direct exchange of carbon between the pelagic and the benthos. In the same area SERPENT also captured the first *in situ* footage of monkfish (*Lophius piscatorius*) feeding (Figure 4 k) (Laurenson et al., 2004). Further direct evidence of carbon flux to the seabed is highlighted by the observations of large numbers of *Pyrosoma* carcasses on the Mauritanian continental slope (Figure 4 e) (Lebrato and Jones, 2009). These observations, along with the direct scavenging of the carcasses by epibenthic megafauna, provide insight into the importance of the role of gelatinous detritus in the biological carbon pump. The encounters of large elasmobranch carcasses on the deep sea floor off Angola

(Figure 4 g) were the first observations of their kind and add to the understanding of the role of scavengers on carbon inputs to the deep sea (Higgs et al., 2014).

Quantitative video observations are carried out on all offshore visits. These may be benthic (Figure 3.4), mid-water (Figure 3.2) video transects or surveys of subsea structures. Benthic transects are used to assess the abundance and diversity of the megafaunal assemblage and document the extent of drill cuttings around the well. Typically a minimum of 8 and up to 24 video transects are carried out radiating from the well head. The survey design is, of course, limited by the length of ROV tether available on the stationary platform so multiple visits to an area during a programme of several wells are required to make contributions to understanding broader scale ecological patterns. When used in conjunction with other studies, such as industry baseline surveys, data acquired from ROVs on oil rigs can be valuable. For example, initial observations of the fauna inhabiting asphalt mounds off Angola initiated a more detailed industry ROV survey of the area. This revealed large areas of these features and demonstrated the importance of asphalt mounds to habitat heterogeneity and therefore species diversity on the west African margin (Jones et al., 2014). On the Nigerian margin ROV video surveys carried out from vessels supporting drilling in the area showed changes in the proportion of megafaunal deposit and suspension feeders in relation to increasing seabed slope (Jones et al., 2013). In the Norwegian Sea, SERPENT data from four drilling sites >1000 m depth were used to supplement the large habitat mapping programme MAREANO which had identified high densities of the burrowing amphipod *Neohela* sp. (Buhl-Mortensen et al., 2016). SERPENT close-up video footage of the amphipods in their burrows demonstrated the use of antennae to sweep material into the burrow, presumably as a mechanism to draw food towards it. Given the abundance of *Neohela* in the area the burrows may have an important sediment structuring role in large areas of the deep Norwegian Sea.

Specimen collection using ROVs at industry locations can add additional samples to aid taxonomic studies. These may also facilitate species identifications in unexplored areas that are subject to hydrocarbon exploitation. The integration of photographs, video data and specimens of organisms in context with location and environmental parameters from multiple visits to twelve sites deeper than 500 m in the North East Atlantic were used to produce a photographic identification guide to the megafauna inhabiting the cold water (Norwegian Sea deep water) of the oil and gas drilling areas in the Faroe-Shetland Channel and Norwegian Sea (Jones and Gates, 2010). This provides a resource for environmental baseline studies and impact assessment in the management of offshore oil and gas activities in the deeper waters of UK and Norway. Samples collected as part of the same SERPENT visits using simple baited traps were used to in a taxonomic study to revise the amphipod

genus *Paracallisoma* (Horton and Thurston, 2015) and studies on other amphipod groups continue.. Specimens collected by larger baited trap deployments on the Australian North West Continental Shelf (NWS), in parallel with video images, were used to study the giant isopod *Bathynomus pelor*. The specimens were analysed in conjunction with the *in situ* behavioural observations and demonstrated the mechanics of the mouthparts and antennae in feeding in this enigmatic species (Thomson, 2010; Thomson et al., 2009). Samples collected by the SERPENT Project have also been used in description of the European athecate hydroids (Schuchert, 2010) and in a synthesis of stalked jellyfishes (Staurozoa) (Miranda et al., 2016).

3.1.1. Natural products

Marine invertebrates such as sponges, corals and anemones produce a suite of natural chemicals for defence and communication that have been widely exploited for the pharmaceutical applications (Skropeta, 2010). Over 30,000 of these natural metabolites (natural products), have been described to-date. However, owing to the expense and logistical difficulty of conducting deep-sea research, <2% are reported from deep-sea organisms (> 100m depth). Through the SERPENT Project, researchers have gained access to a vast array of Australian deep-sea marine life to conduct detailed and fundamental natural product research. An Australian Research Council Linkage funded project on drilling effects on deep-sea ecosystems enabled natural products chemists to access a range of deep-sea fauna from the Australian continental shelf, including sponges, anemones, echinoderms and molluscs, which were assessed for their cytotoxic and antiviral activity (Skropeta, 2008). These studies demonstrated an exceptionally high hit-rate for bioactivity in deep-sea sponges, including inhibitors of enzymes that play key roles in cancer progression (Skropeta et al., 2011; Zivanovic et al., 2011). Further studies into the chemical signatures and bioactivity profiles of a range of deep-sea sponges are underway (Wei and Skropeta, 2011, 2012).

3.2. Anthropogenic disturbance

There are numerous environmental effects associated with the oil and gas industry including the routine discharges from drilling a well such as drill cuttings and produced water (Bakke et al., 2013), the presence of artificial structures (Benn et al., 2010), accidental discharges such as blow-outs or oil spills (Fisher et al., 2014) and global changes related to anthropogenic climate change to which the hydrocarbon industry contributes (Ramirez-Llodra et al., 2011). Many of these impacts are difficult to quantify but the use of industry ROVs launched directly from a drilling rig can enhance the study of the local scale impacts.

3.2.1 Routine operations

At exploration drilling wells, under typical best practice in the North East Atlantic the top section of the well is drilled without a marine riser, resulting in discharges of drill cuttings and drilling mud to the seabed. Drilling mud is used to lubricate the drill bit, circulate cuttings and maintain pressure and integrity of the well (Hyne, 2001). Barite is a key component, used as a weighting agent in drilling muds (Hartley, 1996). Initial SERPENT studies at exploration wells have demonstrated that there is the impact to the sediment surrounding the well resulting from drilling the top section at 6 sites over various benthic habitats: Ragnarokk (114 m depth, North Sea, NE Atlantic), Foinaven (510 m, Faroe-Shetland Channel, NE Atlantic), Scheihallion (420 m, Faroe-Shetland Channel, NE Atlantic), Morvin (380 m Norwegian Sea, NE Atlantic), Orca (453 m, Orinoco Fan, off Atlantic coast of Venezuela), Laggan (600 m, Faroe-Shetland Channel, NE Atlantic). The effect common to all the sites is the reduced heterogeneity at close proximity to the well, as the sediment is smothered by drill cuttings and drilling mud (examples in Figure 5). At Morvin, measurements of graduated marker buoys located 10 m from the well indicated up to 400 mm vertical accumulation of sediment which reduced with distance from the well (Gates and Jones, 2012).

Sediment samples collected along the disturbance gradient at Ragnarokk revealed barium concentration of 6000 mg kg sediment dry weight⁻¹ at 10 m from the well, reducing to 150 mg kg sediment dry weight⁻¹ at 100 m). This was compared to values of 39-80 mg kg sediment dry weight⁻¹ before drilling. (Hughes et al., 2010). Similar sampling methodology at Morvin before drilling showed low barium concentration (150 mg kg sediment dry weight⁻¹) but high concentration close to the well (5450 mg kg sediment dry weight⁻¹) immediately after drilling, again reducing with distance (230 mg kg sediment dry weight⁻¹ at 100 m) (Gates and Jones, 2012). Samples collected at both sites indicate a reduction in particle size on the cuttings pile compared to further from the well, and before drilling. At Ragnarokk before drilling and at 100 m from the well after the disturbance percentage fines (<63 µm) was 6-6.3% whereas at 10 and 25 m from the well after drilling it was 50.1-54.9% (Hughes et al., 2010). At Morvin pre-drill particle size was lower (38-53% fines) but was still reduced by discharge of drill cuttings (80% fines 10 m from the well after drilling) (Gates and Jones, 2012). The general reduction in particle size with depth in background sediments in for example the Faroe-Shetland Channel (Bett, 2001) or Norwegian Sea (Buhl-Mortensen et al., 2015) may result in a differential disturbance with similar drilling scenarios. Deep-water organisms may be exposed relatively coarse particle size sediment relative to their background in contrast to animals in shallower water experiencing disturbance by finer material than background, which likely has consequences for re-settlement and recovery from drilling disturbance.

These changes to the benthic environment have a direct impact on the megabenthic assemblages. At the six SERPENT sites megabenthic abundance was reduced within 50 m of the well (Figure 6). The effects of top-hole drilling on benthic habitats appear to be on a relatively local scale. On a very fine scale there seems to be more variation. For example at Laggan there was an increase in scavenger abundance at intermediate distances, considered to be a response to additional food supply from moribund organisms (Jones et al., 2006), while apparent smaller impacts of drilling at the Orca well off Venezuela's Atlantic coast may be because the benthic invertebrates are adapted to greater sedimentation regime owing to the proximity of the Orinoco river. At Rangarokk in the North Sea the megabenthic assemblage was dominated by the echinoid *Echinus acutus* which abundance was reduced close to the well. The abundance of echinoids at Ragnarokk, and the time available to work with the ROV enabled detailed, more time consuming analyses to be carried out at drilling locations. Experimental methods were employed to explore the sub-lethal effects of burial by sediment to simulate drilling disturbance. The resulted in responses in significant changes in *stress-70* gene expression but this varied depending on the tissue sampled (Hughes et al., 2010). Further evidence of the effect on individual organisms seems to suggest important impacts of bioturbators. The burrows of the locally abundant, large burrowing amphipod *Neohela monstrosa* were absent in the vicinity of drilling wells in the deep Norwegian Sea (Buhl-Mortensen et al., 2016).

Although several studies have investigated drilling disturbance (Currie and Isaacs, 2005; Mojtahid et al., 2006; Netto et al., 2010; Netto et al., 2009) SERPENT studies benefit from using ROVs directly from the drilling rig. This enables the fine-scale characterisation at the time of drilling, which is not possible from survey vessels that generally have to remain outside of a 500 m exclusion zone to avoid dangerous proximity to drilling rigs. Furthermore, much of the most cited literature about drilling disturbance refers to older practices including the discharge of oil-based drill cuttings on the seabed (Breuer et al., 2004; Olsgard and Gray, 1995). The recent SERPENT papers from the north-east Atlantic study attempt to provide some updated studies demonstrating the effects of the modern methods where water-based drilling muds are discharged following changes in legislation (OSPAR Commission, 2000).

The development of a dataset detailing the initial impact of drilling at 21 sites in the north east Atlantic creates the possibility to revisit the sites to study the process of recolonization and recovery in deep water. On return of a drilling rig to the Lancaster site, west of Shetland, UK, one year after drilling there had been of colonization of the cuttings pile by large numbers of small polychaete worm tubes (Figure 5 f). A single non-quantitative sediment sample from this area of the cuttings pile revealed spionid polychaetes of the genus *Polydora*. This genus is recognized as a pioneer

species and is often one of the first colonizers of disturbed shallow benthic marine habitats (Van Colen et al., 2008). Experimental evidence demonstrates colonization of water-based drill cuttings by polychaetes of the same genus off Norway (Trannum et al., 2011). More detailed, ROV visual studies of recovery were carried out from survey vessels at the Laggan site at 595-640 m depth in the Faroe-Shetland Channel (Jones et al., 2012a) and Morvin at 380 m depth in the Norwegian Sea (Gates and Jones, 2012). These studies both show some evidence for recovery of megabenthic assemblages but there is persistence of the disturbance after three years. At Laggan the examination of a ten year old well also indicated persistence of disturbance over a smaller area. In both cases the megafaunal assemblage remained reduced in abundance over a smaller area close to the well but species composition was similar to earlier surveys.

3.2.2 Accidental impacts

The non-routine, accidental impacts from oil and gas drilling are more difficult to assess. The use of the SERPENT approach across a range of sites can improve understanding of the typical impacts under normal conditions which can assist with assessing changes in relation to accidental discharges. The Deepwater Horizon oil spill in the Gulf of Mexico during 2010 highlighted the relative paucity of data available to assess the biological impacts of the spill on deep-sea megafauna. Gulf SERPENT surveys from the Deepwater Horizon conducted in February and March 2010 immediately prior to the spill indicated which taxa were commonly present in the vicinity of the BOP. These observations, though not quantitative, provided the only data on megafauna available at that site prior to the spill. In follow up to the spill, Gulf SERPENT water-column and seafloor survey protocols were used during August 2010 to quantify the distributions and abundances of megafauna at five sites located 500 m North and at 2000 m North, West, South, and East of the Macondo well. Comparisons of animal abundances indicated that 2000 m north and 2000 m west had the greatest abundance and taxonomic richness while 2000 m east had slightly lower values. In contrast 500 m north and 2000 m south had the lowest megafaunal abundance and taxonomic richness (Valentine and Benfield, 2013). These results generated from SERPENT quantitative surveys demonstrated the utility of statistically comparing megafaunal densities from different deep-sea sites.

3.2.3 Subsea infrastructure

Access to offshore operations through the SERPENT Project allows detailed studies of the biological communities that develop on industry structures (e.g. Figure 4 o). In the North Sea, a diverse range of taxa were observed associating with oil rig legs. Cnidarians *Lophelia pertusa* and *Metridium senile* were important colonisers and there was evidence for zonation with depth and assemblage variation

with the age of the structures (Guerin et al., 2007). On Australia's NWS, detailed studies have revealed a broad range of fish species associating with obsolete oil and gas structures located at 85-175 m depth. Species were functionally diverse, ranging from small reef-dependent planktivores (e.g. red-belted anthias *Pseudanthias rubrizonatus*) through to large pelagic predators (e.g. greater amberjack *Seriola dumerili*) and included ten commercially important species from the region (Pradella et al., 2014). This study also provided the deepest video record (175 m) of the whale shark (*Rhincodon typus*), which can be seen repeatedly approaching structures in the drilling area. The small reef fish *Pseudanthias rubrizonatus* collected in this study showed that they can develop unique otolith chemical signatures and otolith shapes over spatial scales of just 10-84 km (Fowler et al., 2015). Such information can potentially be used to identify movement of fish between structures and natural reefs, as well as trace fish back to their structure of origin. The latter would allow estimation of secondary production and export of fish biomass – a critical element for assessment of the habitat value of industry structures (Claisse et al., 2014). Such studies are important in the light of increasing interest in artificial structures in relation to future decommissioning of hydrocarbon infrastructure (Macreadie et al., 2011).

The hard substratum provided by industry structures is often in areas where natural reef is rare. In some regions, industry structures represent the largest addition of artificial habitat to the marine environment (e.g. northern Gulf of Mexico), and have the potential to alter surrounding ecosystems through both physical and biological interactions (see Gallaway et al., 2009; reviewed by Macreadie et al., 2011) (Gallaway et al., 2009; Macreadie et al., 2011). Debate about the reef effects of oil and gas structures is ongoing, particularly with regard to their ability to produce 'new' biomass rather than simply attracting and removing it from surrounding natural habitats (the 'attraction vs production' debate; (Bohnsack, 1989)). The debate has been fuelled by a lack of data, resulting from the logistical difficulties associated with studying reef habitats in deep water. For example, SERPENT investigations demonstrated that isolated, long established (>20 years) industry structures on Australia's North West Shelf (NWS) develop and sustain populations of reef fish for periods of up to 5 years (Fowler and Booth, 2012) provides the first evidence that industry structures are capable of generating fish biomass. The finding also indicates that industry structures can act as suitable settlement and nursery habitat for at least some species of deeper-dwelling reef fish with planktonic larval stages.

4. Limitations

There are some key limitations to SEREPENT activities on board oil rigs and drill-ships. Firstly, the ROV is launched from a stationary vessel so the length of the tether (that connects the ROV with a

depressor weight, cage/garage or “top hat” tether management system, Figure 2) limits the area it can explore. All observations therefore take place within approximately a 100-500 m radius of the well. The work is also carried out in an area subject to anthropogenic disturbance from drilling activity. This results in reduced abundance of sessile fauna around the well owing to discharges related to drilling, while the structures in place may also attract motile fauna (Vardaro et al., 2007). Although limiting in terms of studies of the natural environment this does present the opportunity to address questions relating to drilling disturbance and the presence of structures on the deep sea. Moreover, electro-hydraulic ROVs are acoustically loud vehicles equipped with bright white lights. These factors likely induce different degrees of avoidance responses in the suite of organisms present thereby biasing biodiversity measurements towards sessile taxa and those that are least averse to the presence of the ROV. Site-specific investigations are also usually limited to the timeframe of a drilling campaign (typically ≤ 3 months), following which there are few opportunities to return to the same site. This can prevent the investigation of longer-term drilling effects, and the assessment of recovery end-points for ecosystems disturbed by drilling activity. Furthermore there is limited space on a working drilling rig. Laboratory space is unlikely to be available and workshop space is shared with a variety of users.

Additional limitations can arise as a result of working with industry. Sensitive subjects such as disturbance from drilling and the effects on marine organisms require contractual assurance about publication of results. There are also practical limitations related to the working environment on board exploration drilling rigs. Personnel requirements change regularly depending on the operations and visits by scientists are low priority and the first to be removed from schedules when accommodation is limited. This can occur, even at very short notice, resulting in wasted time and money.

5. Value to stakeholders, education and outreach

The SERPENT Project has benefits beyond scientific research. A key benefit is knowledge exchange between the industry and science. Much of SERPENT activity is driven by the desire of hydrocarbon exploration companies to assess their offshore impacts and to collect more data about the environment they operate in. This information is essential for effective environmental management and data collected through SERPENT has resulted in changes in drilling, including avoiding cold-seep habitats during drilling operations in West Africa. In addition, the survey approaches developed through SERPENT have been used by oil companies and regulators in pre-drill assessments. The environmental data collected through SERPENT has been used in environmental statements and drilling permit applications, supplementing surveys of oil and gas areas.

Beyond oil and gas there is likely value in similar approaches to other industries operating in the deep sea. The use of opportunistic methods similar to SERPENT could potentially provide additional data or samples to understand the background environment and species assemblages present by opportunistic sampling and observations. Furthermore, the observable impacts of disturbance in over short time-scales that may aid understanding of the longer term impacts. The nascent deep-sea mining industry is expected to have sedimentation and burial impacts on benthic organisms (Vanreusel et al., 2016) so observations at the time of impact may assist understanding of interaction of the mining tools with the seabed and the subsequent local scale impact (although wider scale effects of sediment plumes could not be addressed using this method).

SERPENT has been active in public engagement on environmental issues, particularly highlighting the importance of deep-sea systems. The high-resolution photographs and videos of deep-sea species have been used to generate public interest in the environment of active industry areas. This has been achieved through a popular website (www.serpentproject.com), as well as numerous talks, magazine articles and exhibitions at scientific and industry events (approximately 80 industry and popular magazine or web articles about the project). This has led to increased awareness of environmental issues inside the oil companies and their contractors. Increasing awareness has been particularly valuable on the oil installation itself. As part of SERPENT visits the researchers engage in education activities. Presentations are made during visits to drilling rigs as part of Health Safety and Environment training to raise awareness of the unseen deep-sea environment that offshore operations influence, leading to greater engagement with sustainability initiatives and increased efforts to limit operational damage to the environment.

Educational outreach activities at schools and science exposition such as Louisiana Sea Grant's Ocean Commotion and Royal Society Summer Science Exhibition provide an opportunity to bring the deep sea directly into the classroom. New 3D HD video camera systems operated on some Oceaneering ROVs working for Shell provide students with an immersive educational experience.

Novel video and images of deep-sea species generate media interest and are useful for public outreach, providing the opportunity to raise public awareness of the deep sea and issues affecting it. This is evident by the willingness of media outlets such as the BBC, Washington Post, New Scientist and Daily Mail to run stories on SERPENT observations. Examples include Oarfish termed "Giant Sea Serpents", resulting in a 580% increase in visits to the SERPENT website, carcasses of large elasmobranchs described as a "Deep-sea Graveyard" (410% increase) and video footage of a deep-sea siphonophore (*Bathypphysa* sp.), which resembled the fictitious deity the "Giant Spaghetti Monster" (1057% increase and estimated >10M views online across numerous sources).

527 **6. Future Direction**

528 When the SERPENT Project began in 2002 there were few projects providing ROV video footage and
529 imagery. There are now increasing efforts to explore the deep sea and provide image and video
530 material of high quality. Projects such as the Ocean Exploration Trust's *E/V Nautilus* (Bell et al., 2014)
531 and NOAA's *Okeanos Explorer* (Hammond et al., 2010) provide publicly accessible live ROV video
532 feeds with real-time commentary from experts, a feature unlikely to be possible through the
533 SERPENT Project. As data from such programmes, SERPENT included, increase and data are archived
534 greater understanding of faunal distributions, behaviour, associations and symbioses will be
535 revealed. It is therefore important to continue access to industry data. The SERPENT approach
536 remains highly relevant because using ROVs launched from active drilling rigs can provide a means to
537 increase observations in some of the areas most impacted by industry. The use of existing
538 technology in this way adds value to ROVs already on board.

539 While SERPENT generally provides a resource for opportunistic data collection over wide spatial
540 areas longer term data are also required to understand deep-sea ecosystems. Longer term time-
541 series observations are increasing through the development of deep-sea observatories such as
542 Neptune Canada (Juniper et al., 2013) and the European Multidisciplinary Seafloor and water
543 column Observatory network (EMSO) (Favali and Beranzoli, 2009). Such developments highlight the
544 increasing need to understand and monitor a range of parameters from deep sea habitats (Ruhl et
545 al., 2011). This is particularly true in areas of anthropogenic disturbance such as oil and gas
546 exploration and production (Purser and Thomsen, 2012) and decommissioning (Fowler et al., 2014).
547 These observations can supplement other ongoing industry efforts to understand the environment
548 they operate in such as, in the eastern Atlantic off Angola, the time-series ocean observations made
549 in collaboration with industry through the DELOS platform (Vardaro et al., 2013). Alongside targeted
550 baseline environmental surveys there is the potential for detailed understanding of temporal and
551 spatial faunal variation of faunal assemblages that can be supplemented through additional SERPENT
552 ROV observations.

553 Access to drilling locations through SERPENT has been used to begin to address the trajectory of
554 recovery from drilling activity (Gates and Jones, 2012; Jones et al., 2012a). The studies of recovery
555 carried out at existing sites (Laggan and Morvin) should be repeated to continue to monitor the
556 recovery trajectory over longer time periods. However, studies of recovery at the deepest drilling
557 sites have not yet been attempted. The Laggan study was carried out to around 600 m depth,
558 beyond this depth the water temperature in the area reduces considerably (Jones et al., 2012a). The
559 deepest drilling sites west of Shetland and in the Norwegian Sea are influenced by Arctic water

masses with sub-zero water temperature (Bett, 2001). Long term faunal responses to anthropogenic change at such temperature and depth are unknown. Similar knowledge gaps exist for all the deeper drilling sites and in the more remote areas where drilling is taking place, where knowledge of the deep-sea fauna is even more limited. There is value in continued studies of initial disturbance at new drilling locations in order to provide more sites where there may be opportunities to return to study recovery. This is particularly true in deeper water.

Biological interactions between industry structures and surrounding ecosystems represent a major knowledge gap regarding industry impacts on the marine environment. Key questions yet to be answered are the degree to which industry structures facilitate connectivity and population persistence of deep reef communities, the extent to which they export biomass of commercially- and ecologically- important taxa, and the extent to which industry structures spread invasive species (Macreadie et al., 2011). SERPENT'S access to arrays of industry structures allows investigation of the dispersive capabilities of reef organisms over a range of spatial scales, through both visual observations and collections of organisms using faunal traps.

The spread of invasive species is recognised as a major potential impact of industry structures on the marine environment (Fowler et al., 2014), yet there has been surprisingly little investigation of this threat to date. Industry structures may act as 'stepping stones' for invasive species, facilitating their spread in regions where natural reefs were previously too isolated to allow dispersal (Macreadie et al., 2011). Some industry structures are also known to support high densities of exotic invertebrates, for example, high densities of three exotic invertebrate species were found on oil platforms off California (Page et al., 2006). Such exotic invertebrates may pose a risk to natural reefs that have not yet been colonised in the region, depending on their invasive potential.

At present in the UK alone some 475 installations, 10,000 kilometres of pipelines, 15 onshore terminals and 5,000 wells will eventually have to be decommissioned. Of these, over 50 fields will either be approaching or undertaking decommissioning by 2018 (Oil and Gas UK, 2015). The Oslo and Paris (OSPAR) Convention, which provides the legislative framework for protecting and conserving the north-east Atlantic, has prohibited the dumping, and leaving wholly or partly in place, of disused offshore installations (OSPAR Decision 98/3 on the Disposal of Disused Offshore Installations). However, it is possible to gain permission to leave some large concrete and steel structures in place or partially in place (Derogation cases). The initial two UK installations that have already received DECC approval for decommissioning programmes with derogation from OSPAR 98/3, are NW Hutton, operated by BP, and Frigg MCP01, operated by Total. Several other installations and pipelines have been identified to be likely to apply for OSPAR derogation owing to

their size and difficulty in removing safely. In total in the UK there is the potential for up to: 9 concrete platforms, between now and 2029; 31 large steel platforms, between now and 2035; and 5300 km of large diameter trunk pipelines (U.K. Fisheries Offshore Oil & Gas Legacy Trust Fund Limited). SERPENT has already started theoretical work in decommissioning decision making (Fowler and Booth, 2012; Fowler et al., 2014; Macreadie et al., 2011) and has accessed large archives of structural inspection footage for scientific assessment (Guerin, 2009). The SERPENT approach could be used in the future to develop cases for decommissioning and derogation decisions by completing new or refining existing structural surveys or monitoring of cuttings piles and pipelines. There are many stages of the decommissioning process when ROVs are present around the infrastructure and would have time available for SERPENT work.

In other regions of the globe, decommissioning regulations are considerably more flexible (e.g. the US) or have not yet been formalised (e.g. Southeast Asia). A range of alternatives to complete removal exist and may be considered during the decommissioning decision process. For example, the conversion of obsolete platform jackets into artificial reefs (rigs-to-reefs, RTR) is becoming increasingly popular in the US, with over 190 structures already converted to artificial reefs in the northern Gulf of Mexico (Kaiser and Pulsipher, 2005). The decision to remove an obsolete structure or leave it in the marine environment is complex, and 14 separate environmental considerations have been proposed for inclusion in the decision process (Fowler et al., 2014), for most of which there is little information available (e.g. spread of invasive species). The SERPENT approach and industry network will be important for addressing these knowledge gaps and integrating them into formal decision processes, both in specific decommissioning cases and on a global scale. Such information will also be essential for the development of decommissioning regulations and processes in those regions that do not already have policies in place.

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884

885 **Tables:**

886 Table 1: 100 SERPENT visits. All scientific visits to industry rigs and vessels by the SERPENT Project
887 (FSC = Faroe-Shetland Channel, GOM = Gulf of Mexico, WIO = Western Indian Ocean, NS =
888 Norwegian Sea)

number	Rig / Vessel	Site Name	Company	Location	Depth (m)	Date of visits	Lat	Lon
1	M.V. Regalia	Schiehallion	BP	FSC, UK		20-28 July 2002	60.4	-4.1
2	Paul B Loyd Junior	Foinaven	BP	FSC, UK	508	14-28 May 2003	60.3	-4.3
3	M.V. Nordica	Schiehallion	BP	FSC, UK	400	25-28 July 2003	60.4	-4.1
4	Transocean Leader	Schiehallion	BP	FSC, UK	400	09 Sep - 03 Oct 2003	60.4	-4.1
5	Jack Bates	Laggan	Total	FSC, UK	600	14-23 Apr 2004	60.9	-2.9
6	Subsea Viking	Schiehallion	BP	FSC, UK	400	Sep 2004	60.4	-4.1
7	Boa Deep C	TIOF	Woodside	Mauritania	<1400	16-23 Sep 2004	17.9	-16.9

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8	Ocean Bounty	Calister 1	Santos	Otway Basin, Australia	130	21 Oct - 01 Nov 2004	-39.0	141.0
9	Jack Bates	Enfield 1	Woodside	Australia	550	21 Mar - 01 Apr 2005	-18.5	115.5
10	Paul B Loyd Junior	Schiehallion	BP	FSC, UK	400	23 - 27 Apr 2005	60.4	-4.1
11	Transocean Leader	Onyx	Shell	NS, Norway		May 2005	64.5	6.8
12	Jack Bates	Enfield 2	Woodside	Australia	495	24-27 May 2005	-18.5	115.5
13	Sedco 703	Pluto	Woodside	Australia	360	30 Jul - 03 Aug 2005	-18.5	115.5
14	Jack Bates	Enfield 3	Woodside	Australia	545	12-23 Dec 2005	-18.5	115.5
15	Sedco Express	Block 18	BP	Angola		Jan 2006	-8.5	-12.3
16	Paul B Loyd Junior	Schiehallion	BP	FSC, UK	400	26 Feb - 05 Mar 2006	60.4	-4.1
17	Jack Bates	Enfield 4	Woodside	Australia	534	15-21 Mar 2006	-18.5	115.5
18	Eirik Raude	Uranus	Statoil	Barents Sea, Norway	230	17-23 Mar 2006	72.0	26.0
19	West Alpha	Morvin	Statoil	NS, Norway	370	20-27 Apr 2006	65.1	6.5
20	Eirik Raude	Edvarda	Statoil	NS, Norway	1730	17-23 May 2006	64.2	4.0
21	Maersk Guardian	Thylacine-3	Woodside	Otway Basin, Australia	92	22-26 May 2006	-39.2	142.9
22	Eirik Raude	Edvarda	Statoil	NS, Norway	1730	19-20 Jun 2006	64.2	4.0
23	Stena Don	Brugdan	Statoil	FSC, Faroe	480	10-13 Jul 2006	61.3	-4.9
24	Ocean Bounty	Mutineer	Santos	Carnarvon Basin, Australia	146	19-27 Jul 2006	-19.3	116.6
25	Stena Don	Brugdan	Statoil	FSC, Faroe	480	07-14 Aug 2006	61.3	-4.9
26	Stena Don	Brugdan	Statoil	FSC, Faroe	480	30 Aug - 04 Sep 2006	61.3	-4.9
27	Polar Pioneer	Tornerose	Statoil	Barents Sea, Norway	408	31 Aug - 04 Sep 2006	71.6	-22.9
28	Stena Don	Brugdan	Statoil	FSC, Faroe	480	11-17 Oct 2006	61.3	-4.9
29	Polar Pioneer	Nucula	Hydro	Barents Sea, Norway	293	29 Jan - 03 Feb 2007	71.6	25.2
30	Fugro Mercator	Laggan	Total	FSC, UK	650	Apr 2007	60.9	-2.9
31	Transocean Rather	Rosebank	Chevron	FSC, UK	1085	04-12 Apr 2007	61.0	-3.8
32	Transocean Rather	Rosebank	Chevron	FSC, UK	1085	07-13 Jun 2007	61.0	-3.8
33	Transocean Leader	Midnattsol	Statoil	NS, Norway	928	01-05 Jul 2007	64.0	5.3
34	West Epsilon	Ragnarokk	Statoil	North Sea, Norway	114	26-30 Jul 2007	58.9	2.4
35	Sovereign Explorer	Orca	Statoil	Venezuela	543	22 Jul - 03 Aug 2007	9.7	-59.7
36	Transocean Leader	Midnattsol	Statoil	NS, Norway	928	23-29 Aug 2007	64.0	5.3
37	West Epsilon	Ragnarokk	Statoil	North Sea, Norway	114	30 Aug-05 Sep 2007	58.9	2.4
38	Songa Mercure	Mutineer 13	Santos	NW Shelf, Australia		24 Sep – 03 Oct 2007	-20.0	115.1
39	Transocean Rather	Rosebank	Chevron	FSC, UK	1125	26 Sep - 01 Oct 2007	61.0	-3.8
40	Songa Mercure	Mutineer 13	Santos	NW Shelf, Australia		22 – 25 Oct 2007	-20.0	115.1
41	Discoverer Enterprise	Mississippi Canyon 777	BP	GOM, USA	1716	01-02 Nov 2007	28.3	-88.5
42	Mad Dog Spar	Green Canyon 782	BP	GOM, USA	1353	11-13 Dec 2007	27.0	-90.0
41	Thunder Horse PDQ	Mississippi Canyon 778	BP	GOM, USA	1792	15-18 Jan 2008	28.2	-88.5
42	Discoverer Deep Seas	Walker Ridge 677	Chevron	GOM, USA	2101	19-22 Feb 2008	26.3	-91.1
43	Ocean Bounty	Wheatstone 3	Chevron	NW Shelf, Australia		9-12 Mar 2008	-19.9	115.3
44	Ocean Bounty		Woodside	NW Shelf, Australia		2-7 Apr 2008		
45	Songa Mercure	Ichthys West 2	Inpex	NW Shelf, Australia		13-23 May 2008	-13.9	123.1
46	Ocean Vanguard	Cashel	Statoil	NW. Ireland	174	18-22 May 2008	54.7	-10.4
47	Stena Clyde			NW Shelf, Australia		29 May - 02 Jun 2008		

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48	Ocean Patriot	Jarver 1	Santos	NW Shelf, Australia	600	30 May - 06 Jun 2008	-41.3	144.2
49	Havila Harmony		Woodside	NW Shelf, Australia		04-10 Jun 2008		
50	Ocean Vanguard	Cashel	Statoil	NW. Ireland	174	13-18 Jun 2008	54.7	-10.4
51	Havila Harmony		Woodside	NW Shelf, Australia		18-30 Jun 2008		
52	Havila Harmony		Woodside	NW Shelf, Australia		20-26 Jun 2008		
53	Ocean Vanguard	Cashel	Statoil	NW. Ireland	174	27 Jun - 01 Jul 2008	54.7	-10.4
54	Thunder Horse PDQ	Mississippi Canyon 778	BP/Exxon Mobil	GOM, USA	1841	30 Jun – 07 Jul 2008	28.2	-88.5
55	Ocean Bounty	Wheatstone 4	Chevron	NW Shelf, Australia	222	06-20 Jul 2008	-19.8	115.3
56	Havila Harmony		Woodside	NW Shelf, Australia		15-19 Jul 2008		
57	Stena Clyde	Van Gogh 3	Apache	NW Shelf, Australia	375	31 Jul – 03 Aug 2008	-21.4	114.1
58	Wilcraft			Bonaparte Gulf, Australia		29 Jul-04 Aug 2008	-12.0	126.0
59	Songa Mercure	Mutineer 14	Santos	NW Shelf, Australia		18-26 Aug 2008	-20.0	115.1
60	Havila Harmony		Woodside	NW Shelf, Australia		20-25 Aug 2008		
61	Stena Clyde		Santos	NW Shelf, Australia		27-31 Aug 2008		
62	Stena Clyde		Santos	NW Shelf, Australia		09-15 Sep 2008		
63	Stena Clyde	Van Gogh	Apache	NW Shelf, Australia	370	24 Sep – 01 Oct 2008	-21.4	114.1
64	Transocean Leader	Haklang	Statoil	NS, Norway	1250	23 Sep - 08 Oct 2008	67.0	7.1
65	Transocean Leader	Haklang	Statoil	NS, Norway	1250	15-18 Oct 2008	67.0	7.1
66	Sedco703	Torosa5	Woodside	NW Shelf, Australia	402	02 - 12 Nov 2008	-14.0	122.0
68	Sedco703	Torosa5	Woodside	NW Shelf, Australia	402	29 Nov – 02 Dec 2008	-14.0	122.0
69	Stena Carron	Rosebank North	Chevron	FSC, UK	1186	11-14 Dec 2008	61.1	-3.7
70	Discoverer Deep Seas	Walker Ridge 316	Chevron	GOM, USA		27-29 Jan 2009	26.0	-91.0
71	Transocean Leader	Asterix	Statoil	NS, Norway	1350	17-24 Feb 2009	67.0	5.3
72	Stena Carron	Rosebank North	Chevron	FSC, UK	1186	20 Feb - 12 Mar 2009	61.1	-3.7
73	Transocean Legend	Brecknock-4	Woodside	NW Shelf, Australia	660	28 Apr – 04 May 2009	-14.4	121.7
74	Leiv Eiriksson	Gro	Shell	NS, Norway	1380	30 Apr - 7 May 2009	66.1	3.9
75	Jack Ryan	Akpo	Total	Gulf of Guinea, Nigeria	1366	1-6 May 2009	3.1	6.8
76	Acergy Petrel	Morvin	Statoil	NS, Norway	370	2-7 May 2009	65.1	6.5
77	Leiv Eiriksson	Gro	Shell	NS, Norway	1380	6-13 Jun 2009	66.1	3.9
78	Stena Carron	Rosebank	Chevron	FSC, UK	1124	23 Jun-3 Jul 2009	61.0	-3.8
79	Bourbon Diamond	Usan	Total	Gulf of Guinea, Nigeria	750	9-18 Jul 2009	3.5	7.5
80	Deepwater Horizon	Keithly Canyon 102	BP	GOM, USA	1257	17-23 Jul 2009	26.9	-93.3
81	Noble Clyde Bourdreaux	Alaminos Canyon 857	Shell	GOM, USA	2476	28-31 Jul 2009	26.1	-94.9
82	Leiv Eiriksson	South Uist	Shell	FSC, UK	1157	2-7 Aug 2009	61.3	-3.0
83	Developmental Driller 2	Green Canyon 743	BP	GOM, USA	2103	03-06 Aug 2009	27.2	-90.0
84	Byford Dolphin	Lancaster	Hurricane Energy	FSC, UK	155	21-28 Aug 2009	60.2	-3.9
85	Noble Jim Thompson	Mississippi Canyon 765	Shell	GOM, USA	1081	05-07 Sep 2009	28.1	-89.1
86	Stena Carron	Tornado	OMV	FSC, UK	1050	19 Sep - 02 Oct 2009	60.6	-4.5
87	Stena Carron	Tornado	OMV	FSC, UK	1050	16-22 Oct 2009	60.6	-4.5
88	Deepwater Nautilus	Mississippi Canyon 392	Shell	GOM, USA	2207	22-25 Nov 2009	28.7	-88.0
89	ENSCO7500	Chandon-2	Chevron	NW Shelf, Australia	1165	17-22 Jan 2010	-19.5	114.1
90	ENSCO7500	Geryon-2	Chevron	NW Shelf, Australia	1217	07-12 Mar 2010	-19.9	114.9

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91	Edda Fauna	Morvin	Statoil	NS, Norway	370	17-21 Mar 2010	65.1	6.5
92	Frontier Driller	Green Canyon 248	Shell	GOM, USA	990	08 – 09 Apr 2010	27.7	-90.6
93	ENSCO7500	Clio-3	Chevron	NW Shelf, Australia	965	04-09 Apr 2010	-20.3	114.7
94	Atwood Eagle	Brederode-1	Chevron	NW Shelf, Australia	1413	23-31 May 2010	-19.8	112.4
95	Borgsten Dolphin	Lancaster	Hurricane Energy	FSC, UK	155	24 May - 1 Jun 2010	60.2	-3.9
96	Atwood Eagle	Acme-1	Chevron	NW Shelf, Australia	894	04-08 Jul 2010	-20.2	114.9
97	ENSCO7500	Geryon-2	Chevron	NW Shelf, Australia	1217	12-15 Jul 2010	-20.0	114.9
98	Borgsten Dolphin	Whirlwind	Hurricane Energy	FSC, UK	184	10-14 Sep 2010	60.2	-3.8
99	Borgsten Dolphin	Whirlwind	Hurricane Energy	FSC, UK	184	04-11 Oct 2010	60.2	-3.8
100	Aker Barents	Dalsnuten	Shell	NS, Norway	1450	29 Oct - 09 Nov 2010	66.6	3.5
101	Stena Carron	Lagavulin	Chevron	FSC, UK	1567	05-11 Nov 2010	62.7	-1.1
102	Aker Barents	Dalsnuten	Shell	NS, Norway	1450	29 Nov - 10 Dec 2010	66.6	3.5
103	Discoverer Americas	Kiwi	Statoil	Nile Fan, Egypt	2720	14-22 Dec 2010	32.3	28.6
104	Atwood Eagle	Chrysaor-2	Chevron	NW Shelf, Australia	920	11-14 Apr 2011	-20.1	114.9
105	Stena Carron	Lagavulin	Chevron	FSC, UK	1567	13-19 Apr 2011	62.7	-1.1
106	Atwood Osprey	Gorgon-3B,3C	Chevron	NW Shelf, Australia	196	18-23 Aug 2011	-20.6	114.8
107	Wilphoenix	Whirlwind	Hurricane Energy	FSC, UK	184	4-12 Sep 2011	60.2	-3.8
108	Wilphoenix	Whirlwind	Hurricane Energy	FSC, UK	184	16-25 Oct 2011	60.2	-3.8
109	ENSCO8502	Green Canyon	Nexen	GOM, USA	1108	25 – 27 Nov 2011	27.5	-90.9
110	ENSCO8502	Green Canyon	Nexen	GOM, USA	1108	01 – 08 Nov 2011	27.5	-90.9
111	Atwood Osprey	Gorgon-1E	Chevron	NW Shelf, Australia	215	20-23 Dec 2011	-20.6	114.8
112	Ocean Rig Poseidon	Zafarani	Statoil	WIO, Tanzania	2580	23 Jan - 07 Feb 2012	-9.2	40.4
113	Atwood Osprey	Gorgon-1F	Chevron	NW Shelf	217	Feb 2012	-20.6	114.8
114	ENSCO DS5	Walker Ridge 206	Petrobras America	GOM, USA	2483	24 – 28 May 2012	27.7	-90.5
115	Ocean Rig Poseidon	Lavani	Statoil	WIO, Tanzania	2400	26 May - 10 Jun 2012	-9.4	40.4
116	ENSCO DS5	Walker Ridge 206	Petrobras America	GOM, USA	2483	11 – 14 June 2012	27.7	-90.5
117	Deepsea Metro I	Mzia-2	BG	WIO, Tanzania	1620	7-24 Apr 2013	-9.9	40.5
118	Deepsea Metro I	Ngisi-1	BG	WIO, Tanzania	1325	15-29 May 2013	-8.3	40.1
119	Deepsea Metro I	Pweza-3	BG	WIO, Tanzania	1384	09-20 Sep 2013	-8.4	40.1
120	Deepsea Metro I	Mzia-3	BG	WIO, Tanzania	1780	2-11 Nov 2013	-9.8	40.5
121	Sedco 712	Lancaster	Hurricane Energy	FSC, UK	150	22-25 Apr 2014	60.2	-3.9
122	Sedco 712	Lancaster	Hurricane Energy	FSC, UK	150	28 May - 05 Jun 2014	60.2	-3.9
123	Deepsea Metro I	Kamba-1	BG	WIO, Tanzania	1380	22 Sep - 02 Oct 2014	-8.4	40.1
124	Vantage Titanium Explorer	Walker Ridge 469	Petrobras America	GOM, USA	2704	30 Jan – 05 Feb 2015	26.5	-90.5
125	Vantage Titanium Explorer	Walker Ridge 469	Petrobras America	GOM, USA	2704	02 – 04 Mar 2015	26.5	-90.5
126	Vantage Titanium Explorer	Walker Ridge 469	Petrobras America	GOM, USA	2704	18– 20 Apr 2015	26.5	-90.5
127	Vantage Titanium Explorer	Walker Ridge 469	Petrobras America	GOM, USA	2704	29 Apr – 01 May 2015	26.5	-90.5

891 Table 2: Data collection methods and topics addressed in SERPENT field visits

Equipment	Method	Topic
Standard ROV video cameras	ROV seafloor video transects (e.g. 8 x benthic video transects radiating from well)	Megabenthic assemblage Drilling disturbance
	Midwater ROV video transect (e.g. transects at regular depth intervals to the seabed)	Meso- and bathypelagic planktonic and nektonic assemblage (large)
	Inspection of structures	Artificial structures as habitat
	Targeted inspection	Megafaunal assemblage
	Chance encounters	Distribution and behaviour of large marine fauna
Stills camera (e.g. Kongsberg OE14-408)	High resolution imagery	Improved resolution for identification
Push corers	Use of manipulator arms to collect replicated sediment samples	Meiofaunal assemblage Sediment chemistry
	Specimen collection	Identification Taxonomy Morphological studies
Ekman core	Use of manipulator arms to collect sediment samples	Macrofaunal assemblage Sediment chemistry
	Specimen collection	Identification Taxonomy Morphological studies
ROV deployed time-lapse camera (Insight Pacific Scorpio)	Deployed with bait	Large scavenging assemblage Scavenging Megafaunal/fish behaviour
	Deployed without bait	Megafaunal/fish behaviour
CTD	Deploy on ROV or cage	Water column parameters
Current meter	Deployment during drilling	Distribution of drill cuttings at time of drilling
	Deployment with baited time-lapse experiment	Estimation of scavenger abundance
Baited trap	24 hour deployment at seabed with consistent bait at multiple sites or bait choice	Taxonomy Spatial variation in scavenging assemblage
Larval light traps	24 hour deployment on seabed or midwater; attracts range of photopositive pelagic and epibenthic fauna including fish larvae	Spatial and depth patterns in epibenthic and pelagic larvae and small adults
Settlement frames	Variety of methods of deployment of free-standing or attached to industry infrastructure	Larval settlement Biofilms

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894 **Figures:**

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897 Figure 1: Locations from which SERPENT data has been collected. Red circles show locations where
898 visits have been made to oil and gas infrastructure. Grey circles represent data on the SERPENT
899 archive and video/images provided by drilling companies

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Figure 2: Examples of ROVs used for SERPENT Project research: a) Centurion 05 HD work class ROV with top hat tether management system on the Transocean Rather drilling rig west of Shetland; b) Fugro FCV609 prepared for a dive from the Transocean Sedco 714 west of Shetland; c) Launching a Seaeye Falcon Inspection Class ROV from the Wilphoenix at a drilling site west of Shetland, UK; d) Launching the cage deployed Oceaneering Millennium 073 from the drillship Ocean Rig Poseidon in the western Indian Ocean

Figure 3: Idealised SERPENT visit. ROV launched from semi-submersible drilling rig. The tether management system (TMS) and Blow out preventer (BOP) are shown. 1) Water column data with a CTD; 2) Midwater video transects, preferably at multiple water depths; 3) Chance encounters with large marine organisms, can occur anywhere; 4) Benthic video transects used to assess megafaunal assemblages and drilling disturbance, typically 8-24 transects are carried out on a SERPENT visit; 5) Sediment sampling, use of push corers or Ekman grabs are used to assess meiofauna and macrofauna as well as physical and chemical aspects of the sediment; 6) Specimen collection for taxonomy, morphological studies and chemistry; 7) Experimental studies; can be ecophysiology of deepwater organisms or settlement plates; 8) Use of a current meter to understand distribution of drilling disturbance or for use with baited camera; 9) Time-lapse camera, used with bait to assess scavenging assemblage or without for megafauna behaviour; 10) Baited or light trap for collection of scavenging fauna for taxonomic or morphological studies. (not to scale)

Figure 4: New insights from SERPENT observations. a) The deepest record of scalloped hammerhead (*Sphyrna lewini*) at 1043 m depth; b) One of five examples oarfish (*Regalecus glesne*) from Gulf of Mexico ROV observations; c) large medusa *Stygiomedusa gigantea*; d) One of many deep-water observations of ocean sunfish (*Mola mola*); e) Pipeline survey showing accumulated *Pyrosoma* sp. carcasses, Echinothuriids also visible; f) Manefish in the Gulf of Mexico; g) Scavenging assemblage attending a Mobulid ray carcass encountered in a deep-sea ROV video survey off Angola; h) Tripodfish swimming behaviour in the Campos Basin off Brazil; i) *Munida* sp. feeding on krill from the water column west of Shetland in the Atlantic Ocean; j) Asphalt mounds and associated epifauna on the Angolan margin; k) Monkfish (*Lophius piscatorius*) feeding on cod (*Gadus morhua*) at 350 m depth, west of Shetland in the North East Atlantic; l) *Porania pulvillus* apparently feeding on hydroids west of Shetland; m) *Teuthidodrilus* (Squidworm) from the western Indian Ocean; n) *Phormosoma*

935 sp. from the West African margin, ROV surveys showed changes in assemblage composition with
936 seabed slope; o) ROV video surveys are used to record species associated with subsea structures,
937 here 10 European Conger (*Conger conger*) were counted in a protective subsea structure; p)
938 *Bathysaurus mollis* from the Gulf of Mexico.

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941 Figure 5: Observations of drilling disturbance. a) the BOP at a well at 930 m depth in the Norwegian
942 Sea b) homogenous appearance of seabed on drilling cuttings pile 20 m from a well at 930 m depth

in the Norwegian Sea; c) Distinct change in the sediment appearance at a drilling well on the Irish continental shelf; d) similar change in appearance of seabed at the edge of a cuttings pile at 650 m depth in the Faroe Shetland Channel; e) undisturbed sediment >100 m from a well at 930 m depth in the Norwegian Sea f) image of drill cuttings pile colonised by numerous tube worms including spionids one year after drilling disturbance

Figure 6: The effects of drilling disturbance on megabenthic abundance at 6 wells visited by the SERPENT Project