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Review

Eyes in the sea: Unlocking the mysteries of the ocean using industrial, remotely operated vehicles (ROVs)

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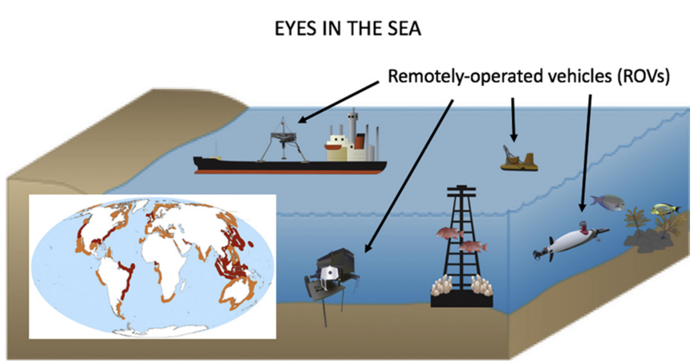
HIGHLIGHTS

- Industry remotely operated vehicles (ROVs) are the 'eyes in the sea'.
- ROVs collect millions of observations each year, fuelling scientific discoveries.
- We identify 10 key scientific questions that can be addressed with ROVs.
- Partnerships between academia and industrial ROV operators are key.
- We suggest ways to maximise industry-collected ROV data for scientific purposes.

GRAPHICAL ABSTRACT



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ABSTRACT

For thousands of years humankind has sought to explore our oceans. Evidence of this early intrigue dates back to 130,000 BCE, but the advent of remotely operated vehicles (ROVs) in the 1950s introduced technology that has had significant impact on ocean exploration. Today, ROVs play a critical role in both military (e.g. retrieving torpedoes and mines) and salvage operations (e.g. locating historic shipwrecks such as the RMS Titanic), and are crucial for oil and gas (O&G) exploration and operations. Industrial ROVs collect millions of observations of our oceans each year, fueling scientific discoveries. Herein, we assembled a group of international ROV experts from both academia and industry to reflect on these discoveries and, more importantly, to identify key questions relating to our oceans that can be supported using industry ROVs. From a long list, we narrowed down to the 10 most important questions in ocean science that we feel can be supported (whole or in part) by increasing access to industry ROVs, and collaborations with the companies that use them. The questions covered opportunity (e.g. what is the resource value of the oceans?) to the impacts of global change (e.g. which marine ecosystems are

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Gas
Petroleum
Exploration
Deep sea
Remotely operated vehicles (ROVs)
Decommissioning
Biodiversity

most sensitive to anthropogenic impact?). Looking ahead, we provide recommendations for how data collected by ROVs can be maximised by higher levels of collaboration between academia and industry, resulting in win-win outcomes. What is clear from this work is that the potential of industrial ROV technology in unravelling the mysteries of our oceans is only just beginning to be realised. This is particularly important as the oceans are subject to increasing impacts from global change and industrial exploitation. The coming decades will represent an important time for scientists to partner with industry that use ROVs in order to make the most of these 'eyes in the sea'.

Contents

1. Background

Modern exploration of the deep sea began in the mid-19th century during an era of expanding transocean communication and scientific curiosity regarding marine geology and natural history (Wüst, 1964; Rozwadowski, 2001). However, comprehensive study of our oceans, especially deeper regions, has only recently accelerated with the advent of underwater intervention technology. Submersible vehicles now allow access to even the most inaccessible regions, as demonstrated by Jacques Piccard's ten kilometre descent into the Mariana Trench in the bathyscaphe *Trieste*, marking the deepest dive in human history. Exploration of our oceans is now limited by cost and access to dedicated research infrastructure, which have proven formidable barriers to scientific progress.

The world's deep seas provide important services (Thurber et al., 2014) and resources (Levin and Le Bris, 2015). They are subject to anthropogenic disturbance from global change and increasing industrial exploitation (Glover and Smith, 2003; Ramirez-Llodra et al., 2011). New deep-sea industries such as deep-sea mining are developing environmental monitoring and impact assessment protocols (Durden et al., 2018) to ensure evidence-based management, while more established industries such as oil and gas (O&G) exploration and production seek greater efficiency for their environmental monitoring (Nilssen et al., 2015). Despite this need, there is limited research and few institutions and even countries in the world that have extensive deep-sea research programmes (Ruth, 2006). This is because multi-disciplinary open ocean research is expensive and requires specialist infrastructure such as ships, autonomous underwater vehicles, and remotely-operated vehicles (ROVs).

The global O&G industry has been operating in the marine environment for over a century, and deeper offshore areas have been exploited for >50 years (Cordes et al., 2016; Lange et al., 2014). In that time, tens of thousands of offshore wells have been drilled and there are over nine hundred large-scale offshore O&G platforms around the world (Lange et al., 2014). Industry activity is global in distribution, with major work infrastructure in areas such as the Arctic, parts of the North Atlantic Ocean (UK and Norwegian waters), East and West Africa, the Gulf of Mexico, South America, India, Southeast Asia, and Australia (Fig. 1). Offshore O&G accounts for between 37 and 28% of global production, respectively (Lange et al., 2014). Increasing attention is focussed on the more remote and deep-water areas of the world to meet hydrocarbon demands, and over 50% of the larger offshore fields (totalling 480 fields from 2007 to 2012) recently discovered were in deep water (>400 m; Lange et al., 2014). A major subsea industry has grown to support these activities worth tens of billions of dollars each year. Much of this industry activity requires underwater observation, intervention, and control, which is increasingly provided by remotely operated vehicles (ROVs) - underwater tethered robots controlled from the surface. Globally, there are over 700 ROVs in operation, of which, over 550 are work-class vehicles (IMCA, 2015).

ROV systems are "eyes, and hands in the sea", being equipped with cameras that stream live video to the surface, including some where pilots can manoeuvre the vehicle and operate manipulators that allow the vehicle to interact with subsea infrastructure. The global industrial ROV fleet has produced many millions of hours of video and millions of still images. These images potentially have important scientific value (Jones, 2009; Gates et al., 2017b), particularly as they are often obtained at soft-sediment sites on the continental slope that would not typically be of priority for investigation using research ROVs (Table 1; Fig. 1).

The recent uptake of marine autonomous systems (MAS) such as Autonomous Underwater Vehicles (AUV), underwater gliders, and Unmanned Surface Vehicles (USV) provide new opportunities for efficient deep-ocean observation and data collection at lower cost than ROV operations. MAS are particularly suited to efficient high-resolution geophysical mapping of the seafloor (Wynn et al., 2014), yet these

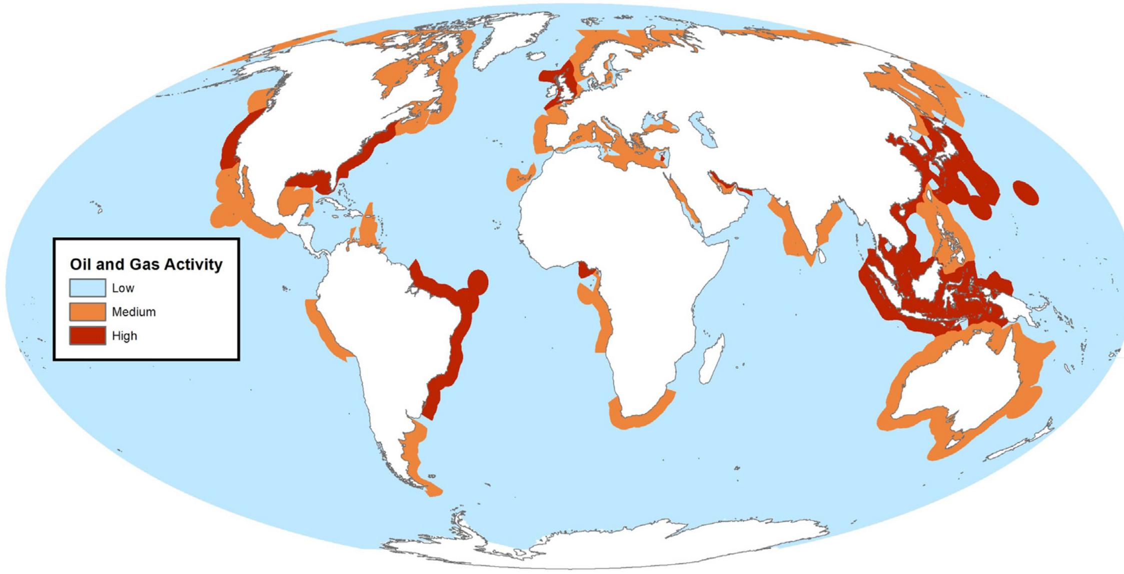

Fig. 1. Map indicating the present distribution of offshore O&G (EEZ). The map shows the number of static lights in the sea presumed to be associated with oil rigs (Halpern et al., 2008) in each EEZ. The number of 1 km^2 pixels with static lights (Halpern et al., 2015) was summed within each EEZ but not standardised by the EEZ area. The red EEZ have high densities of oil activity (>25,000 pixels with static lights); orange have medium densities (5000–25,000) and blue areas have low density (<5000). There is little O&G activity outside EEZ areas. Some large oceanic territories of larger EEZ (e.g. the Marcus Islands off Japan) have been removed from the map as they have no known oil activities.

systems generally lack the capability for real-time in situ inspection and sample collection.

This study reviews the scientific benefits of access to marine industry infrastructure (primarily within the O&G sector), focussing on insights that can be gained from industry ROVs in the marine environment. Our objectives were to: (1) illustrate how ROVs have facilitated many major scientific discoveries in the oceans; (2) identify key questions in ocean science that can be addressed using ROVs; and (3) offer practical recommendations for establishing and improving relationships between offshore industries and academia, as well as enhancing the quality and utility of industry-collected ROV data for scientific purposes.

Table 1
Comparison between industrial ROV data and those obtained by dedicated research infrastructure. *Here 'Industry ROV fleet' primarily refers to their use for routine surveys of O&G infrastructure and for exploration.

Attribute	Research ROV fleet	Industry ROV fleet*
Location	Global	Global
Depth	All	Typically to 3000 m
Targeting	Typically targeted to features of known or expected research/conservation interest.	Areas of industry activity, includes both unimpacted and impacted areas.
Primary areas with images	Fluid flow features (hydrothermal vents, cold seeps), seamounts, canyons, unusual areas, time-series sites.	Typical flat sedimented seabed without expected priority species or habitats. Water column footage common. Focus on infrastructure.
Resource availability	<50 systems worldwide	>700 systems worldwide including >550 work-class vehicles worldwide
Image quality	High: 1080i typical for video, high-resolution digital stills normally obtained from separate camera. Uncompressed recording common.	Medium: Standard definition most common e.g. 576i/480i. HD (1080i +) increasing. Dedicated still cameras rare. Recording medium often introduces compression.
Associated data	Usually good metadata and images associated with a wide range of other scientific information.	Range of metadata often available, but not always collected or accessible.
Samples	Samples of example organisms often collected for ground-truthing and improving taxonomic resolution. Appropriate preservation methods available for a range of analyses.	Samples typically not collected, and if collected, specialist preservation generally not available.

2. Materials and methods

Leading experts in this field of scientific research were invited to a workshop at the Indian Ocean Marine Research Centre in Perth, Western Australia (August 2-3rd 2017). Experts were selected based on their publications and extent of work in this area, particularly in the fields of marine ecology, oceanography, and offshore engineering, including O&G industry projects that involve ROV data, infrastructure, and decommissioning. Some participants are members of SERPENT (the Scientific and Environmental ROV Partnership using Existing Industrial Technology - www.serpentproject.com), which has a long history of collaboration with the O&G industry worldwide. In addition, Western Australian-based O&G industry representatives and ROV operations specialists were invited to provide their essential operational perspectives. Day 1 involved a round table discussion on 1) the scientific value of industry-collected ROV data; and 2) feasibility of enhancements to standard ROV operations that would increase their ability to provide valuable scientific data into the future. On Day 2, leading scientists (12) and key industry experts (9) were each asked to list 10 key issues/opportunities associated with the use of offshore O&G ROVs for scientific research. These responses were grouped according to similarity and subsequently revised into a single question. The full list of questions was then consolidated by consensus into the final list of the top-10 questions described below in the text, boxes and figures.

3. Results

The 10 key issues/opportunities that could benefit from access to marine industry infrastructure were grouped into three broad categories: improving basic understanding of the deep ocean and the animals that reside within it (Questions 1–5); investigating how the deep ocean is changing, either from natural or anthropogenic influences (Questions

6–8); and identifying how ROV programs can support further development of the deep ocean blue economy (Questions 9 and 10).

3.1. Q1. How do organisms behave in deep water environments?

Nets and trawls have long served as traditional tools for sampling life in the deep sea (Wiebe and Benfield, 2003). However, sampling of deep sea organisms with nets is problematic for behavioural studies. Most deep-sea organisms are highly fragile and struggle to recover once brought to the surface. Moreover, when animals are collected by nets, there is little context upon which to relate structure and function to the demands of the habitat from which each specimen was collected. A quote from Richard Harbison in Haddock (2004) summed this up as: 'Sampling with plankton nets is akin to flying over London with a grappling hook. You might pick up hats and umbrellas and a few tree branches, but you can only speculate as to where hats belong, and what umbrellas are good for.' In contrast, direct imaging using video and still cameras mounted on ROVs can provide a completely different picture of life in the depths. These types of in situ observations have contributed to a rapid increase in our understanding of deep-sea ecology (Robison, 2009).

A large proportion of pelagic deep-sea organisms are gelatinous including ctenophores, siphonophores, scyphozoans, medusae, appendicularians, radiolarians, and foraminifera. The only effective way to study such fragile taxa is through observation. When collection is necessary, suction samplers mounted on ROVs can often enable collection of live specimens for detailed taxonomic, and/or physiological examination. New instrumentation such as particle imaging velocimetry (PIV) has been mounted on ROVs to study the complex relationship between feeding currents generated by giant larvaceans, their fragile mucous "houses", and carbon flux to the depths (Katija et al., 2017). This same PIV system has provided evidence that larvaceans collect and transport microplastics from near the surface to bathyal depths (Katija et al., 2017). Such instrumentation could be adapted for use on industrial systems. For example, during the 2010 Gulf Oil Spill, laser line-projectors were mounted on struts in front of an industrial ROV to provide confirmation that organisms were enumerated as they passed through a defined image area (NRDA, 2013).

Direct observation of deep-sea organisms can provide insights into their feeding mechanisms and behaviour. Without cameras, the remarkably complex feeding net extended in a spiral by the "galaxy" siphonophore would remain unknown because the feeding geometry of this animal is very different from its contracted morphology (Fig. 2A–B). Direct observations of manefishes (Fig. 2C) in proximity to siphonophores (Benfield et al., 2009) has provided evidence of their remarkable swimming ability, which may help them to manoeuvre when they steal food from these cnidarians, while ROV video of the dorsal fin undulations of the oarfish *Regalecus glesne* (Ascanius, 1772) (Fig. 2D) has provided biomechanical insights into how these, and other species of fishes, use their fins as linear propellers (Bale et al., 2015).

Cameras provide valuable information on associations and interactions between individuals of the same or different species. Observations of pairs of fishes belonging to Giganturidae (Teleoscopefish) and Paralepididae (Barracudinas) (Fig. 2E–F) suggest that males and females remain together, possibly to enhance the probability of finding a mate in an environment where the probability of encounter is low. The commensal association between the scyphomedusan *Stygiomedusa gigantea* (Browne, 1910) and the fish *Thalassobathia pelagica* (Cohen, 1963) (Fig. 2G–H) would not be obvious from their mutual presence in a trawl, but it is clearly evident in ROV video footage (Benfield and Graham, 2010). Time-lapse images of ophidiidids (cusk eels) and antipatharians (black corals) (Fig. 2I) have shown that individual fishes shelter beneath these invertebrates (Gates et al., 2017a).

Foraging excursions by pelagic species into the mesopelagic or bathypelagic zones such as those belonging to Thunnini (tuna) are difficult to document. Such behavior is typically studied using ultrasonic tags (e.g. Brill et al., 1999) or time-depth recording tags (e.g. Dagorn et al., 2006). This approach has revealed new insights into how deep large tunas will travel to forage. Dagorn et al. (2006) documented a dive to 1160 m by an adult yellowfin tuna, *Thunnus albacares* (Bonaterre, 1788), while Schaefer et al. (2011) documented a yellowfin tuna that reached 1423 m. ROVs routinely observe large tuna swimming in the mesopelagic and upper bathypelagic zones (Fig. 2J–K illustrate yellowfin tuna at 1142 m and 1387 m, respectively). ROV observations (e.g. Fig. 2L) were used to document mesopelagic foraging at depth by the ocean sunfish *Mola mola* (Linnaeus, 1758) (Phillips et al., 2015). Observations of even larger surface predators, such as scalloped hammerhead *Sphyrna lewini* (Griffith & Smith, 1834) (Moore and Gates, 2015) and sperm whales *Physeter macrocephalus* (Linnaeus, 1758) at great depths, have been also documented by ROVs (Fig. 2M).

When the demersal siphonophore *Bathyphysa conifera* (Studer, 1878) was observed by an industry ROV off Angola (Fig. 2N), this observation represented a major range extension for the species. Moreover, this species, along with the scyphomedusa, *Deepstaria reticulum* (Larson, Madin & Harbison, 1988) (Fig. 2O), attracted a great deal of attention from the public for their God/alien-like appearance (see Q10 for more details).

While acoustics have revealed the complexities of diel vertical migration patterns, echograms from single-frequency echo sounders or acoustic doppler current profilers (ADCPs) remain taxonomically ambiguous. ROV observations provide a means of "sea-truthing" acoustic data and over time, videos and still photographs can be assembled to provide a "picture" of the vertical migration patterns of different taxa, as well as the taxonomic composition of different scattering layers. Moreover, direct measurements of individuals using acoustic transducers mounted on ROVs (Warren et al., 2001) can provide better estimates of acoustic target strength, which can then be used to refine abundance estimates from down-looking echosounders.

3.2. Q2. What are the distributions and ranges of ocean organisms?

There are numerous examples of ROVs providing observations of species new to science, documenting distributions and depth ranges – e.g. including depth distribution of deep-sea benthic shrimp (Stylodactylidae; Wicksten et al., 2017), discovery of a new carnivorous sponge *Chondrocladia lyra* (Lee et al., 2012), observations of ectoparasites on deep-sea fishes (Quattrini and Demopoulos, 2016) and three new acorn worm species (Enteropneusta: Priede et al., 2012).

Insights into the distribution and behaviour of marine organisms can also be gained through serendipitous encounters by industry ROVs. By their nature, these encounters cannot be planned for in research expeditions, so the network of industry ROVs provides a valuable resource. Examples that demonstrate the potential to enhance scientific understanding of ocean biogeochemistry include observations of gelatinous food-falls (Lebrato and Jones, 2009) and the first observations of large, non-cetacean food falls in the deep sea (Higgs et al., 2014), each highlighting their importance in the biological carbon pump. Industry ROV observations revealing new distribution records or behaviours include a South Atlantic rhizophysid siphonophore *Bathyphysa* (Jones and Pugh, 2016), the oarfish *Regalecus glesne* (Benfield et al., 2013), the large jellyfish *Stygiomedusa gigantea* (Browne, 1910) (Benfield and Graham, 2010), the deepest known record of the aforementioned scalloped hammerhead *Sphyrna lewini* (Griffith & Smith, 1834) (Moore and Gates, 2015), depth records for sunfish species (Phillips et al., 2015) and fish associations with artificial habitats (McLean et al., 2017). These examples are large animals that easily capture the attention and imagination of ROV and oilfield personnel, while the examples of new discoveries made during academic research expeditions often feature less charismatic species, or those that require expert identification. The *SERPENT* network has proved successful in accessing such observations and publishing them in the scientific literature (Gates et al.,

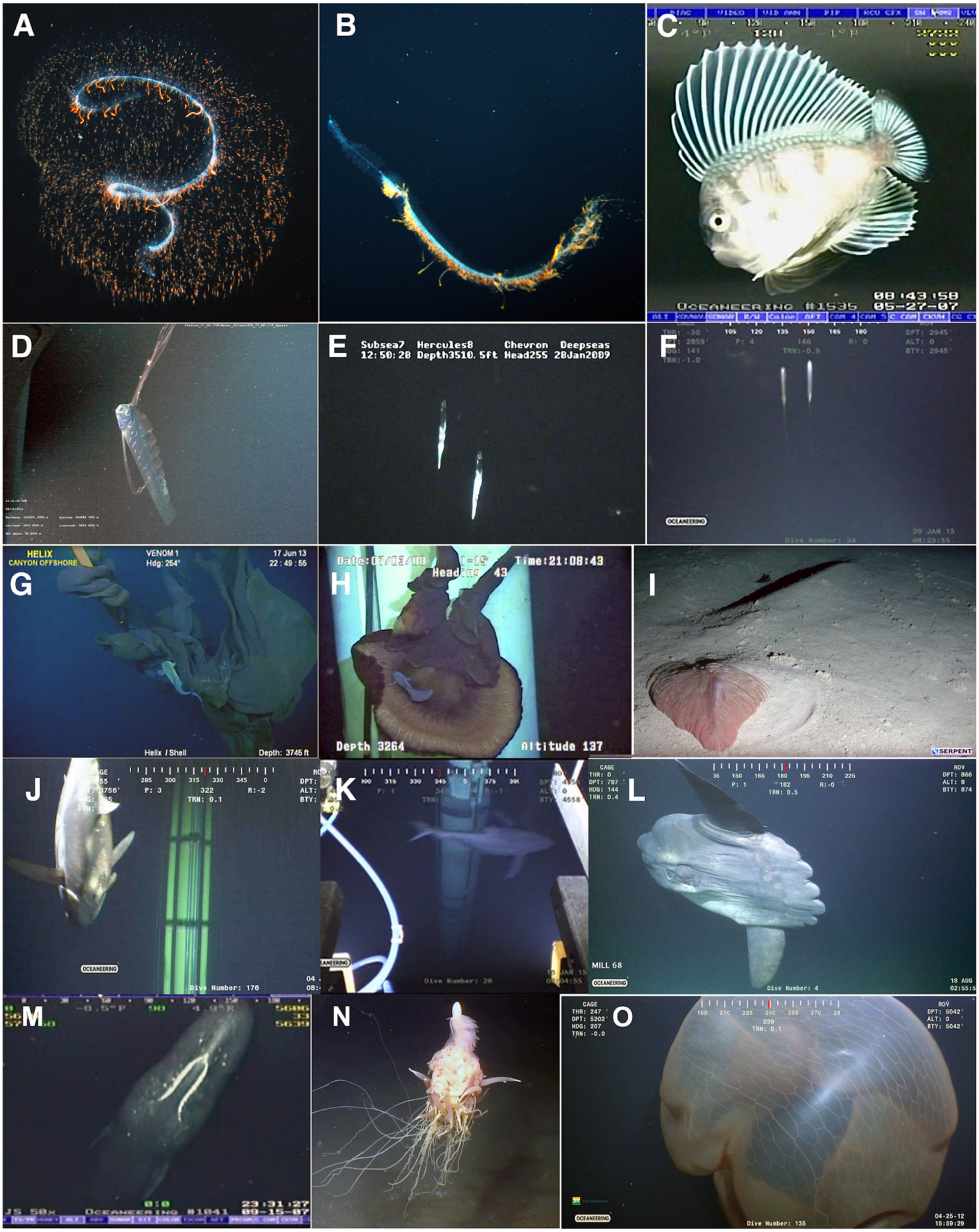

Fig. 2. Examples of ROV observations of marine life. A: A galaxy siphonophore with tentacles extended in a spiral feeding posture; B: the same siphonophore with tentacles retracted; C: a manefish (*Paracaristius* spp.) observed in situ with an ROV; D: an oarfish (*Regalecus glesne*) swimming in front of an ROV using undulations of its dorsal fin; E: a pair of fishes, family Paralepididae; F: a pair of fishes, family Giganturidae; G-H: a fish *Thalassobathia pelagica* swimming in close association with the scyphozoan medusa *Stygiomedusa gigantea*; I: a cusk eel *Bassozetus* sp. sheltering under a coral (*Schizopathes* sp.); J-K: yellowfin tunas swimming at 1142 and 1387 m, respectively; L: an ocean sunfish (*Mola mola*) in the mesopelagic at 264 m; M: a sperm whale (*Physeter macrocephalus*) observed by an ROV at 1079 m; N: siphonophore (*Bathyphysa conifera*); O: scyphomedusa *Deepstaria reticulum*.

2017b), but remote use of the global network of ROVs realistically restricts such insights to large animals that can be identified in video.

The industry ROV fleet is increasingly using high definition cameras for routine operations, so ROV footage is becoming more valuable for scientific observation and it is expected that insights will increase. Despite these improvements, video footage is often not sufficient to allow examination of morphological features needed to confirm the identity of most organisms. Identification of organisms seen in such footage generally requires assessment by a taxonomic expert for that group, and for many taxa, specimens are needed in order to confirm identities and therefore extend knowledge of each species' depth, range, and behaviour. It is imperative that available footage reaches the relevant experts and that these experts are available and willing to work with industry ROV operators and oilfield personnel. There is also the requirement that ROV personnel making such observations recognise their value, and this is often only the case for the more "charismatic" organisms. Detailed study of biodiversity also requires expert assessment, usually at the microscopic level, and examination of larger numbers of typically smaller organisms is needed to explore broader scale ecological patterns. Such thorough studies will become possible through more direct engagement (e.g. scientist visits to drilling installations, participation in baseline surveys) when specimen collection is attempted. Use of baited traps deployed by researchers from drilling rigs or during baseline surveys have yielded specimens (necrophagous amphipods) for taxonomic description (e.g. Horton and Thurston, 2015) and biodiversity studies (Duffy et al., 2016). Wider uptake of such approaches, with associated metadata, has the potential to dramatically increase our understanding of species distributions over a range of scales.

3.3. Q3. What are the physical processes within the deep ocean?

Industry ROVs offer a novel approach to oceanographic investigation. Traditional ship-based oceanographic sampling has been supplemented by autonomous vehicles such as Argo buoys and ocean gliders (Gould and Turton, 2006; Pattiaratchi et al., 2017). ROVs also provide a platform for collection of physical oceanographic data that can inform on the behaviour of organisms through the water column and in the deeper ocean observed through ROV footage. Many oceanographic instruments such as conductivity-temperature-depth (CTD) units and optical sensors (to measure nutrients, dissolved oxygen, fluorescence, turbidity, and dissolved organic matter) are self-contained and may be easily mounted on an ROV. In some cases, ROVs already measure temperature routinely. ROVs therefore offer a convenient and cost-effective solution to the deployment of oceanographic instruments in situations where ROVs can collect data during routine industry operations. The global network of ROVs also provides an opportunity for oceanographic monitoring and sampling at a range of scales, from single sites through to ocean basins.

ROV-collected oceanographic data could be particularly useful for developing re-analysis products using models with data assimilation (as shown, for other oceanographic data, in Cummings and Smedstad, 2014). ROVs frequently traverse the water column as part of routine operations, often from the surface to the sea floor. This provides regular information on water column structure that allows for the characterisation of seasonal and inter-annual variability (if the records are sufficiently long). These data may be collated and integrated with other routine data sets (for example temperature obtained from satellites, Argo buoys etc.) and would provide input into ocean and atmospheric models for forecasting (as shown for gliders; Liblik et al., 2016).

Industry ROVs can also be used to deploy oceanographic instruments and conduct experiments in deep water. ROV manipulator arms can be used to place instruments such as current meters on the seabed and retrieve them following a suitable period of data collection. Deployment and retrieval can be done opportunistically during routine industry operations, eliminating the need for dedicated dives. Such opportunities provide valuable insights into oceanographic processes in deep water, including deep ocean currents that would otherwise be challenging and costly to obtain. For example, data from current meters may be used to document sediment transport in the deeper ocean (Fig. 3). Classical sediment transport theory postulates that sediment is transported when a critical mean velocity is exceeded. In the deep ocean, where the currents are relatively low, the critical velocity is rarely exceeded and thus, in theory, sediment transport should not occur. Observations of the seabed through ROVs, and measurements made using instruments deployed by ROVs, have indicated that sediment transport occurred even when velocities were below the mean critical values and were associated with intermittent turbulent events (Salim, 2017). In some instances, dye releases near the seabed and subsequent dispersion can be defined by ROV footage and related to the background current field. Equipped with video imagery, transmissometer, and CTD a research ROV was used to collect unique observations and measurements of the structure and evolution of a 119 m thick dilute turbidity current over a 1.5 h period (Sumner and Paull, 2014). Such processes are poorly understood but represent hazards to industries operating in deep waters, particularly where O&G pipelines may be vulnerable to drag, loss of stability, under-mining from scour or rupture as a result of turbidity currents (Clare et al., 2017).

3.4. Q4. How do we relate biological processes to the physical environment, and vice-versa?

Apart from the intrinsic value of oceanographic data collected from ROVs to provide insights into deep ocean currents (see previous and next section), these data can provide fundamental insights into the mechanisms and pathways of biological connectivity and the structure of metapopulations in deep water. Dispersal of marine organisms is known to be widespread and even at the level of ocean basin in scale (e.g. Longmore et al., 2014). Understanding ocean currents is one way to elucidate possible connectivity patterns over such scales (e.g., Yearsley and Sigwart, 2011). Alternatives include population genetics modeling and fish otolith microchemistry (e.g., Longmore et al., 2014). ROV-based oceanographic instrumentation can provide continuous data streams at depths not serviced by conventional ocean monitoring systems. This will be more relevant to dispersal of deep-water organisms than surface circulation models. Given that ROVs surface regularly, they can also provide regular water column wide current profiles and data can be recovered regularly.

Coupled biophysical models (e.g., Hilário et al., 2015) to understand ocean larval dispersal often incorporate ocean general circulation models (OGCMs), which are inadequate for describing processes occurring at fine spatial and temporal scales, which are of greatest relevance to a larva (Metaxas and Saunders, 2009). ROV-generated water current data at these finer scales will be critical to link to OGCMs to develop superior larval dispersal models, which can be applied to key ocean management and conservation questions.

Many deep-water production facilities are connected to the seabed via risers and moorings that provide conduits for hydrocarbons and structural stability, respectively. Over time, these hard surfaces are colonized by a wide variety of cnidarians, poriferans, echinoderms, and other invertebrates (Wolfson et al., 1979). Predicting the natural depth distributions of such encrusting organisms based on observations of their presence on natural rocky or carbonate outcrops is challenging, particularly in areas where the predominant substrate is soft sediment. Their occurrence on uniform vertical surfaces that extend from the surface to the seabed provides an unusual opportunity to evaluate vertical distribution patterns in the context of prevailing hydrographic conditions (e.g. temperature, salinity). In the case of the cold water coral *Lophelia pertusa* (Linnaeus, 1758), vertical distributions on production risers can be estimated (Fig. 4) using archival footage from routine riser inspections conducted by industry to evaluate corrosion of anodes and the general condition of the riser system. These distribution patterns are quite pronounced. Repeated surveys of new risers over time allow the same colonies to be surveyed as they grow so that growth rates can be estimated as a function of temperature. Dimensions of the structure upon which they are attached provide a useful scaling metric. Moreover, presence of these corals and other species on risers represent another stepping stone that needs to be considered in the context of larval dispersal models. Currently, climatological means of temperature and salinity are required to estimate the hydrographic conditions associated with the presence of *L. pertusa*. If industrial ROVs could be equipped with a logging CTD system, then precise, high frequency

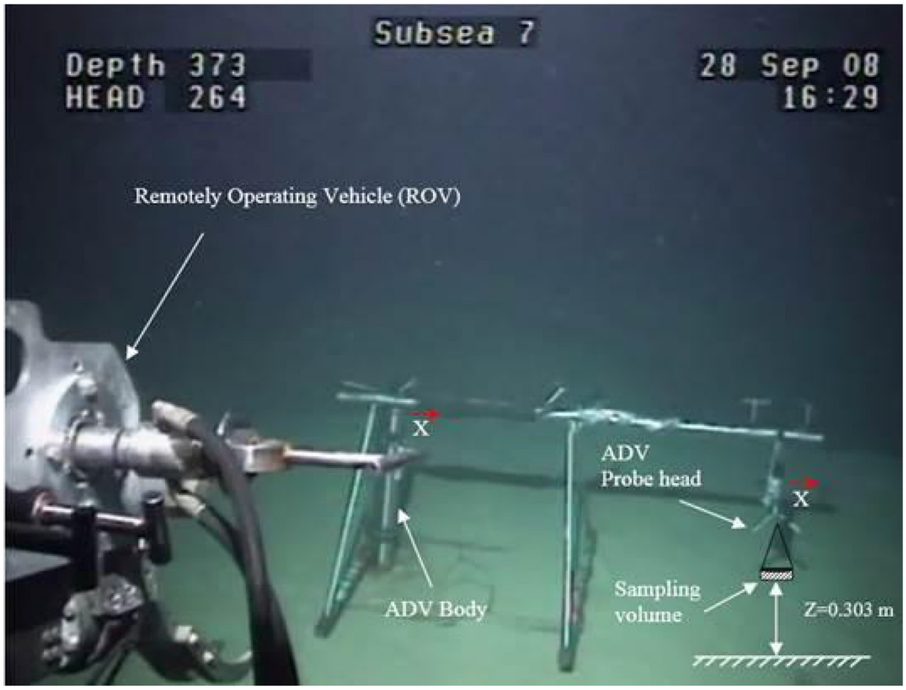

Fig. 3. An ROV preparing to recover an instrument set-up designed to measure currents and sediment transport (ADV – acoustic Doppler velocimeter) at a water depth of 373 m.

hydrographic casts could be conducted at a large number of locations with benefits to physical, biological, and chemical oceanographers.

3.5. Q5. How can we generate rigorous science for the ocean?

Deep sea science is hampered by logistics that impair how experimental science can be conducted. The immense expense of underwater sampling often means low spatial and temporal replication. ROV video footage, both current and archival, taken from O&G installations distributed over a wide region (Fig. 1), gives scope for deep-sea questions to be answered as rigorously as those in shallow waters or the terrestrial environment. Global oceanographic and fisheries surveys using dedicated vessels have traditionally provided a wealth of information, but this is usually compressed into specific expeditions at specific locations, and any samples recovered are of dead or moribund organisms. ROVs on platforms have the potential to provide a stable (i.e., allowing long temporal replication) and large spatial scale (extensive network of platforms globally) record of ecological and behavioural processes of a range of organisms in the deep sea.

Another aspect of rigorous science, which builds on the earlier discussion on 'How do organisms behave in deep water?', is making accurate behavioural inferences. Inferences pertaining to the behaviour of organisms through examination of dead (preserved) specimens has been widespread historically, but has provided only predictions based on either anatomical approaches and/or bioimaging. In order to validate these predictions and structure-function relationships, it is important to combine them with video of natural behaviours, wherever possible. A classic example of the need for both of these approaches is that of what we know about a living fossil, the coelacanth (*Latimeria* sp.), which was first discovered in 1938 with behavioural inferences (e.g., parental care, locomotion) made after the retrieval and preservation of one dead specimen. Once ROV data from the Comoros Islands were collected, a more complete and accurate record of the behaviour and physiology of this species was made (Fricke et al., 2011). While dedicated ROV drops from oceanographic research vessels, and manned submersibles, offer advantages in terms of scientific exploration, there is a real opportunity to collect high definition ROV data over greater time periods, and more locations, which can account for seasonal variation and long-term environmental change. Having a greater control of ROV protocols can provide a way of integrating industrial requirements and meeting scientific scrutiny, allowing more expansive and globally rare opportunities.

3.6. Q6. How is the ocean changing?

The oceans are vast and, in most places, poorly explored. This is particularly true in deeper water where only an estimated 0.01% of the deep ocean floor has been sampled and explored in detail (Ramirez-Llodra et al., 2010). The deep water column is considered the largest biome on the planet and is also poorly researched (Robison, 2009; Webb et al., 2010).

Changes in the ocean are challenging to observe because limited research facilities exist to study the oceans below the reach of divers. To highlight the limited understanding of the deep sea, it is only recently that the role of abyssal hills in structuring benthic ecosystems was identified, despite these being potentially the most abundant habitat feature on Earth's ocean floor (Durden et al., 2015). The wide distribution of O&G industry infrastructure has the potential to dramatically increase observation in inaccessible areas, improving the ability of scientists to describe and explain the links between habitats and species.

Spatially, there is great variation in the ocean, driven on a global scale by oceanographic conditions of the ocean basins that broadly determines the species assemblages present. On a regional scale, depth, latitudinal gradients, and associated parameters such as light, temperature, pressure, and food availability, as well as habitat heterogeneity, drive species diversity. Over time, variation in environmental conditions may drive changes in benthic and pelagic communities. For example, El Niño and La Niña oceanographic conditions influence Pacific deep-sea invertebrate populations through changes in food availability (Ruhl and Smith, 2004).

Anthropogenic climate change is also causing warming water temperature, melting ice, and ocean acidification, and deep sea ecosystems may be especially vulnerable to these changes (Ruhl and Smith, 2004; Sweetman et al., 2017). A long-term observatory in the Arctic Ocean has revealed a gradual increase in seabed water temperature at 2500 m depth over a 15 year period (Soltwedel et al., 2016). These

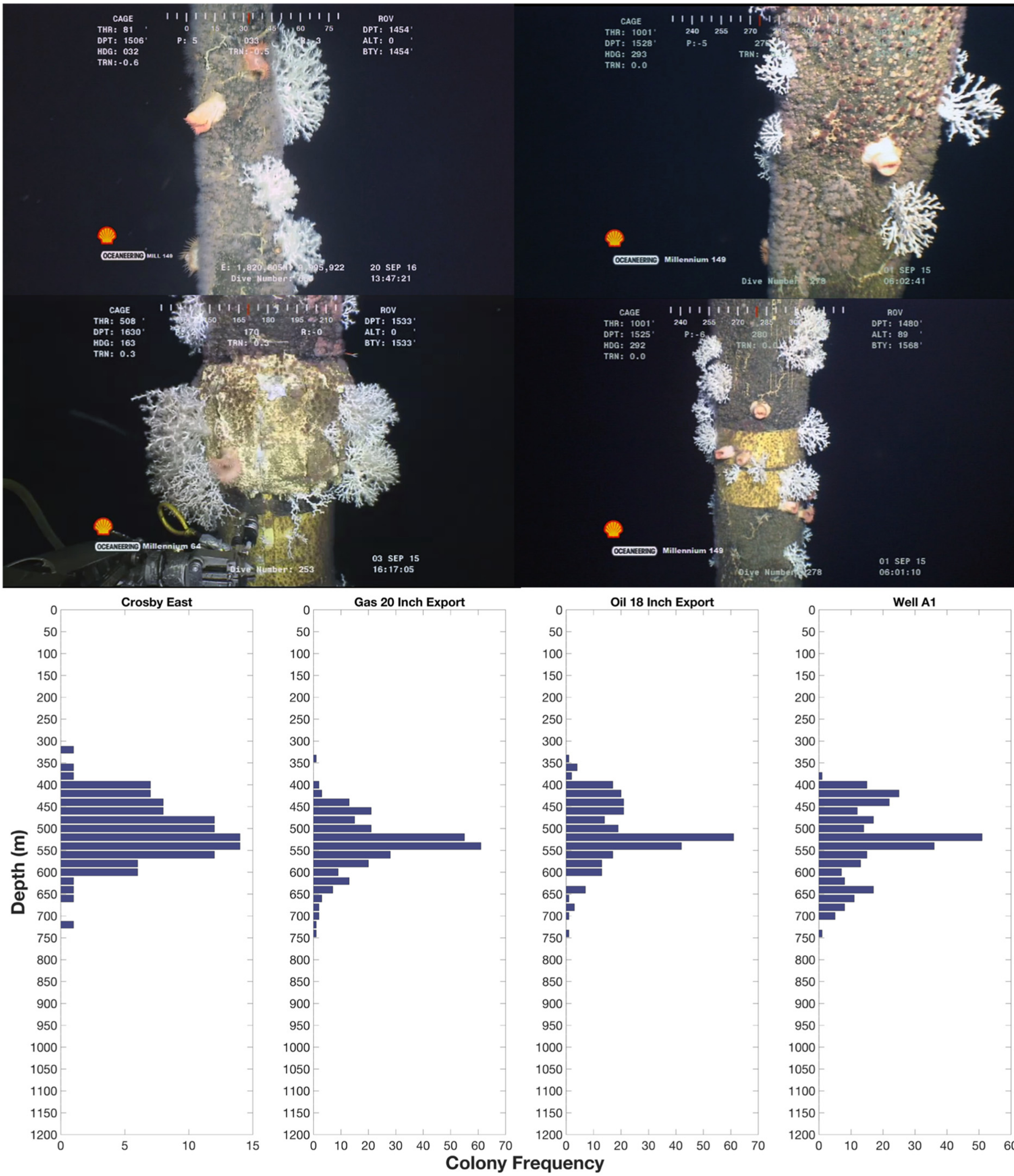

Fig. 4. Top: Inspection video frame grabs illustrating the coldwater coral *Lophelia pertusa*, venus flytrap anemones (*Actinoscyphia aurelia* Stephenson, 1918), and other unidentified invertebrates growing on the moorings of the Shell Auger production platform in the Gulf of Mexico. Bottom: Vertical distribution patterns of *L. pertusa* estimated from inspection videos of four risers on the Shell Ursa production platform in the Gulf of Mexico.

changes are principally identified at long-term observatory locations, which are an extremely limited resource. The O&G industry carries out activities over widely varying time scales e.g. survey work (days to weeks), exploration drilling campaigns (months), and production from an established field (decades). This long-term and widespread presence of O&G infrastructure offers opportunities to make sustained observations over extended time periods and over broad spatial scales. Regular data collection using sensors on ROVs (or other industry infrastructure) can increase the network of deep monitoring of essential ocean variables (EOV). The EOVs are defined by the Global Ocean Observing System (GOOS) as the ocean part of the Global Climate Observing System's essential climate variables (Cristini et al., 2016). They are designed to have high impact and to be highly feasible cross platform parameters to address climate, operational ocean services, and ocean health.

Oil and gas infrastructure is well placed to help in understanding human influences on the ocean by acting as a network of static stations where ROV operations can monitor the changing oceans. By using ROVs to collect biological and physical data around these structures, whilst considering and potentially accounting for the impact of the structures themselves on these measures, we can improve our scientific understanding of changing oceans in tandem with the impacts of O&G infrastructure.

3.7. Q7. Which marine ecosystems are most sensitive to anthropogenic impact?

The global oceans have impressive biodiversity, with over two hundred thousand marine species described and it is estimated that there are hundreds of thousands more yet to be described. This biodiversity is not homogeneous and is often clustered in areas of particular habitat types. In deeper waters, geological features (such as seamounts, canyons, scarps, salt-domes, and fluid flow features), and some habitat-forming species (such as cold-water corals) tend to harbour particularly high levels of diversity and, as such, are areas where industry impacts can be particularly consequential. This patchy distribution of biodiversity appears to be linked to many key ecosystem services and functions (Thurber et al., 2014). The concept of vulnerable marine ecosystems has been used in international fora (such as the United Nations General Assembly - see UNGA Resolution 61/105) for identifying areas that may be particularly impacted by fishing activity (Martin et al., 2015) and is likely to be directly relevant to other industrial impacts. As well as vulnerable habitats, some species or functional groups appear particularly susceptible to anthropogenic impact. For example, suspension or filter feeders, such as sponges or corals, may be vulnerable to impacts caused by suspended sediment (e.g. Bell et al., 2015) or water column pollution (e.g. Fisher et al., 2014). Mobile organisms may be less likely to be impacted than sessile organisms (Gates and Jones, 2012; Jones et al., 2012).

Our understanding of vulnerable marine ecosystems and the extent of their degradation is extremely limited, owing to the challenges associated with scientific investigation beyond diver depth (among other reasons, availability of funding for deep-sea research). The distribution of sensitive habitats remains a key knowledge gap (Vierod et al., 2014), particularly at scales relevant to conservation and management efforts. Without this information, such habitats cannot be effectively protected from impacts like trawling or seabed mining. Industry ROVs could play a crucial role in mapping these habitats (for example contributing to Seabed2030; Mayer et al., 2018), because their global distribution and number offer an unparalleled survey coverage that is unachievable through independent scientific research. The ongoing presence of ROVs in the marine environment may also assist with monitoring the effects of climate change on vulnerable ecosystems. Deep-water coral reefs are particularly susceptible to ocean acidification because they exist closer to the threshold for calcium carbonate formation than corals in shallow water (Roberts et al., 2006; Hennige et al., 2015). ROV video may provide an early warning system for coral degradation and changes to associated biological communities. Industry ROVs could also be used to quantify the diversity of deep ecosystems and identify species that are particularly susceptible to disturbance. Such information will be essential for prioritising conservation and resource management efforts. Lastly, ROV video offers a non-destructive survey method, which is particularly important when studying vulnerable ecosystems over time.

3.8. Q8. To what extent does industrial infrastructure enhance ecosystem value?

Industry structures may be an important source of fish production globally (Gallaway et al., 2009; Macreadie et al., 2011; Claisse et al., 2014), but the challenges associated with surveying fish assemblages in deep water have hindered investigation in most regions. Underwater video can be used to estimate the fish biomass associated with structures by providing data on abundance and size. Production (biomass increase through time) can then be estimated from repeated video surveys, providing site-fidelity and mortality rates are known (see Claisse et al., 2014). Industry ROVs provide a practical approach for surveying infrastructure at a global scale, owing to their number (>700) and broad geographic distribution (IMCA, 2015). The broad distribution will also allow a comparison of production among the wide range of ecosystems that structures are deployed in, from shallow tropical seas through to the deep sea.

Industry structures may act as de facto Marine Protected Areas (MPAs), owing to the fishing exclusion zone surrounding them (Schroeder and Love, 2004). When these structures are decommissioned, large areas of seabed and a substantial biomass of organisms will be accessible to fishing. This may further impact exploited populations, as well as damage benthic habitats and non-target species in the newly opened areas (Thrush and Dayton, 2002; Althaus et al., 2009). Knowledge of the communities on and around industry structures will be essential for determining their current value as MPAs and the subsequent impacts of decommissioning. ROV video provides a useful method for quantifying the diversity of communities associated with industry structures, including species of ecological and commercial significance (Pradella et al., 2014; McLean et al., 2017).

The diverse and abundant reef communities that can develop on industry structures are generally considered to enhance the marine environment (Pradella et al., 2014; Friedlander et al., 2014). However, the impacts of these “accidental” ecosystems on the structure and function of natural communities remain largely unknown. For example, the appearance of large predators in areas previously dominated by lower trophic groups may alter food web structure and disrupt recruitment and nursery functions (Cowan et al., 1999). Visual methods are the only suitable and relatively non-invasive method for observing ecological interactions between infrastructure communities and surrounding ecosystems beyond diver depth. Industry ROVs offer a cost effective source of video data for assessing community impacts and interactions across the broad range of marine environments in which industry structures are found.

3.9. Q9. How can we develop emerging industries in the deep sea?

The economic value of our oceans, the so-called blue economy, encapsulates a wide range of established commercial enterprises including O&G production, container shipping, fisheries, aquaculture, and cruise line tourism, along with rapidly expanding newer areas such as ocean energy, offshore wind energy, desalination, and sea-bed mining (CSIRO, 2015). Two areas for further sustainable development in the deep ocean are bioprospecting and deep sea mining. Both of these potential industries require knowledge on likely global biodiversity “hotspots” and species distribution and abundance patterns on potentially complex terrain, to inform efficient resource development, but also must minimise disturbance of vulnerable species and habitats. Data collected from industry ROVs, such as high resolution mapping and imaging of complex habitats can support a broader understanding of deep ocean environments than possible from shipborne or AUV platforms, providing initial knowledge to support these emerging industries. Relevant examples from research ROV systems include studies of cold water corals (Robert et al., 2017) and hydrothermal vents (Marsh et al., 2013).

Deep-sea animals survive in the dark, under extreme pressure and low temperatures, and are adapted in terms of their chemistry, biology, and physiology, including maintaining the structure and function of their core proteins and cellular components. Thus, it is possible that the natural chemicals isolated from such organisms will give rise to new pharmaceutical and industrial applications. One such example is the Nobel Prize winning research on green fluorescent protein isolated from the jellyfish *Aequorea victoria* (Murbach & Shearer, 1902) that has revolutionised cell biology (Marshall et al., 1995; Misteli and Spector, 1997; Tsien, 1998). Heat shock proteins (HSP) play a heightened role in the maintenance of both protein integrity in the deep-sea as well as in cancer progression (Ravaux et al., 2003). Deep-sea organisms represent an exciting new source of these so-called “wonder drugs" currently in clinical trials, which selectively kill tumour cells by simultaneously targeting several critical functions in these cells, thereby leading to lower chances of drug resistance (Ciocca and Calderwood, 2005). Industry ROVs provide a rare opportunity to examine and sample deep-sea organisms with minimal damage, thereby maximising their potential for drug isolation and extraction.

ROVs with their visual inspection capabilities and the precise manipulators enable targeted sampling to investigate specific features such as microbial communities along an anthropogenic disturbance gradient (Nguyen et al., 2017), meio- and macrofaunal organism diversity along temperature gradients at a hydrothermal vent (Sarrazin et al., 2015), and geochemical, microbial, meio- and macrofaunal sampling of specific habitats on an unexplored lobe of the Congo deep-sea fan (Rabouille et al., 2017). Deep oceanic sediments, hydrothermal vents, and cold-seeps are host to high levels of microbial diversity that are sources of unique biocatalysts able to withstand high pressure and variable temperatures (Duncan et al., 2015; Jensen et al., 2005; Xiong et al., 2015). Microbial communities present grow in extreme cold (psychrophilic), heat (thermophilic) (Urbieta et al., 2015), pressure (barophilic), salt (halophilic) (Yin et al., 2015) or acidic (acidophilic) conditions. This gives rise to a range of biotechnological applications in industrial processes including for food preservation and low-temperature manufacturing processes and biomining, where acid-tolerant bacteria are used to leach metals, such as iron and copper from low-grade sulphide ores such as pyrite (Cavicchioli et al., 2011; Norris et al., 2000). Deep-sea fauna are also an exceptional source of bioactive compounds, with a single 100 m deep collection in New Zealand waters found to produce twice as many anticancer compounds as the average number obtained from >5000 shallow-water collections (Dumdei et al., 1997). Couple this with the relatively high success rate of translating marine natural product discoveries into marketable products, and it is clear that there is a wealth of untapped, high value resources waiting on the deep-sea floor to be discovered. This includes new species, genera and potentially entire ecosystems that are hitherto unknown to science, as well as identifying new modes of biological action that can be harnessed as weapons in the fight against antimicrobial resistance and other current disease threats to society, as well as potential indicators of climate change.

Deep-sea mining is an emerging industry that has relied heavily on the use of ROVs to explore abyssal depths for valuable mineral deposits. Currently, lease permits exist to explore hydrothermal vents for deposits of polymetallic sulphides, seamounts for cobalt crusts, and margin sediments for phosphates (Mengerink et al., 2014); however, the international governing body (International Seabed Authority) stipulates that baseline survey of benthic biota must be undertaken prior to exploration. Conducted using ROVs, these surveys can provide species distribution and abundance patterns (Amon et al., 2016), with the potential to inform efficient resource development and the mitigation of disturbances to vulnerable species and habitats. However, there still remains a need for scientific investigation of the mining activities at a scale beyond exploration boundaries (Lodge et al., 2014; Barbier et al., 2014) and ROVs are becoming routinely used to undertake this research (Schlacher et al., 2013, Vanreusel et al., 2016). Although an emerging industry, the use of ROVs in deep sea mining exploration and its associated environmental assessments demonstrates clear value to industry and deep sea science.

3.10. Q10. How can we improve policy and practise?

Good ocean governance involves laws, institutions and processes to sustainably manage human activities in marine areas, informed by detailed scientific data (IUCN, 2017). The availability of accurate information is critical in understanding the ocean environment and marine resources, as well as monitoring changes and predicting future impacts. ROVs have revolutionised the way data are collected in remote and deep subsea areas to inform decision-making with benefits to governments, industry, and the public. Having accurate information available enables improvements in planning, management, environmental assessment, monitoring, regulation of anthropogenic activities, and conservation of marine habitats (Jones, 2009).

For the regulator, industrial data may offer the primary approach for understanding ecosystems, species and habitats, and enable more nuanced science-based environmental policy development. ROV footage can enhance understanding of conservation status and environmental impacts, and therefore assist in determining priorities for prospective planning and management. For example, ROV footage has shown the extent of marine debris in deep water and thereby exposed the need for new law and policy to control this impact (Ramirez-Llodra et al., 2011). ROVs have also been used to demonstrate established fish assemblages around offshore infrastructure (Pradella et al., 2014; McLean et al., 2017). This information can be used to inform debates and law reform proposals to permit in situ decommissioning. ROV data can also be used reactively in response to requirements for environmental impact assessment and permit conditions. In this way, it can assist regulators in decision-making, to support decision-making on specific projects and licence conditions. Once approved, ROV technology can be utilised as part of ongoing monitoring, often a condition of approval, to measure environmental impacts. This information is therefore important for improving the management of particular projects to reduce specific impacts, and also for broader scale management approaches, such as regional or strategic environmental assessment (Therivel, 2010). To achieve these broader benefits, wide-scale, long-term data must be collected, collated, and shared; overcoming intellectual property and confidentiality issues remains a challenge here.

Industry already utilises ROVs to collect data to support project proposals and to meet licence and permit conditions requiring monitoring of activities, in the offshore O&G industry for example (NOPSEMA, 2015). Therefore, from an industry perspective, improved environmental transparency helps industry obtain government approval for activities and attract social licence to operate (e.g. Smits et al., 2017). In respect to the latter, ROV footage can allay societal concerns and reduce project costs by lessening the risk of community opposition. It is clear that public resistance can be influential in disrupting planned operations, as seen for example in the decommissioning of the Shell Brent Spar facility in the North Sea (Jørgensen, 2012). ROV visual data are particularly powerful in allaying environmental concerns where it is shared with communities through consultative processes. Similarly, ROV footage can help attract positive community support, for projects such as the construction of artificial reefs, where the benefits can be demonstrated to the public.

ROV data are therefore important at a high level, in exploring and prospectively planning for new ocean activities. They have a role in providing targeted information to support arguments for changes in government policies to shift away from an area or use of the ocean, and also to support the opening up of new opportunities. It is not only governments that can use ROV data in this way, but also industry and the public advocating for policy shifts. Increasingly, governments and industry are also concerned about public perceptions of the risks and impacts of ocean activities. Building trust between government, industry and communities is important and the provision of objective, irrefutable data from ROVs has a critical role to play.

Another important aspect of the 'social licence to operate' is public engagement and education. Occasionally, observations from industrial ROVs generate unexpected interest from the general public for reasons that are unrelated to science. When the demersal siphonophore *Bathyphysa conifera* was observed by an industry ROV off Angola (Fig. 2N), this observation represented a major range extension for the species; however, its resemblance to the deity worshipped by the Church of the Flying Spaghetti Monster resulted in it becoming an immediate, viral internet phenomenon. In 2011, a video of an unusual, large, gelatinous object imaged by an ROV working for Petrobras-America at 1536 m, in the Gulf of Mexico (Fig. 2O) went viral. Its unusual appearance resulted in enormous public interest with theories about its identity ranging from a whale placenta to an alien organism. It's true identity, the scyphomedusa *Deepstaria reticulum*, was less extraordinary; however, these videos illustrate how captivating observations of unusual deep sea organisms can be to the public.

ROV footage has also played an important role in reporting of the detrimental aspects of offshore O&G. A prime example is the 2010 Deepwater Horizon oil spill in the Gulf of Mexico, where many of the major US news networks (e.g. CNN) played live footage (as an inset video on the bottom of the screen) of the wellhead leaking plumes of oil into the water column (Black, 2010). Traditionally viewers were exposed to the implications of oil spills with footage of oil slicks on beaches and surface waters, but ROV footage provided a unique opportunity for viewers to witness the unfolding disaster at the source (Black, 2010). Also, once again, scientists opportunistically used the live video footage to estimate the magnitude of the oil leak (based on optical plume velocimetry; Crone and Tolstoy, 2010).

4. Looking ahead

The O&G industry uses ROVs across the complete infrastructure O&G life cycle. From exploration to development (construction) and operations, to decommissioning. Typically ROVs are used to investigate areas to determine environmental sensitivities or geological hazards; install, inspect, and maintain subsurface infrastructure; and remove or decommission this equipment at the end of its life (Table 2). From an environmental perspective, the information collected helps to inform environmental impact assessments, compliance monitoring and environmental risk management, and mitigation strategies. These industrial operations may all result in data that is valuable to science, for understanding organism distribution, behaviour, interactions, population dynamics, community ecology, as well as ecosystem structure, and function (Table 2). The global offshore industry can also benefit from working with environmental researchers. The primary benefit is increased understanding of the environment in which they operate in and their impacts upon it. A secondary benefit is it allows industry employers, contractors, regulators, and key stakeholders to get a better understanding of the rich and diverse habitats that occur around deep water infrastructure. While providing access to industry data may be challenging to achieve for commercial reasons, many benefits arise from sharing ecological data (Michener, 2015).

Table 2
Scientific uses of data from typical industry ROV operations.

Oil and gas life-cycle stage	Industry ROV operation	Description	Resulting data	Scientific use
Exploration	Pre-spud survey	Short ROV survey radiating from proposed well location to look for hazards (visual and sonar survey), prior to addition of infrastructure.	ROV video transect and more detailed survey of any feature of interest.	Opportunistic observations of species, ground-truth/point data on habitats and common species (e.g. to provide a baseline pre-impact assessment).
Exploration	"As found" survey	Short ROV survey radiating from well before leaving an exploration location to ensure seabed is left "as found". Items encountered will be recovered by ROV.	Sonar survey and ROV visual transects with closer inspection of targets.	Opportunistic observations of species, ground-truth/point data on habitats and common species. Quantification of impact of well on seabed.
Exploration	Hazard/unexploded ordnance (UXO)/wreck survey	ROV survey in area of interest to check for potential hazards to operations.	ROV video transect and more detailed survey of any feature of interest.	Opportunistic observations of species, ground-truth/point data on habitats and common species.
Development	Environmental survey	ROV survey in area of interest, usually to check for potential sensitive habitats or species. These can be more in-depth assessments, aimed at producing data on biology or habitat type.	ROV video or still images obtained in a structured survey.	Quantitative ecological assessment of (typically benthic) megafauna.
Operations	Inspection	Typically a short unstructured survey of a specific piece of subsea equipment. It may result in taking a specific measurement (e.g. tilt) or a real-time observation for engineers. Inspections may be regular and frequent (e.g. daily checks of BOP levelling "bullseyes")	ROV video data and potentially high-resolution stills of infrastructure	Opportunistic observations of megafauna. Still photos and information on infrastructure (install date and size) may allow growth rate studies.
Development	Construction	Using the ROV to perform or observe some aspect of subsea construction.	ROV video of construction work.	Rarely of value as ROV in one place facing infrastructure and image may be obscured by sediment. Sound and light may attract or repel mobile species.
Operations	Jacket inspection/marine growth survey	Structured, survey of subsea jacket (steel structure supporting an offshore platform) usually to evaluate marine growth or mechanical damage.	ROV video or still images obtained in a structured survey.	Quantitative ecological assessment of organisms growing on hard substratum.
Operations	Pipeline inspection/integrity survey	Structured survey of a pipeline. The ROV usually runs along the pipeline on rollers and is equipped with three cameras, a central camera looking down onto the pipe and cameras on booms to view either side of the pipe.	Usually good quality scaled ROV video dataset covering much of the length of the pipeline (often tens of km).	Quantitative ecological assessment of organisms growing on and associated with hard substratum in space.
Operations	Riser inspection/integrity survey	Structured survey of a marine riser (a vertical pipe connecting a subsea installation with the surface).	Scaled ROV video dataset that may run from the seabed to near the surface.	Quantitative ecological assessment of organisms growing on and associated with hard substratum and their variation with depth.
Operations	Beacon installation, calibration or survey	Installation (dropping) and calibration of long-baseline positioning navigation beacons or calibration of ultrashort baseline navigation beacons.	Midwater or seabed video transect during transit between sites and measurements.	Opportunistic observations of megafauna. Possible qualitative data on mid-water fauna.
All stages	Sediment sampling	Obtaining a sample of seabed sediment.	Sediment sample, usually not quantitative (scrape sample).	Analysis of sediment properties (if appropriate processing and preservation is available and used).
Decommissioning	Recovery	Recovery of riser or subsea infrastructure.	Possible to obtain faunal samples.	Can be used to confirm identifications on video and for a range of other analyses, including size/biomass determination, growth rate studies, recolonisation studies.

5. Challenges to overcome

While industry ROV data may offer great potential, they come with some limitations over and above those of scientific ROV data. There are three approaches for the scientific use of data from industry ROVs and each has a separate set of challenges.

First, access to opportunistic stills and videos collected during the deep-water ROV work programs. These data can highlight new species, further allow us to understand species distribution and abundance, and collect valuable behavioural understanding. This type of data does not need specialist scientific expertise offshore with the ROV operators. The main challenges to obtaining these data are the concern of industry time constraints to collate, catalogue, and provide data (imagery) to scientific organisations and individuals.

Second, issues with adding additional work scope or equipment to an operation or the ROV. These additions can be used to collect physical data, biological samples or structured quantitative data. These types of programs usually require extra offshore scientific support and/or additional equipment and can raise issues in regards to insurance, health and safety concerns, confidentially, operational risk from the additional workscopes.

Third, reluctance from industry to share ROV data because of the risk that it might reveal industry standard or legal framework violations. Confidentiality agreements can be put in place, but these may be overcome by whistle-blower protections.

6. Maximising ROV data collection through improved industry – science collaboration, instrumentation and training

We suggest that the aforementioned challenges can be largely overcome by partnerships between industry and scientists. For example, the *SERPENT* program (discussed earlier) is a strong example of how close relationships between scientists and industry has led to optimised ROV operations that dramatically improved the value of ROV imagery and additional work programs for scientific purposes, while also building trust and understanding between academia and industry that has ultimately improved data sharing arrangements.

Increasingly, industry has a requirement to understand the environment in which it operates and its likely impacts on that environment (both over the short and longer-terms). In many cases the cost of collecting this knowledge in deep water, on dedicated offshore environmental surveys, can be very high. Industry-science partnership can support the collection of robust scientific knowledge during non-environmental ROV workscopes leading to better and far less costly outcomes.

There is great value for industry in understanding the marine growth on structures that will inform hydrodynamic loading, highlight the need for consequent antifouling strategies to ensure pipeline integrity surveys meet regulatory requirements, as well as identifying the habitat value of structures and their potential as artificial reefs as a decommissioning option (Macreadie et al., 2011; Thomson et al., 2013; McLean et al., 2017). Furthermore, understanding impacts of low visibility around pipelines through dense fish aggregations and sediment resuspension by currents and tides will enable savings through informed scheduling of ROV inspections (McLean et al., 2017). While industry wins through cost savings, it can further benefit by contributing greatly to its environmental social licence to operate, especially if ROVs can be tasked to scientific endeavours, whilst in “idle” time.

From a science perspective, collaborating with industry will help unlock critical data from a range of habitats, with oceanographers and marine ecologists gaining access to previously inaccessible areas. ROVs can also be our “hands” in the ocean, by placing sensors onto the substrate and/or carrying a range of oceanographic instruments to take unprecedented (bio)physical measurements of parameters such as light, sound, chemical concentrations, and hydrodynamic disturbances. ROVs can survey the diversity, growth, and complexity of attached communities, record behavioural observations of animals interacting with these communities and even collect biological specimens. This more holistic approach to understanding the physical and biological drivers of these deep water ecosystems, will undoubtedly lead to a greater understanding of the ecology of these microcosms, while fulfilling industry requirements.

Technological advances to ROVs will maximise their benefits for a range of ocean stakeholders. There have been improvements in the quality of cameras on many ROVs across the O&G industry, incorporating high definition video (e.g. 1080p or 4 k) to improve their inspection capabilities compared to the former standard definition cameras. This has led to clear benefits for the identification of marine organisms (Fig. 5), their abundance and uncovering more subtle aspects of animal behaviour. Often multiple cameras are used, providing a wider field of view without sacrificing spatial resolution; multiple camera fields can be combined for later analyses (e.g. McLean et al., 2017). Some systems now also offer 3D high definition video which, while designed to provide the pilot with better depth perception, can allow precise measurements of organisms and other objects in the field of view. However, it should be noted that trends toward higher resolution, higher frame rate and multiple cameras has consequences both for data storage (more space required) and post-processing burden (longer times and greater computing power needed). In addition, as video quality improves, so must our understanding of how to assess marine life (sessile and active) without disturbance. This may mean monitoring (and mitigating) the effects of the ROV light sources, movements and the noise on the behaviour of animals and plants. At present, there is little known about the effects of the lights used (with respect to intensity and colour) on marine organisms, where, under some circumstances, the lights used may attract or deter organisms into the field of view, thereby not recording a true representation of the underwater scene. Some O&G industries have reported the inability to record video footage of the integrity of critical areas of pipelines and platforms due to the attraction of large numbers of fishes. Technological advances in light emitting diodes (LEDs) and polarization imaging may also improve the resolution and visual range of the ROV cameras, which may be critical in areas prone to sediment resuspension. Neurobiological advances in our understanding of the sensory abilities of deep-water organisms may also provide critical insights into how the impacts of ROVs can be minimised, for instance by reducing their acoustic signal at frequencies where animals have particularly high animal auditory sensitivity.

One roadblock to maximising data collection by ROVs is a lack of understanding of basic scientific data collection principles by pilots and operators. As it is not always possible or practical for scientists to be present during deployments, empowering operators to undertake data collection in a rigorous, repeatable manner will prove an efficient way to utilise ROVs for scientific endeavours. To do so, pilots will require training, which could range from simple instructional videos and printed technical procedures through to formalised components within ROV pilot courses. Some protocols produced by the *SERPENT* Project are already available for use by industry. For example, Gulf SERPENT operating in the Gulf of Mexico has produced an instructional video for ROV pilots to carry out simple survey procedures (http://bit.ly/2yrpa48). Training packs consisting of detailed procedures for recording behavioural observations, capturing specimens, habitat mapping and water column surveys could easily be provided. Ideally, simple, short modules in science data collection principles and procedures would be included in ROV pilot courses in the future as industry-science collaborations mature and mutually beneficial synergies are identified. In addition, data access and archiving needs to be considered. Calibration of ROV-based oceanographic data is also a challenge, especially if they are to be used for long-term study, comparison with other datasets and forecasting. Protocols should be established with data centres (e.g. Australian Ocean Data Network) where the data and associated metadata could be stored and shared.

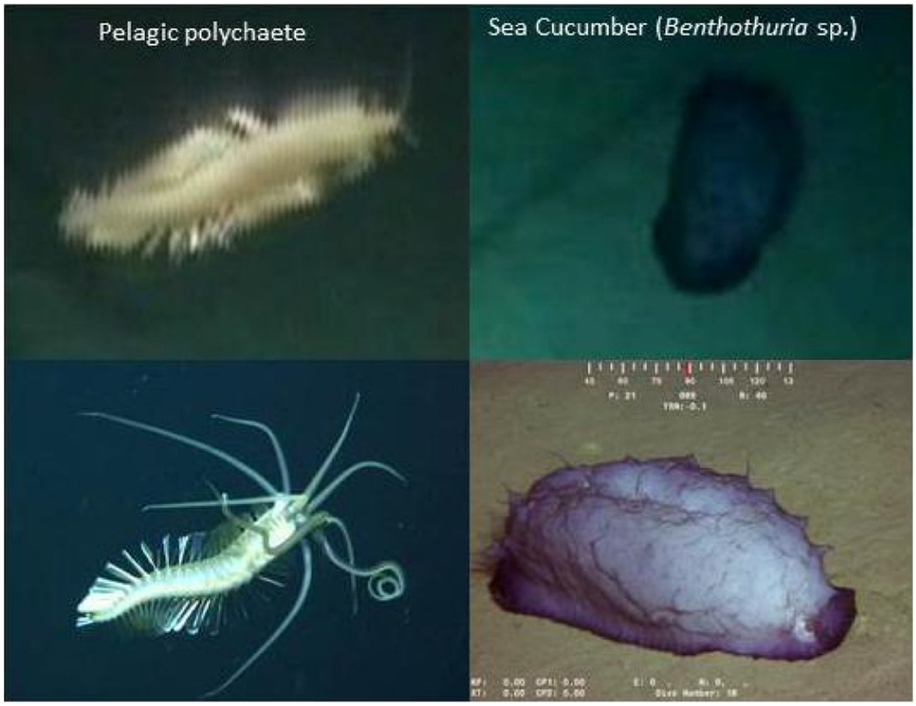

Fig. 5. Recent improvements in video imagery from industry ROV. Top Row, standard definition video grabs of a pelagic polychaete (*Teuthidodrilus* sp.) and sea cucumber (*Benthothuria* sp.). Bottom row, Deep Ocean Pro high definition (1080i) video grabs of similar organisms from Oceaneering Millennium vehicle.

With training and instructions, pilots will be capable of independently collecting data during ROV operations, which could become increasingly more sophisticated with greater communication between industry and the scientific community. Previously, data collection was performed by ROV pilots using standard procedures provided by scientists who may or may not have been present onsite. However, it is now possible for ROV footage to be viewed in real time from locations remote from the survey area. This could revolutionise the way scientific data are collected by ROVs, allowing scientists near- or real time viewing of footage whilst in communication with the pilot. This type of industry-academia partnership (and possibly "citizen science") will accelerate the rate at which we can unlock the mysteries of the ocean, and bring immense value to our society both economically and environmentally, as well as raising our fundamental understanding of the deep oceans that surround us.

In summary, there is a strong scientific case for ROV programs to better support improved understanding of the deep ocean and how it is changing; this knowledge can lead to improved management approaches and a potential expansion of the deep ocean blue economy. An effective route to increasing ROV data collection for science is through industry-science collaborations that operate on a "win-win" principle.

'*The real voyage of discovery consists not in seeking new landscapes, but in having new eyes*.' [Marcel Proust]

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