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A Southeast Atlantic deep-ocean observatory: first experiences and results

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Abstract

The DELOS (Deep-ocean Environmental Long-term Observatory System) project is a long-term research program focused on understanding the impacts of oil and gas extraction on deep-sea ecosystems. We have installed two seafloor observation platforms, populated with ROV-serviced sensor modules, at 1400 m water depth in the Southeast Atlantic off the coast of Angola. The 'impact' Near-Field platform is located 50 m from subsea oil production facilities. The 'control' Far-Field platform is 16 km distant from any industry seafloor activity. Each platform includes oceanographic, acoustic, and camera sensor modules. The latter carries two still cameras providing close-up and wide-angle views of the seabed. The Far-Field platform is also equipped with a sediment trap that deploys to 100 m above the seafloor. The instrumented platforms were installed in Feb 2009, and the sensor modules subsequently serviced in Aug 2009, Feb 2010, and Aug 2010. Here, we report on our first experiences of operating the observatories and present some of the first data. The oceanographic data (temperature, salinity, oxygen concentration) and biological observations (demersal fish and benthic invertebrates) suggest that the two study sites have near identical environmental characteristics. We, therefore, believe that these sites are appropriate as control and impact locations for long-term monitoring of potential anthropogenic effects referenced to natural background environmental variation. We suggest that DELOS-type observatories, particularly operated as pairs (or in networks), are a highly effective means of appropriately monitoring deep-water resource exploitation—both hydrocarbon extraction and mineral mining.

As human activities continue to move further offshore (Bett 2001; Glover and Smith 2003), they come into contact with deep-sea environments and populations that are often not well understood. Deep-ocean basins cover more than 60% of the Earth's surface, yet much of the deep-sea remains unexplored. Recent efforts have been made to address the historical under-sampling of the deep sea by establishing long-term seafloor observatories, some autonomous and some connected to shore stations via electro-optical cables. Here we describe the first results from two long-term autonomous observatory platforms used to study deep-sea ecology in the vicinity of oil and gas industry activity in the Atlantic Ocean offshore of Angola. The DELOS (Deep-ocean Environmental Long-term

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Observatory System) platforms are constructed of unique materials, are the first in the Southeast Atlantic, and the first to be specifically sited within a deep-water oil field.

The longest studies of deep-sea ecology (Smith et al. 2009) have taken place at two sites: Station M in the Northeast Pacific Ocean (4100 m), which has been observed nearly continuously by autonomous camera moorings since 1989 (Smith and Druffel 1998); and the Porcupine Abyssal Plain Sustained Observatory site (PAP, 4850 m) in the Northeast Atlantic Ocean (Lampitt et al. 2010a), which also began autonomous deployments in 1989. Ongoing studies at Station M have used time-lapse (Smith et al. 1993; Vardaro et al. 2009) and towed cameras (Ruhl 2007; Ruhl and Smith 2004), sediment trap moorings (Smith et al. 2001; Smith et al. 1994), and sediment community oxygen consumption measurements (Smith and Kaufmann 1999) to characterize and identify seasonal, annual, and inter-annual variability. A broad range of seafloor, water column, and surface ocean observations have been undertaken at the PAP site (Billett and Rice 2001; Lampitt et al. 2010b) that now provide data on surface-to-seafloor connections and dynamics in the NE Atlantic. Other long-term observation sites include the HAUSGARTEN observatory in the Fram Strait (Arctic; Soltwedel et al. 2005) and Japan's Sagami Bay (Northwest Pacific; Kitazato and Ohga 1995). More recent observatory projects include NEPTUNE Canada (cabled; Tunnicliffe et al. 2003) and the Monterey Accelerated Research System (MARS, cabled; Massion and Raybould 2006), both in the Pacific Ocean, and the Ocean Observatories Initiative (a mix of cabled and autonomous platforms; www.oceanobservatories.org) in the East Pacific and West Atlantic. Other than DELOS, no long-term observatories, cabled or autonomous, are currently deployed in the Southeast Atlantic.

The offshore environment of West Africa is highly productive, exploited for hydrocarbons and subject to heavy fishing pressure, yet has only recently been extensively studied by oceanographers (González-Dávila et al. 2009; Utne-Palm et al. 2010). The BIOZAIRE program, for example, was initiated in 2000 to characterize the benthic community of the continental margin in the Gulf of Guinea, specifically the Congo River submarine channel and deep-sea fan (Jorissen et al. 2009). The BIOZAIRE surveys, conducted from 2000 to 2005, involved sediment sampling and mooring deployments at 11 different sites in various habitats ranging from 350-4800 m water depth, including hydrocarbon seeps and coral outcrops. The sites were visited intermittently over the five-year study period, prior to the initiation of oil and gas production activity (Sibuet and Vangriesheim 2009). In contrast, the DELOS project focuses on sustained time-series observations of two reference sites at the same depth, supporting identical habitat types. The goal of the DELOS observatory is to compare natural temporal variation at one site (termed "Far-Field") with any anthropogenic changes due to oil extraction activity proximal to the other site (termed "Near-Field").

This article presents our first experiences of operating the two DELOS observatory platforms and examines the DELOS technology and some of the first datasets. We consider oceanographic and camera system data used to study the seafloor currents, oceanographic conditions, seafloor biological activity, and sediment flux rates.

Materials and procedures

Two DELOS deployment sites were chosen offshore of Angola to enable identification of both natural cycles in climate and productivity and any direct or indirect anthropogenic influences on the local deep-sea environment. The study sites were located within petroleum lease Block 18, a mid-slope region with water depths ranging from 1164 to 1514 m (Fig. 1A). Block 18 lies between the deep-sea sediment fans of two major rivers, the Congo and the Kwanza. Predeployment environmental surveys (Bett 2007; Hughes and Bett 2007) and BIOZAIRE surveys (Sibuet and Vangriesheim 2009) showed the area to be highly productive, with seasonal and annual variability in carbon input and benthic populations, influenced by the interactions of the Angola and Benguela current systems and terrigenous inputs from the Congo River outflow. The seabed environment of Block 18 is characterized by salt diapirs, pockmarks, and fine-grained sediment transported and deposited by river outflows (Bett 2007). The DELOS study sites are at a water depth of 1400 m, in an area of level open sedimentary seafloor. The proposed duration of the Angola DELOS project is 25 years, to provide near-continuous monitoring throughout the operational lifetime of the adjacent Greater Plutonio oil field.

The platforms were both deployed at 1400 m water depth in the SE Atlantic off the coast of Angola in February 2009 (Fig. 1B). Both locations have minimal seafloor slope (<1°) and fine-grained brown sediments covering more compact olive-gray clay. The Near-Field platform (DELOS A) was deployed at 07°54.0′S 012°08.4′E at a distance of 50 m from a BP subsea oil production facility (wells, manifolds, and flow-lines). The 'control', Far-Field platform (DELOS B) was deployed ~16 km from the BP site at 07°57.1′S 012°16.8′E.

These platforms serve as long-term seafloor docking stations for exchangeable observatory modules that are serviced by remotely operated vehicles (ROVs) without disturbing the area under observation. The platforms were designed to be sufficiently rigid and firmly emplaced to support a work-class ROV during servicing. The triangular, tripod platforms (Fig. 2A) were constructed from glass fiber reinforced composite material and Super Duplex stainless steel to minimize corrosion and withstand other environmental degradations over the proposed 25-year duration of the project. Each platform is 8 m on a side, stands on three 4.5 m legs, and has docking bays for five observatory modules (Fig. 2B). The modules sit above the seafloor to minimize disturbance of the seabed, facilitate near-seafloor water column measurements, and aid in camera observations of the seafloor processes below and around the platforms.

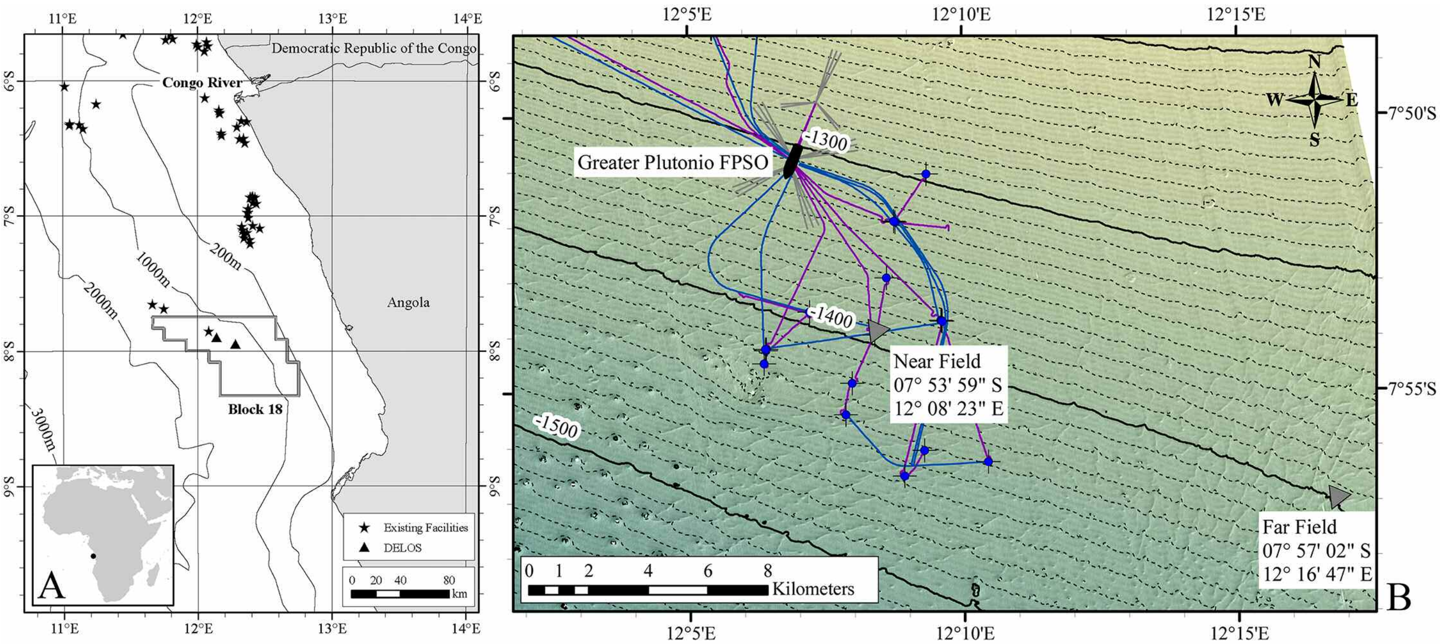

Fig. 1. Maps showing (A) the geographic region of the DELOS observatory and all adjacent oil extraction facilities in the Southeast Atlantic off the coast of Angola, and (B) the location of the Greater Plutonio FPSO, Near-Field, and Far-Field DELOS platforms within lease Block 18.

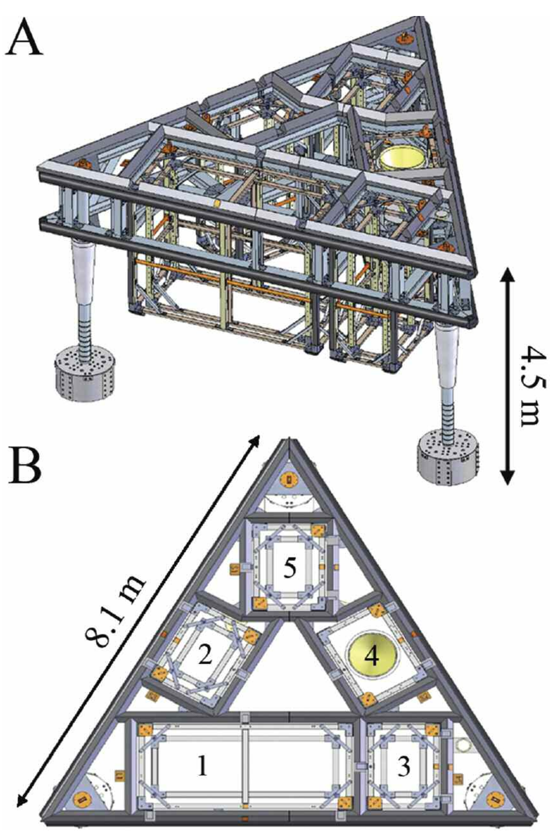

Fig. 2. The DELOS platform design. (A) elevation, (B) plan view, showing the positions of the camera module (1), oceanographic module (2), acoustic module (3), sediment trap module (4; Far-Field site only), and spare module (5).

Four types of observatory module were initially deployed: (i) camera; (ii) oceanographic; (iii) acoustic; and (iv) sediment trap module (at Far-Field site only). Each module has a controller that provides backup data storage and a centralized programming interface for each suite of instrumentation, all originally powered by lithium batteries. The lithium battery packs were replaced by alkaline battery packs in February 2010. Onboard data storage and battery capacity provide for 6 months of continuous operation, after which each module must be recovered, serviced, and redeployed by ROV.

The camera module has 'close-view' and 'wide-view' systems, which both take one time-lapse digital still photograph every 3 hours. The cameras are 5.1 megapixel Kongsberg OE14-208 digital cameras, with flash illumination provided by Kongsberg OE11-242 flash strobes, plus two additional Oceanlab-modified strobes for the wide-view camera. The close-view camera is mounted 1.35 m above the seafloor giving an oblique view of ~2.1 m^2 of the sediment surface. The wide-view camera is mounted ~3 m above the seafloor, giving a ~20 m^2 oblique field of view.

Each oceanographic module houses: (i) 300kHz Teledyne RDI Acoustic Current Doppler Profiler (ADCP; 165 m range), giving current speed and direction in the water column above DELOS; (ii) WET Labs C Star transmissometer (660 nm wavelength, 25 cm path length) providing a proxy for particulate matter concentration in the water column; (iii) WET Labs ECO FLNTU fluorometer (470 nm excitation wavelength, 685 nm emission wavelength) assessing Chlorophyll *a* content of suspended particles; (iv) current meter (Aanderaa 3820R) measuring current speed and direction close to the seafloor; and (v) a

'CTD' unit (Aanderaa 4017E pressure sensor, Aanderaa 3919 conductivity Sensor, and Aanderaa 3975 oxygen and temperature sensor) measuring standard oceanographic parameters.

The acoustic module contains both passive and active sonar systems. The passive sensor will, for example, allow vocalizing cetaceans to be identified and counted from characteristic sound spectra recorded through an omni-directional deep-ocean hydrophone (Sensor Technology) coupled to a broadcast quality hard disk recorder (Sound Devices). The high frequency active sonar (Kongsberg mesotech) allows fish movements to be tracked at ranges of up to 100 m from the DELOS platform. An Oceanlab single board PC based system controls this 675 kHz mechanically scanned visualization sonar, enabling the active sonar to operate autonomously for 6 months. To conserve battery power, an independent microcontroller is used to power the single board PC on a user-defined schedule.

The sediment trap module (Far-Field platform only) collects sedimenting particles (e.g., phytodetritus). The McLane Parflux 78H-21 trap is moored 100 m above the bottom (mab) on a deployable cable from an InterOcean VPS winch system that is controlled by ROV. The winch was originally designed to operate by either preprogrammed timer or acoustic command. During the first service period the winch operated correctly under acoustic command, however the motor was so corroded that it had to be disabled. The winch drum is now manually operated by ROV. Sinking particulate matter is collected in twenty-one 500 mL cups that are sequentially rotated beneath the collecting cone at 9-day intervals. Each cup is filled with 10% formalin solution buffered with sodium tetraborate (Knauer et al. 1984) prior to deployment. The 100 mab trap depth was chosen to reduce the quantities of resuspended sediment collected by the trap, while still being representative of particulate material supply to the seafloor. No sediment trap module was installed on the near-Field platform to prevent potential interference with adjacent oil field operations, as the sediment trap cable represented a potential hazard to ROV tethers. Processing of sediment trap samples (drying, weighing, organic and inorganic carbon analysis, and fluorometric analysis) is conducted at the Instituto Nacional de Investigação Pesqueira in Luanda, Angola, and is currently ongoing.

In addition to the in situ instrumentation on the observatory platforms, the DELOS project also draws on two other data sources. First, an additional 'CTD' unit (see above) is fitted to the tether management system of the servicing ROV to provide full water column profile oceanographic data above the observatories. Second, satellite ocean color data are used to assess seasonality in surface ocean primary production to provide context for the sediment trap observations. Net primary production data, derived using the Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski 1997), were obtained from the Oregon State University Ocean Productivity online resource (www.science.oregonstate.edu/ocean.productivity). The VGPM net primary productivity value was extracted from files of monthly averages using a routine written in MATLAB (Mathworks Inc.). Data were extracted separately for the (1/6° by 1/6°) pixel containing the Near-Field and the Far-Field DELOS platforms. In addition, data were extracted for the 8 pixels immediately adjacent to each DELOS site; these were averaged to give monthly data at one-half by one-half degree resolution. The export flux (to 100 m water depth) of particulate organic carbon (POC) was estimated for all four areas using the Dunne et al. (2005) algorithm. The POC flux to the seafloor (1400 m) was estimated for each month over the VGPM time series (July 2002 to Sept 2010) using the commonly used Pace et al. (1987) algorithm. The Lutz et al. (2007) algorithm was used to provide a single estimate of annual flux to the seafloor over the entire period of the VGPM time series (based on monthly averages from July 2002 to Sept 2010).

Assessment

The two DELOS platforms were successfully emplaced on the seafloor and populated with science modules from the Field Service Vessel (FSV) *Bourbon Oceanteam 101* in February 2009. Three rounds of module recoveries and redeployments have since taken place: Aug 2009, Feb 2010, and Aug 2010 (Fig. 3). Data from the first deployment (Feb-Aug 2009) were only partial as a result of corrosion damage, which led to leaks and offgassing within the battery housings and consequent loss of battery power (since corrected). The damaged battery housings (later found to have dissimilar metals due to manufacturing error) were replaced with new ones, but insufficient backup housings were available at the time to replace all packs. The shortage of battery power required some modules to be uninstrumented during the second deployment (Aug 2009-Feb 2010). The Far-Field platform was fitted with a complete set of modules; the Near-Field platform had only the camera module and an ADCP. The third deployment period (Feb-Aug 2010) commenced with new alkaline battery packs, and provided full acoustic and oceanographic records from both Near-Field and Far-Field sites. However, only 65 days of images were recovered from the camera modules due to strobe malfunctions and battery failures; additional maintenance was required to repair further corrosion damage. Acoustic data are not presented here, as the active sonar modules were largely nonoperational due to corrosion and power loss, and the hydrophone data collected during the third deployment period is still being analyzed.

There was visible evidence of some sediment accumulation on the sensor module frames and the settlement and growth of small tunicates on some of the recovered modules. No evidence of biological growth was seen on the platforms themselves, and the periodic recovery and cleaning of the modules appeared to have prevented significant fouling.

Oceanography

Only incomplete data were recorded during the first two deployment periods, with approximately 1 month of data

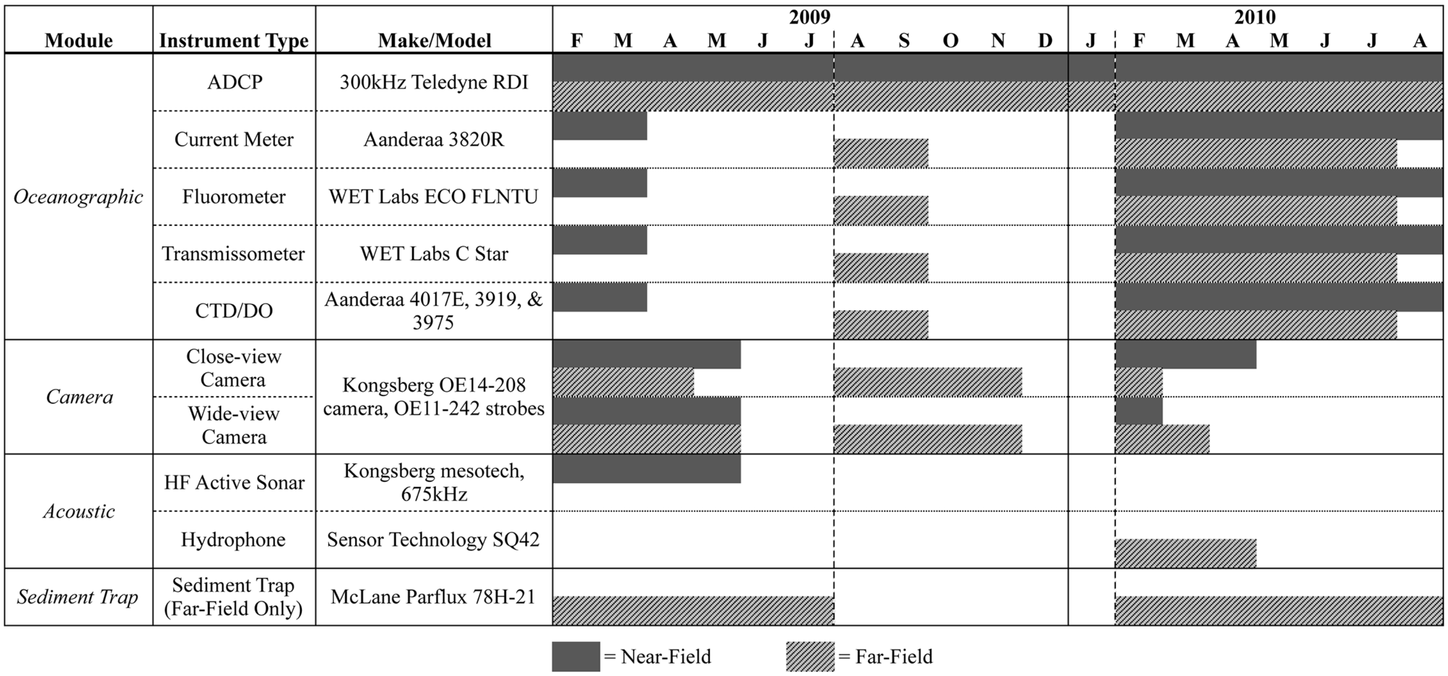

Fig. 3. DELOS modules and active instrumentation at the Near-Field (solid bars) and Far-Field (hatched bars) over the three deployment periods (separated by dashed lines). The sediment trap module was only deployed at the Far-Field platform. The Near-Field platform supported only the camera module and an ADCP during the second deployment (Aug 2009–Feb 2010).

available from the Near-Field (Feb-Mar 2009) and Far-Field (Aug-Sep 2009) oceanographic modules. However, near-complete data were returned from both sites during the third deployment period, from Feb-Aug 2010 (Fig. 4). These data show common trends at both sites in temperature, salinity, and oxygen concentration (Spearman's rank correlations of oceanographic properties between sites give highly significant values, $P < 0.001$). The average recorded current speed at the Far-Field site was 4.81 (± 2.78) cm s^{-1} (max = 19.86 cm s^{-1}, min = 0.06 cm s^{-1}) and 4.18 (± 2.95) cm s^{-1} (max = 19.66 cm s^{-1}, min = 0.08 cm s^{-1}) at the Near-Field site. The Near-Field and Far-Field ADCP data were rotated to reference them to true north, and depth averaged to 50 mab using Bins 2-11. The data were then hourly averaged and low-pass filtered using a 40-h loess filter (Schlax and Chelton 1992). Prevailing near-bottom currents at the Far-Field site generally flowed WNW, along slope. The strongest flows at the Near-Field site were directed to the NW, also following the bathymetry (Fig. 5). A power spectrum analysis showed semidiurnal tidal oscillations, as well as spring-neap cycles, in both Near- and Far-Field pressure sensor records. The transmissometer and fluorometer both experienced severe corrosion and power losses, and no reliable data were recorded during the first few DELOS deployments.

Sediment trap

The sediment trap at the Far-Field site operated correctly during all three deployments. However, very little material was recovered from the second deployment (Aug 2009-Feb 2010), likely as a result of a blockage in the collecting cone. Similar amounts of material were recovered during the first (Feb-Aug 2009) and third (Feb-Aug 2010) deployments, and POC analysis of those samples is ongoing. During the first deployment, there was a generally increasing trend in particle flux, calculated using dry weights from processed samples of the material collected in the sediment trap as well as estimated dry weights from samples that are not yet fully processed (Fig. 6). This trend was substantially in advance of the peak in surface ocean primary production estimated from satellite data, suggesting that the particulate material collected derives from local resuspension or riverine outflows. Rabouille et al. (2009) documented extremely high POC flux rates (as high as 400 mg m^{-2} d^{-1}) in the BIOZAIRE study areas, just north of the DELOS sites. They found that flux rates were higher at 30 mab than at 400 mab, which was attributed to local resuspension of sediment.

Photography

The wide-view camera images revealed substantial water column turbidity with the view of the seafloor often obscured. Although rendered unsuitable for benthic observations, the images were used to assess the amount of suspended material in the water column. ImageJ© software was used to measure the luminosity of each image. Higher values indicate greater backscatter from the suspended material (Fig. 7). The elevated luminosity observed during the first deployment was most likely due to the proximity of one of the three strobes to the camera lens. That strobe was relocated following the first module recovery in August 2009, which resulted in reduced

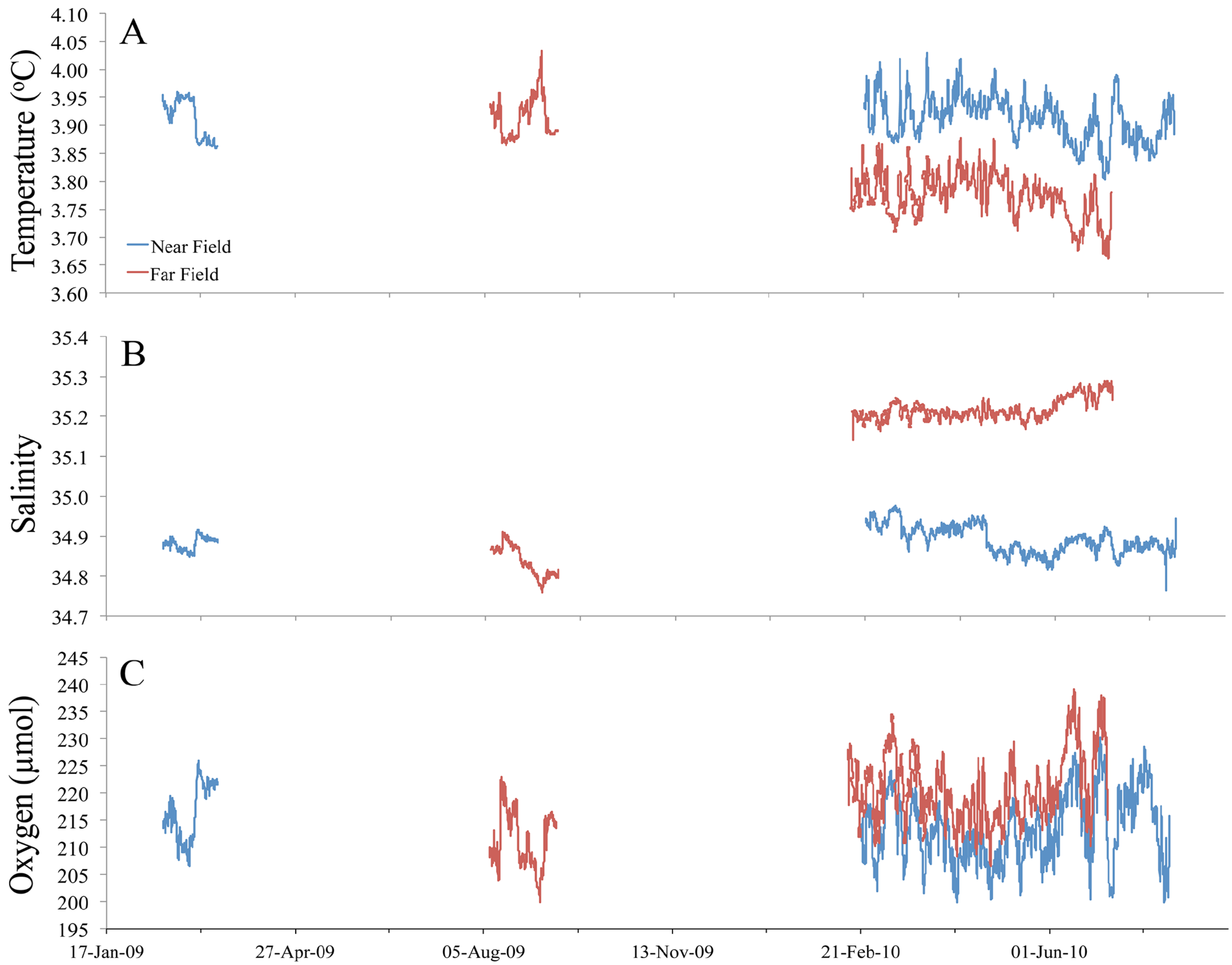

Fig. 4. Oceanographic data (A, temperature; B, salinity; C, dissolved oxygen) from the Near-Field (blue) and Far-Field (red) DELOS sites in the Southeast Atlantic off the coast of Angola collected Feb 2009-Aug 2010.

backscatter in subsequent deployments. Luminosity values were compared with corresponding oceanographic data but no relationship was detected with current speed or direction, temperature, or any other oceanographic parameters at either site (Spearman's rank correlation $P > 0.05$). Unfortunately, the transmissometer data from the corresponding time periods could not be directly compared to the luminosity data, due to biofouling and corrosion that rendered the transmissometer data unusable.

The Near-Field and Far-Field close-view time-lapse cameras recorded clear views of the seafloor and its fauna. Battery power limitations resulted in restricted photographic coverage during the three deployments. The seabed at both Near-Field and Far-Field sites had a scalloped appearance, with multiple shallow depressions. Occasional falls of flocculent particulate material to the seafloor were recorded during the Aug 2009-Feb 2010 and Feb-Aug 2010 deployments. Deposits of material ranging in color from white to pale green and potentially derived from surface phytoplankton, appeared on the seafloor, gathered in the depressions, and then disappeared over a period of several days. No direct consumption of the deposited material was observed, but sediment disturbance (bioturbation) indicated the activity of benthic fauna. This bioturbation appeared to be most pronounced following detritus fall events.

The fish fauna was dominated by species from the genera *Synaphobranchus*, *Aldrovandia*, *Coryphaenoides*, and *Cataetyx*, and the family Squalidae (Fig. 8A-E). Among the invertebrates, decapods (prawns and squat lobsters) were the dominant group; various cnidarian medusae (jellyfish) and holothurians (sea cucumbers) were also observed at or close to the seafloor (Fig. 8F-K). Population estimates for fish and invertebrates

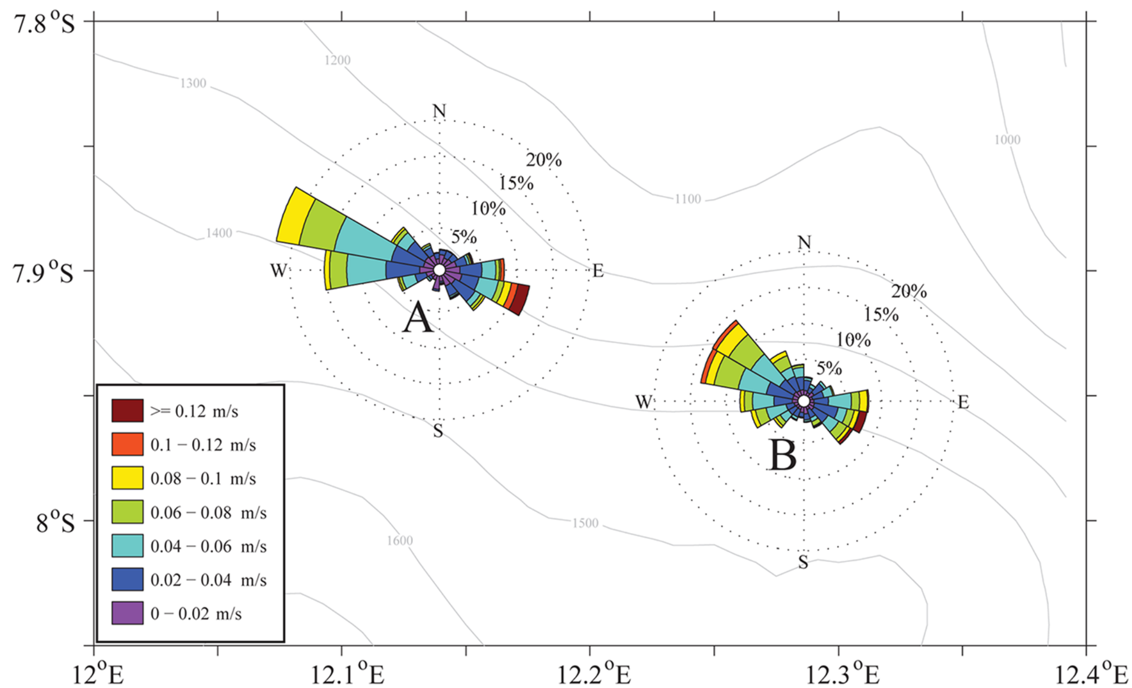

Fig. 5. Current speed and direction recorded at the Near-Field (A) and Far-Field (B) DELOS sites in the Southeast Atlantic off the coast of Angola Feb-Aug 2010.

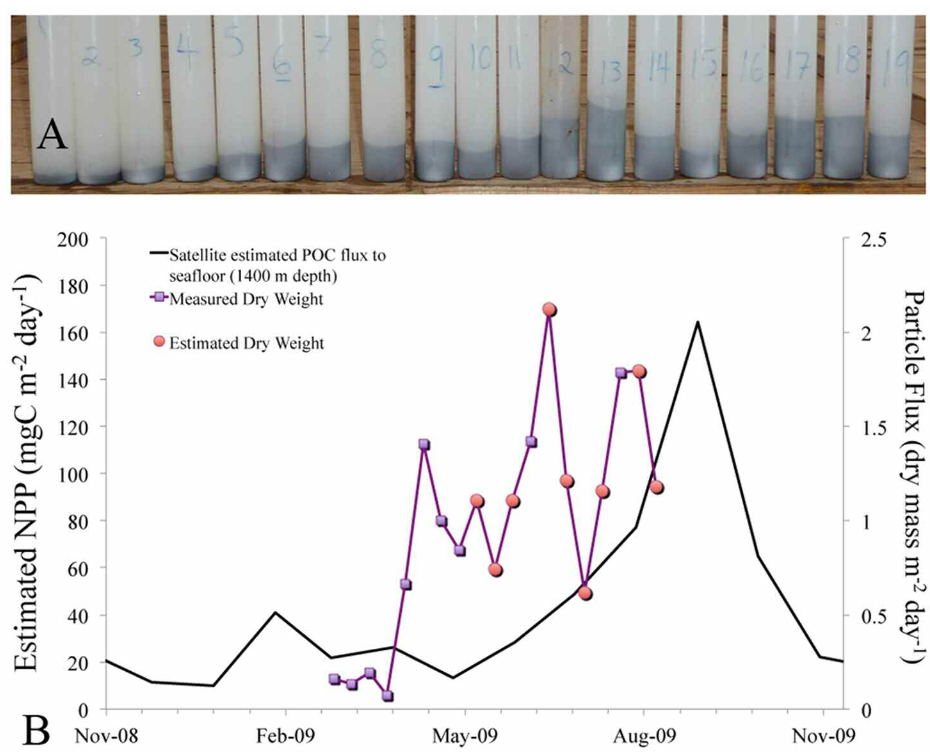

Fig. 6. Sediment trap results from the DELOS Far-Field site in the Southeast Atlantic off the coast of Angola Mar-Aug 2009. (A) material collected by sediment bottles (9-d periods); (B) particle flux rates (dry mass m^{-2} d^{-1}), calculated using dry weights from processed samples of the material collected in the sediment trap and estimated dry weights from samples that are not yet fully processed, compared with satellite-derived surface ocean net primary production.

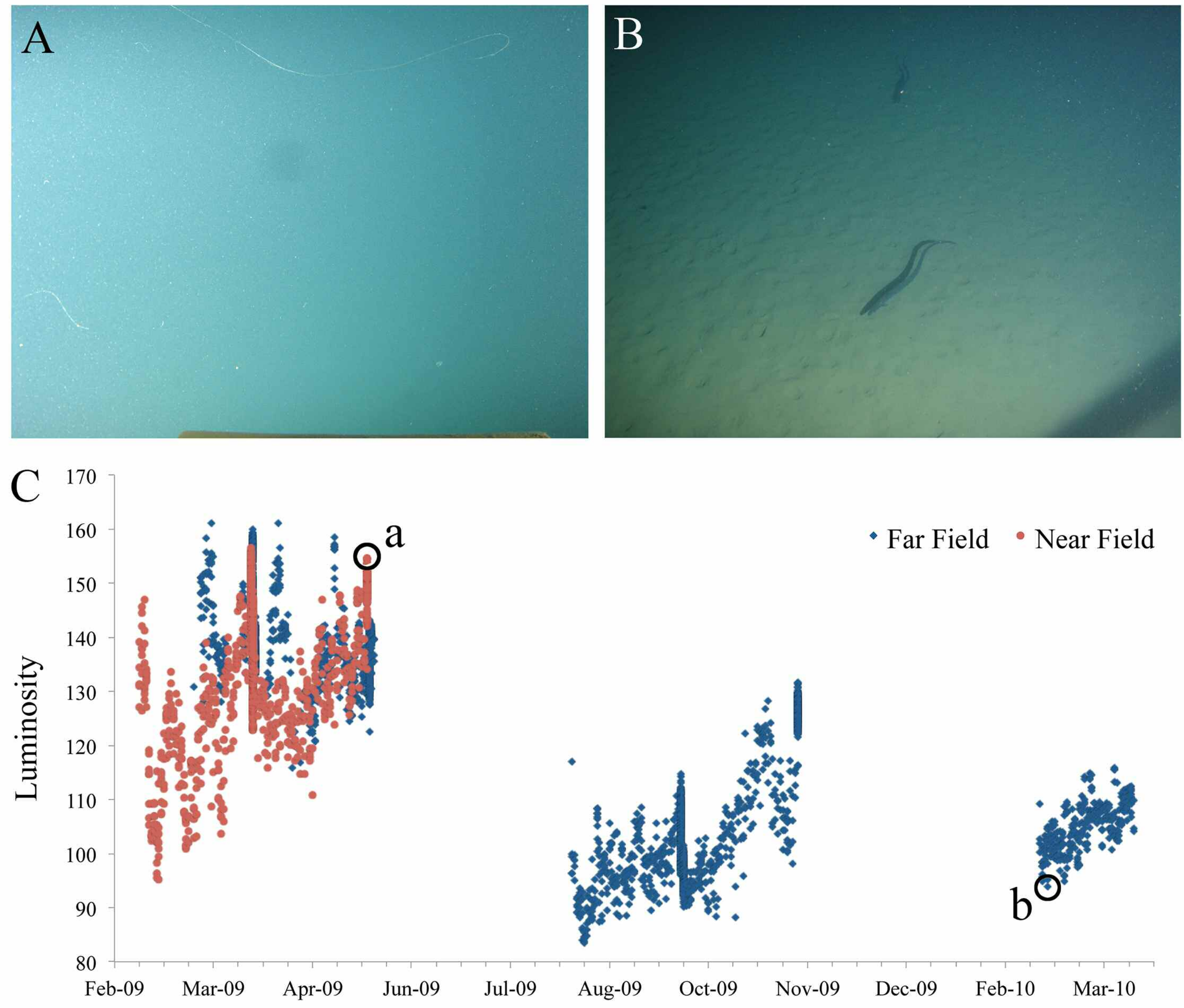

Fig. 7. Images from the DELOS wide-view camera systems during periods of high (A, a) and low (B, b) turbidity. (C) quantified image luminosity, which dropped following the first deployment due to relocation of the strobe nearest the camera lens.

were generated based on total counts of individuals and the total area photographed (number of frames × 4 m^2) per deployment. These values were then averaged to obtain the geometric mean value across available deployments, according to the point transect method established in Bett et al. (2001). Estimated fish population density, at 138 individual ha^{-1}, is broadly comparable with previous towed camera surveys (100 individual ha^{-1}; Bett pers. obs.) and baited camera studies (200 indiv. ha^{-1} Wigham 2006) in the Block 18 area. However, estimated invertebrate density, at 24 individual ha^{-1}, appeared to be very low compared with towed camera surveys (600 individual ha^{-1}; Hughes and Bett 2007).

During April 2010 (deployment 3) the close-view camera recorded the extensive deposition of gray granular material on the seafloor at the Near-Field site, having an appearance consistent with drill cuttings (Fig. 8L-M). Drill cutting deposition has been shown to cause short-term reductions in the diversity and density of local populations of epibenthic organisms, particularly among larger size classes (Jorissen et al. 2009; Trannum et al. 2010). Given that the drill cutting deposition event took place toward the end of the record that is covered here, the effects of the deposition event on the biota could not be quantified, and will be addressed in future analyses of the DELOS data.

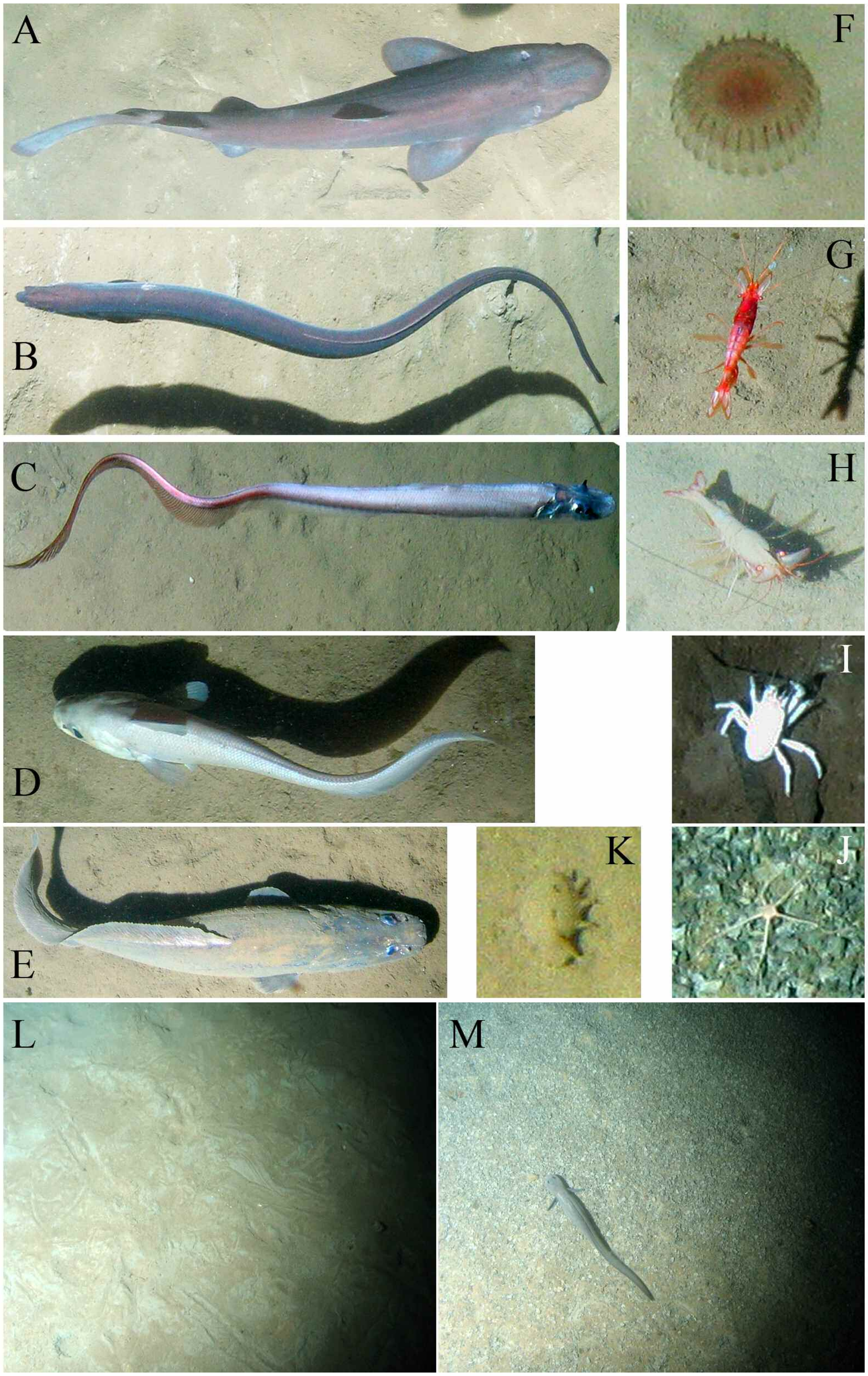

Fig. 8. Example photographs from the DELOS close-view camera systems. A, Squalidae (shark); B, *Synaphobranchus*; C, *Aldrovandia*; D, *Coryphaenoides*; E, *Cataetyx*; F, medusa (jellyfish); G, H, natant decapod (prawn); I, reptant decapod (squat lobster) crab; J, ophiuroid (brittlestar); K, holothurian (sea cucumber); L, Near-Field site 18 Apr 2010 ('normal' sedimentary seabed); M, Near-Field site 27 Apr 2010 (presumed drill cuttings on seabed, with Zoarcid fish).

Overview

The DELOS observatory platform engineering design has proved to be highly effective, providing a robust and stable base for the various sensor packages, and facilitating their servicing by ROV. Once deployed on the seafloor, the platforms remained stable throughout each cycle of module deployment and recovery, which was confirmed by getting a location fix from the ROV, inspecting the penetration depth of the platform feet in relation to the seafloor, and examining a circular level attached to the top surface of each platform at the end of each set of module refurbishment activities. The platform materials proved capable of withstanding the weight of a work ROV on the top surface, and the platforms and modules exhibited little to no biofouling or signs of fatigue over the deployment period. The modules were light enough to be manipulated by a single ROV when lowered using the ship's crane, and strong enough to support multiple sensor packages without any measurable vibration or instability.

Individual sensors and battery packs have suffered from 'teething problems,' but when operational have provided the data necessary for a comprehensive assessment of the seabed and near-seabed environment. The high near-bottom turbidity levels that limited the use of the wide-view camera systems' photographs were unexpected. Near-identical camera and flash set-ups have proved highly effective in other deep-sea applications (e.g., Smith et al. 1993). As noted, following the first deployment one strobe was moved farther from the wide-view camera lenses to reduce backscatter. Otherwise, the number, elevation, and orientation of the strobes have remained constant to provide constant illumination of the fields of view from deployment to deployment.

The two DELOS sites, Near- and Far-Field, appear to be highly consistent in terms of seabed and water column characteristics, with along-bathymetry flows similar to those seen by Vangriesheim et al. (2005). The close-view camera systems' photographs suggest that there is a common fish and invertebrate fauna at both sites. The results of ANOSIM tests on MDS analyses of biological and environmental data using the PRIMER® software package (Clarke and Gorley 2006) were non-significant ($P > 0.1$) over the deployment time periods. The tests were based on a list of 24 'species' (ID to at least family) of which 9 are currently unidentified. The data were standardized and square-root transformed before analysis. At this stage, we have not done any BEST comparisons between the fish and environmental data. The environmental data were sufficiently stable across all deployments to date that any correlations are likely to be artifacts of the data rather than describing any real trends.

That the physical and biological environments of both sites are highly comparable is critical to any future interpretation of anthropogenic effects from the adjacent oil field (e.g., drill cuttings deposition at Near-Field site). It is important to note that the apparently low density of invertebrates noted above applies to both sites and is not related to the drill cuttings deposition—though clearly will be monitored in this context in the future. Rather, the low density of invertebrates is in comparison with earlier estimates derived from a towed camera system. Photographic estimates of seafloor invertebrate density can be highly sensitive to camera altitude, angle, focal length, the illumination system, and water clarity (e.g., relative turbidity).

Discussion

The DELOS observatory design has met its primary requirement to provide a robust seafloor platform in which to mount instrument packages that can be routinely serviced by ROVs. In at least the medium term, the majority of in situ sensors will continue to require periodic recovery to address fouling and calibration drift issues, as well as data offload and power replenishment. Future development of the DELOS concept may include direct connection to power and data networks such as those used in the control and monitoring of deep-water oil fields. However, considerable development is yet required to produce a full suite of sensors that could operate untended for extended periods (years).

The second key requirement of the DELOS Angola project was to enable long-term monitoring of potential anthropogenic impacts with reference to natural environmental change. Site selection seems to have been effective in this respect. The 18-months of observations to date have revealed no major differences in the natural environments of the two sites. The unplanned arrival of drill cuttings at the Near-Field site perhaps illustrates the importance of the paired observatory approach adopted in this project.

Existing long-term deep-ocean observatories have established the extraordinary scope for natural variations in even the remotest of environments (Bett et al. 2001; Ruhl 2007). The paired observatory approach, and potential use of larger observatory networks, is essential to discriminating local (e.g., anthropogenic) from widespread (e.g., natural climatic variation) environmental change. Such information is indispensible to the development of evidence-based, sustainable exploitation of deep-water resources.

The DELOS system is one potential solution to the development of practical deep-ocean seafloor observatories. Its modular construction lends itself to a variety of applications. Indeed, the platforms were designed to accommodate additional 'guest modules,' to enable the inclusion of different sensors and to serve as test beds for new sensor development. The platforms were developed for operation with industry work-class ROVs and so are particularly suited to deep-water oil field applications where such vehicles are in routine use. However, larger science-class deep-water ROVs could also service the observatory.

In addition to oil industry monitoring applications, other commercial deep-sea ventures, such as the mining of manganese nodules and massive sulphides (Halfar and Fujita 2007), that will rely on large surface vessels and ROVs might benefit from a DELOS-type approach. A paired, or multiple observatory approach would be well suited to monitoring mining impacts relative to natural variations. The environmental impact assessments for such ventures are reliant on a very limited knowledge base of long-term change in the deep sea (Sharma 2005). Establishing that the impact predictions were realistic will require extended monitoring of both impacted and control sites—as we have initiated in the DELOS Angola project.

Comments and recommendations

The key objectives of the DELOS Angola project were achieved: installation of robust observatory platforms, with ROV-serviceable sensor modules, at appropriate 'control' and 'impact' sites. There have been individual sensor system failures (corrosion, sediment trap clogging) and unexpected environmental problems (high turbidity). Increased spares, more thorough instrument and housing inspections, and more comprehensive cleaning between turns have been added to the refurbishment protocol. The use of novel nonmetallic materials to construct the frames and modules may have concentrated corrosion on the instrument housings. The recovery and redeployment in February 2010 included several design refinements, including movement of one wide-view strobe farther from the camera lens to reduce backscatter, an increased number of zinc anodes to reduce corrosion, and more alkaline battery packs to ameliorate battery life issues. The most recent six-month service intervals have had limited data loss.

The success of the project to date has had two key critical dependencies: (i) the close and committed collaboration of the industry partner (BP); and (ii) the development of local science support for the project (Instituto Nacional de Investigação Pesqueira, Luanda, Angola). Continued observatory operation requires routine ROV-servicing, as can be provided by oil field support vessels. Prompt processing of sample material (e.g., sediment trap collections) to ensure data quality has required the development of a sediment chemistry facility in Luanda. Setup of the facility required a great deal of planning to identify laboratory space and ship all necessary equipment and supplies, including backup power supplies to handle unexpected power interruptions. Detailed instruction manuals regarding the use and refurbishment of equipment and science modules were created (and translated into Portuguese) to assist in training local science staff and to ensure essential continuity of personnel on the project.

This form of partnership (industry partner, international oceanographic collaboration, and local science team) provides a good model for future applications of DELOS-type observatory systems, potentially including cabled systems with increased power and near real-time data availability. By design, DELOS is particularly suited to oil field operations, but could readily be implemented by other deep-water industries (see above). The modular approach to sensor packages enables the tailoring of the system to different environmental settings and impact/science questions.

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