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NEW METHODS

A novel approach for in situ benthic habitat characterization

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Abstract

Habitat heterogeneity is a key driver of temporal and spatial variability of subtidal marine benthic biodiversity. However, this makes it a challenging environment in which to measure and quantify the factors driving biodiversity in a consistent manner. Current methodologies are either expensive, logistically challenging, require extensive technical knowledge, or are limited to shallow water environments. To overcome some of these limitations, a novel "SeaPen" device was designed as a cost-effective, safe, easily deployable instrument that can provide repeatable and comparable survey results over the small spatial scales required to describe heterogeneous environments. The device, which comprises a tripod frame holding a steel weighted bar in the center, allows gravity to force a graduated metal spindle into the substratum when it is dropped. A video camera fixed to a tripod leg allows the recording of the nature of the seabed and the depth of penetration of the spindle, from which seabed properties can be described. The device does not need to be recovered to the surface between measurements, which allows it to be repeatedly dropped for multiple replicates in a single deployment. The combination of a penetrating spindle and a camera allows for rapid repeat measures and, most importantly, can be used to measure heterogeneity on finer scales (within a site; m) than other more traditional techniques. The SeaPen was used in a shallow water (<50 m) coastal habitat on the West Antarctic Peninsula. The survey area comprised heterogeneous substrata composed of sediments interspersed between boulders, cobbles, and pebbles, which allowed for proof of concept that the SeaPen could discriminate a wide range of seabed habitat types.

Abiotic and biotic environmental variables have a key influence on the composition and diversity of marine benthic communities (McArthur et al. 2010), with variation in the physical environment generating habitat heterogeneity over a range of geographic scales (Post et al. 2017). Understanding the relationship between the properties of the seabed and its associated biodiversity allows findings to be scaled up through habitat mapping, from small sample areas of the seafloor where richness, evenness, and other metrics can be measured. The physical properties of the seafloor which can influence biogeochemical parameters include particle size, rugosity, slope, consolidation, how well mixed/sorted the substratum is, and many others (Røy et al. 2005; Martín et al. 2014). Likewise, there are many biogeochemical parameters of interest to ecologists, such as carbon content and the depth of the redox layer (Trentesaux et al. 1994; Li et al. 2016), which will vary with substratum type. These parameters create habitat niches, which are associated with particular species and therefore allow prediction of likely benthic assemblages (Rhoads 1974; Cummings et al. 2010; Post et al. 2017; Hansen et al. 2020) that are most likely determined through the substratum's influence on organism settlement, recruitment, food availability, and refuge from predators. In highly heterogeneous environments, such as those with frequent disturbance events, these relationships can be difficult to detect, particularly when this variability is over small spatial scales. This information is important for marine planning, environmental impact assessments, and biodiversity assessments, so reliable methods are required (García-Charton et al. 2004; Hoey et al. 2014; Silburn et al. 2018; Mestdagh et al. 2020).

In the austral summer of 2023/24 a team at the British Antarctic Survey undertook a biodiversity and habitat mapping survey adjacent to Rothera Research Station, West Antarctic

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Peninsula, from small boats that can operate in depths shallower than the operating depths of research vessels. The initial plan was to use a single gravity core, deployed from a small rigid inflatable boat (RIB) to obtain sediment samples in which to measure carbon, particle size and biota. The highly heterogeneous nature of the seabed, which was composed of mixed gravel, pebbles and cobbles with lenses of finer sediments, meant that the success rate with the gravity core was less than 5%. It therefore became necessary to develop a device that would work in mixed substratum situations. The requirements for a method to take spatially continuous measurement of seabed hardness and the distribution of firmness profiles has been suggested before (Gingras and Pemberton 2000; Li et al. 2016) and development of such a method is expected to significantly aid benthic marine community studies (Li et al. 2016). The SeaPen was designed and built to measure sediment hardness characteristics around an area to the North of Rothera Research Station (Fig. 1). Crucially this combines a hardness measurement and image capture of penetration depth and substratum characteristics. Sediment characteristics are an important consideration for marine planning, environmental impact assessments and biodiversity assessments, and the highly portable SeaPen is therefore expected to be an advance on previous inshore apparatus (Mestdagh et al. 2020; García-Charton et al. 2004; Hoey et al. 2014; Silburn et al. 2018). The device measures penetration depth of a weighted steel spindle that falls from a set height, allowing a consistent force to be applied to the seafloor.

Current methods to assess sediment characteristics include cone and piezocone penetration tests (CPT/CPTU) (Lu et al. 2020), grabs (Van Veen, day), cores (multicore, box core) and acoustics (sub bottom profiler, CHIRP, multibeam, sidescan, seismic) (Tuit and Wait 2020). Assessments can also be made from imagery (still and video) using autonomous underwater vehicles (AUV), remotely operated vehicles (ROV), towed camera arrays and drop cameras (Barnes et al. 2020). Self Contained Underwater Breathing Apparatus (SCUBA) diving can be used to measure sediment in situ through direct observation of sediment depth, collection of samples using various methods, diver coring or suction sampling (Vause et al. 2019). All of these methods are used extensively but also have clear weaknesses when applied to shallow water, extremely heterogeneous habitats.

Seabed penetrators are often used in the oil and gas industry, such as CPT and CPTU devices; however, they are typically deployed from large offshore survey vessels which can provide power and hydraulic pressure to the device as well as technical experience to operate, deploy, and interpret results (Lu et al. 2020). Penetration depth can infer the hardness, consolidation, and/or thickness of surface sediments, which is a key parameter for seafloor construction projects. Previous attempts to measure seabed hardness include vane testers, digital force gauges, and a cone penetrometer (Takada et al. 2013). These typically require the apparatus to be brought to the surface between measurements. Albatal and Stark (2017) produced a free fall device which does not need to be recovered between deployments that could be hand-deployed from small boats, but it is technologically complicated to build. Simple instruments with manual/mechanical readouts that do not require a power source and computer systems are less common, although Parada (2024) used a cone penetrometer, which used gravity to drive a spindle into soft sediment to measure compaction. The small, lightweight design of these devices is useful for working in soft sediments; but the requirement to recover the device onto the vessel to record the measurements between deployments increases the time required for each sample.

Coring has the benefit of bringing a depth stratified sample on board a vessel and allows a variety of measurements to be taken in a laboratory onboard or ashore (such as dating of layers and sediment accumulation rates). Multicorers allow for multiple samples to be obtained from single deployments, thus reducing the time required to collect sufficient samples, which is often a limiting factor. However, coring only works in soft sediments that allow a core sleeve to penetrate the seafloor. If the sediment is too coarse, then the core may either not penetrate the substratum, or mechanisms may fail to close securely, resulting in the loss of the sample (Tuit and Wait 2020; Moncada et al. 2024). Because of these constraints, corers often require the sea floor to be surveyed by camera first to check the suitability of the substratum before deployment. Such camera deployments also capture down-facing images from which assemblages can be characterized (Barnes et al. 2020). Acoustics provide a detailed description of the seabed characteristics. Depending on the type of equipment used, sediment depth, sediment type, hardness, rugosity, topography, and bathymetry can all be measured. By combining acoustics with camera surveys, the biota correlated with seabed characteristics can provide a tool for scaling up data across large geographic areas (Bridges et al. 2023). Traditionally, acoustics requires specialist technicians, expensive equipment, and a suitable research vessel. Previously, these methods have been difficult to undertake in shallow or inshore locations (e.g., < 100 m); however, there are now acoustic systems designed for recreational purposes that are relatively cheap, easy to use, and can be mounted easily on most vessels. These can be scientifically useful, and little difference in data quality between recreational and professional acoustic systems has been found in some cases (Fletcher et al. 2024). Acoustic measurements allow large areas to be sampled and mapped, but it is still necessary to undertake ground-truthing in order to accurately classify the acoustic results. This is where mechanical instruments or samplers can complement acoustic measures. SCUBA divers can directly measure sediment depth, for example, by pushing a ruler into the sediment (Vause et al. 2019), and samples collected by SCUBA divers can provide crucial insight into the sediment surface layer and the

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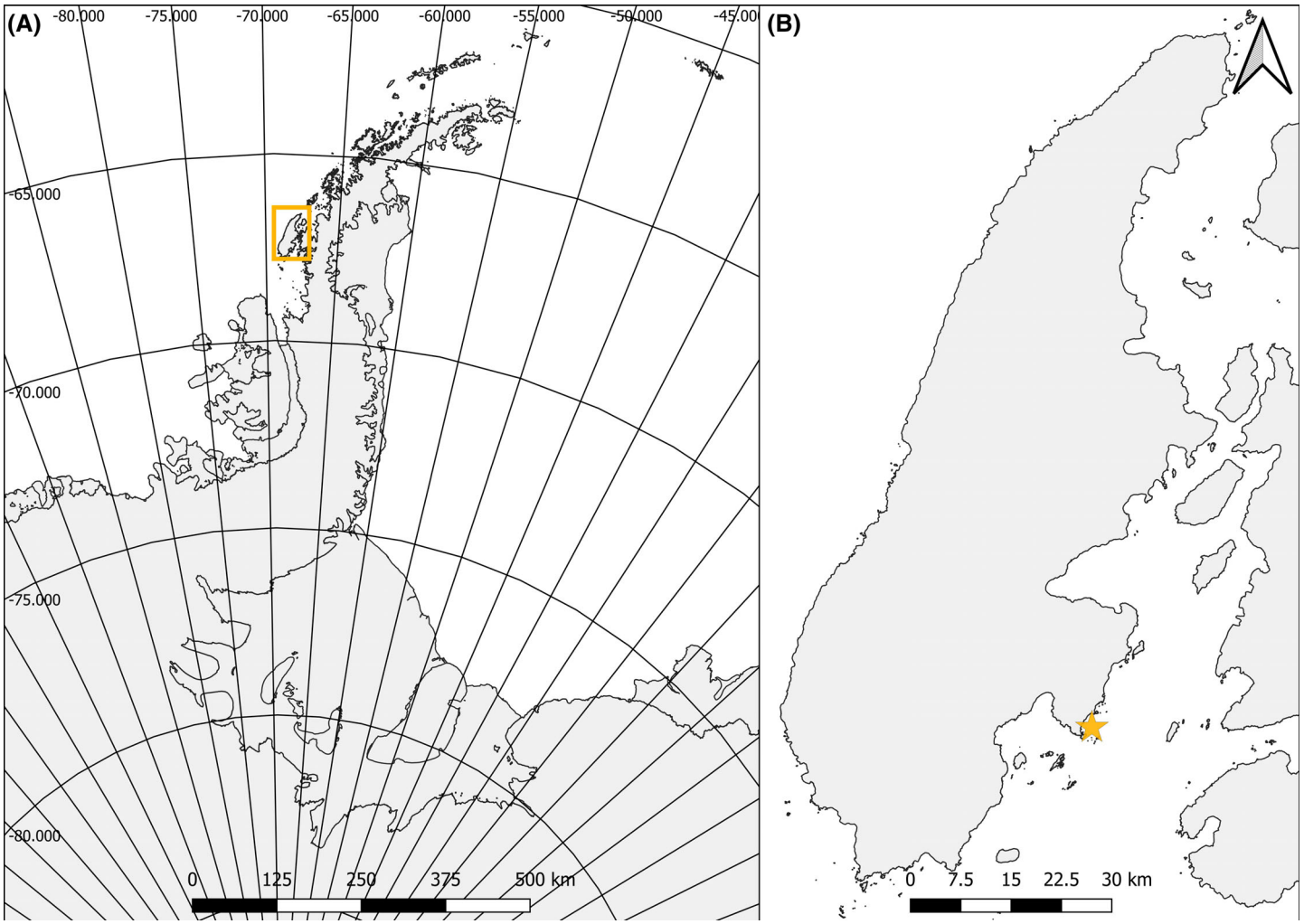


Fig. 1. Shows the location of Rothera Research Station (yellow highights) on (**A**) the West Antarctic Peninsula, with grid lines showing the decimal degrees co-ordinate reference on the edges, and (**B**) on Adelaide Island.

types of organisms that would be expected to be found there, as the physical and biogenic processes are influenced by the overall cohesiveness of the substratum (Gingras and Pemberton 2000). However, SCUBA diving is labor intensive and requires specialist teams, equipment, and safety considerations; but despite this, science diving in shallow water (< 30 m) does occur worldwide. Many scientific institutes do not, however, allow for deeper diving (> 45 m), and due to logistical and safety constraints, SCUBA is not a technique that will provide coverage of large geographic areas.

The SeaPen was designed for the purpose of:

- Quantifying sediment characteristics.
- Allow for multiple samples to be obtained without the need for system recovery between replicates.
- To be used in a range of coastal depths and heterogeneous substrate types.
- To have a small footprint which will allow it to be deployed from a small vessel (rigid inflatable boats RIBs) and over small spatial scales (Fig. 2A).
- Light enough to be hand hauled without the need for winch systems, easily transportable and can be loaded onto the RIB by a single person.
- Safe mechanisms without spring-loaded catchments.
- Easily manipulated clasps which can be done while wearing gloves (for operating in extreme cold temperatures).
- Cheap, easy to build, maintain, and operate.

Materials

A tripod frame made from stainless steel was modified to hold a vertical weighted steel bar in the center of two nylon rings (Fig. 2B). Each leg was 1.30 m long. The legs attached to an acetal plastic ring, with an external diameter of 199 mm, via an inset in the ring and secured with a bolt.

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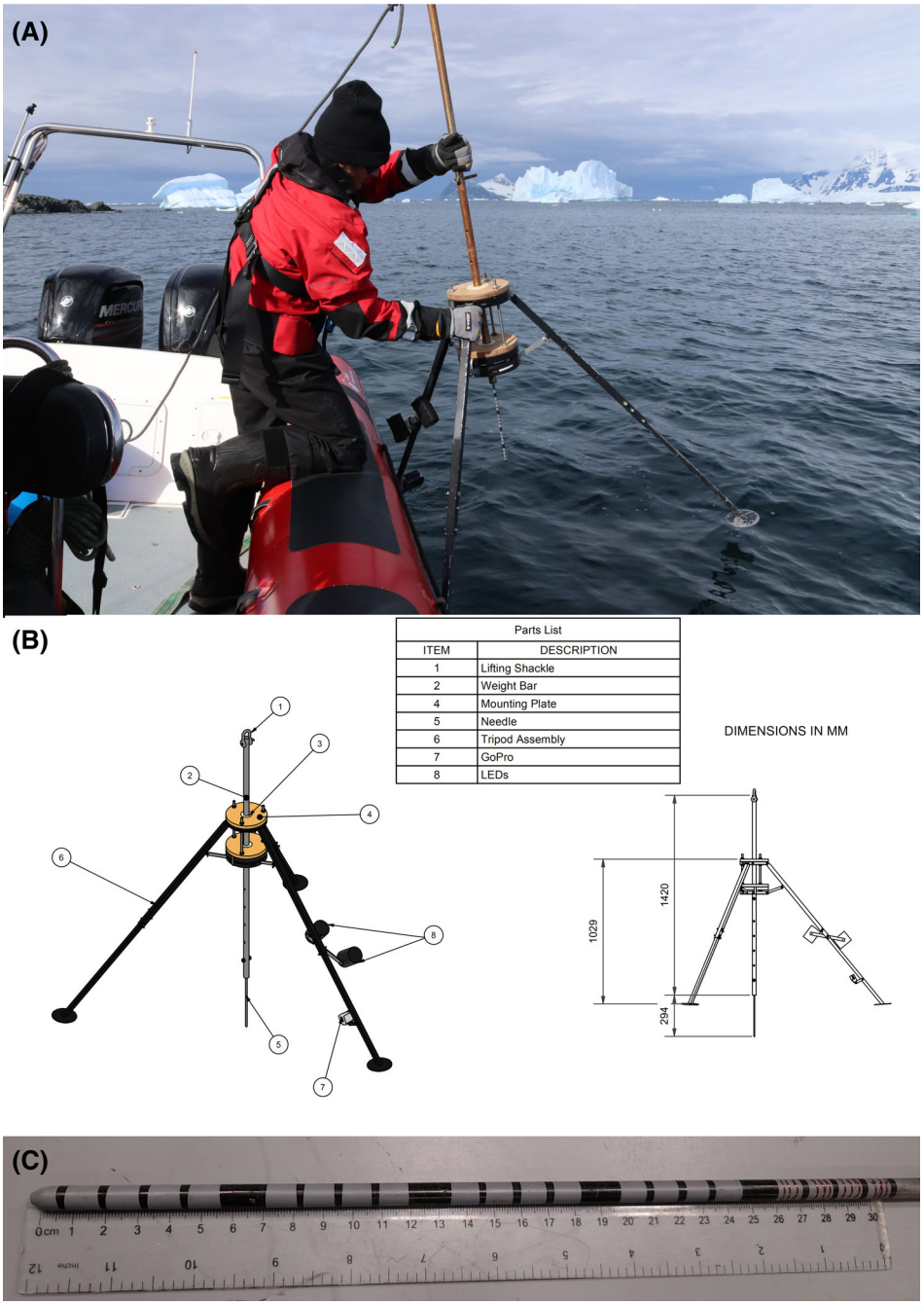


Fig. 2. (**A**) Seabed Penetrator (SeaPen) being deployed. The safety transit pin is in place below the operators left hand. Camera and lights attached to the left leg of the tripod frame. (**B**) SeaPen design diagram. (**C**) Spindle calibration image.

An identically sized lower ring was attached further down the legs with three connector bars. This stopped the legs from swinging apart. Wooden disks with center nylon rings were clamped to these acetal rings using three threaded steel bars which bolted through holes in the rings. The nylon rings had an internal diameter of 5 cm, which was slightly wider than the weighted bar. The entire frame weighed 15 kg.

The 25.4 mm diameter weighted bar, which weighed 5.7 kg, could freely move up and down between the nylon rings. On the bottom of the weighted bar was a 30 cm long steel penetration spindle with an 8 mm diameter. This spindle was marked with graduations (cm) from the pointed tip to the top (Fig. 2C). The spindle was inserted into a hole in the center of the bar and secured with a grub screw. This allowed the spindle to be replaced easily if it was damaged. A lifting pin

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was inserted horizontally through the weighted bar below the nylon bushing. On top of the bar was a shackle, which connected a hauling rope to the surface and vessel. This hauling rope was used to lower the device to the seabed and recover. With no tension on the rope, the weighted bar was free to freefall a set distance and the spindle then penetrated the seabed. The spindle dropped from a height of 40 cm, which equated to an energy of 20 J at the moment of impact with the seabed. When the rope was pulled up from the surface the weighted bar would move freely up through the nylon bushing until the lifting pin encountered the wooden disks. At which point the entire tripod frame was lifted off the seabed. A safety pin was inserted through the bar above the nylon bushing which stopped the bar from dropping during transport. This safety pin was removed on deployment. Two LED lights (SOLA600) were positioned on one of the legs pointing toward the area where the spindle hit the seabed. A GoPro (Hero 11) was also secured onto the legs under the lights to record video footage of each deployment.

Procedures

Before deployment, the GoPro was set to video immediately prior to deployment, and the spindle lowered into view to ensure the spindle drop would be in view and the penetration depth recorded. The time of the start of the video, spindle ID and site ID were also recorded prior to deployment. The SeaPen was then lowered over the side of the vessel (Fig. 2A). When it was over the side the transit pin was removed before the frame was lowered to the seabed using the hauling rope. When the frame legs touched the bottom, the operator could feel the change of weight on the rope. The operator was then able to judge when the lifting pin was at its highest point (without lifting the SeaPen frame off the bottom) and then released the bar to freefall. The graduated spindle penetrated the sediment with a consistent energy on every drop, and the process was recorded on the GoPro. The SeaPen was allowed to remain on the seabed for 5 s to allow the time of the drop, water depth and global position system (GPS) location to be recorded. The operator would then haul the device off the seabed by approximately 2 m. The vessel repositioned or was allowed to drift to ensure a minimum of 2 m space between drops to avoid any disturbed sediment. Only when the position and process data had been recorded would the operator commence the next drop. At the end of a series of drops (completed site), the SeaPen was hauled to the surface. At the surface, the transit pin was inserted into the bar before the device was brought onto the vessel. Removing the GoPro allowed the footage to be reviewed on board and the battery and SD card to be replaced if necessary. The spindle was inspected for damage and replaced if necessary. The SeaPen was then ready for redeployment.

A calibration photo was obtained of each spindle alongside a ruler, to allow calibration of measurements (Fig. 2C). After deployments, the collected video footage was reviewed on a computer screen and screenshots were extracted of each drop. Any images where the spindle was obscured for any reason, or the bar did not freefall properly were removed. Determination of penetration depth was measured using the graduated spindle and corrected using the calibration image. ImageJ software was used to analyze the imagery collected, which has the option to set a scale and measure tool. Using these tools, the substrate was classified using Wentworth size classes as shown in Table 1. The particle size of the substratum surrounding the spindle was measured as Primary and Secondary substrates. The Primary substratum was the substratum visible where the spindle impacted the seafloor. The secondary substratum was the visible substratum within 10 cm of the spindle point of impact.

Assessment

As this device was designed and built in the field, prior testing was limited to a single deployment and review. The deployment highlighted the need for multiple spindles as the painted graduations on the spindle were partially removed by abrasion during deployment. This study therefore acted as an operational test for the SeaPen instrument.

The study area was located in the bays surrounding Rothera Research Station (67°34′8″S, 68°7′29″W) on the Western Antarctic Peninsula (WAP). The SeaPen was deployed at 20 sites (Fig. 4A) between 12th December 2023 and 12th February 2024. At each site, a minimum of 20 SeaPen drops were conducted. After a review of the data, subsequent return trips were made to ensure a minimum of 12 identifiable measurements were acquired for any given site.

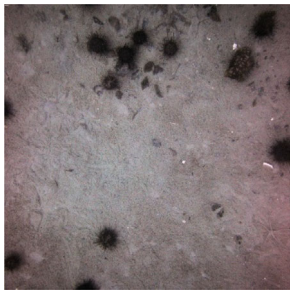
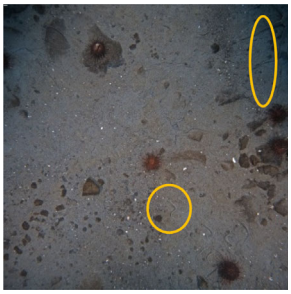
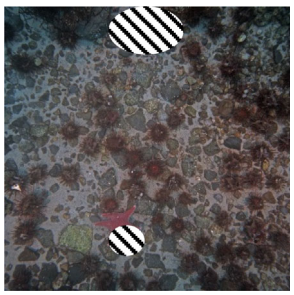
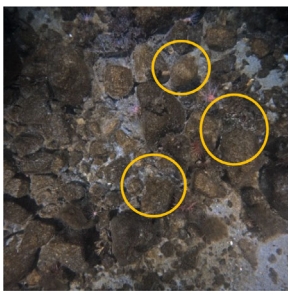
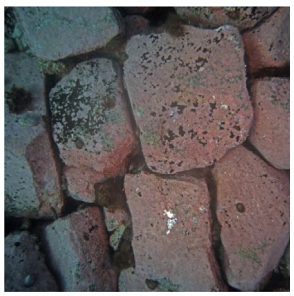
SeaPen videos were identified to deployments by comparing the surface recorded deployment time with the timing on the synced video recording. The depth of penetration was recorded from frame grabs of visible spindles along with the associated primary and secondary substratum (Fig. 3). Sediment depths were not normally distributed and so differences among primary and secondary substratum types were assessed using Kruskal–Wallis tests (Kruskal and Wallis 1952). Pairwise differences were evaluated using Wilcoxon rank-sum tests (Wilcoxon 1945) and Dunns post-hoc tests with Holm adjustment for multiple comparisons (Holm 1979). All analyses were conducted in R (R Core Team 2024).

Results

A total of 510 SeaPen drops were conducted, of which 343 images were extracted from the videos that were deemed of high enough clarity to accurately measure the spindle penetration. SeaPen drop locations were clustered around a 30 m radius from the center of each site (Fig. 4A) and it took between 25 and 35 min to complete deployments at a given site. Examples of good and poor images are shown above (Fig. 3).

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Table 1. Size classes used for substratum determination. The example images are taken from a drop camera and used to illustrate the appearance of each size class. Yellow rings identify the Wentworth size class used for description in the image. Mud and silt were defined as sediments in which particles were not discernible. Black and white circles are used to obscure substratum not in the size class.

Wentworth size class	Maximum diameter on any rock (mm)	Wentworth size class	Maximum diameter on any rock (mm)
Mud to silt	≤ 0.0625	Very coarse sand	≤ 2.00
			
Pebble	≤ 64	Cobble	≤ 256
			
SBoulders	257+		
			

Zero penetration depths were recorded in 55% of sites (ST4, ST5, ST6, ST8, ST9, ST10, ST14, ST15, ST17, ST18, ST19) and the maximum value of 30 cm was recorded at 4 sites (ST6, ST7, ST12 and ST17). The median penetration depths ranged from 0.5 cm at site ST18 and 16.6 cm at site ST7 (Figure 5). The range of penetration depths within each site varied from 5 cm at site ST14 to 30 cm (the maximum length of the needle) in sites ST6 and D2 and the median was 5.5 cm across all sites. There was a significant difference in penetration depths across the sites (Kruskal–Wallis, $H = 112.29$, $p < 0.001$; Figure 5). A Dunns post-hoc test showed 12.4 % of all pairwise comparisons were significantly different (Supporting Information Table S1), however, no explainable patterns could be drawn from these results indicating a highly heterogeneous habitat likely caused by episodic events, such as iceberg impacts (Figures 4B and 5).

The determination of the primary substratum type showed that sand was represented most (110 times) and boulders the least (25 times). In the secondary substratum type pebbles were represented most (128) and boulders least (33). A comparison between substratum type and depth of penetrations showed that in coarser sediments penetration depths were significantly shallower with the primary (Kruskal–Wallis, $H = 87.106$, $p < 0.001$; Fig. 6A) and secondary substrata ($H = 46.042$, $p < 0.001$). However, it is clear from Fig. 6B that within each primary substratum category, there was substantial heterogeneity in depths. Heterogeneity was highest in the softer substratum categories (sand and mud) indicating

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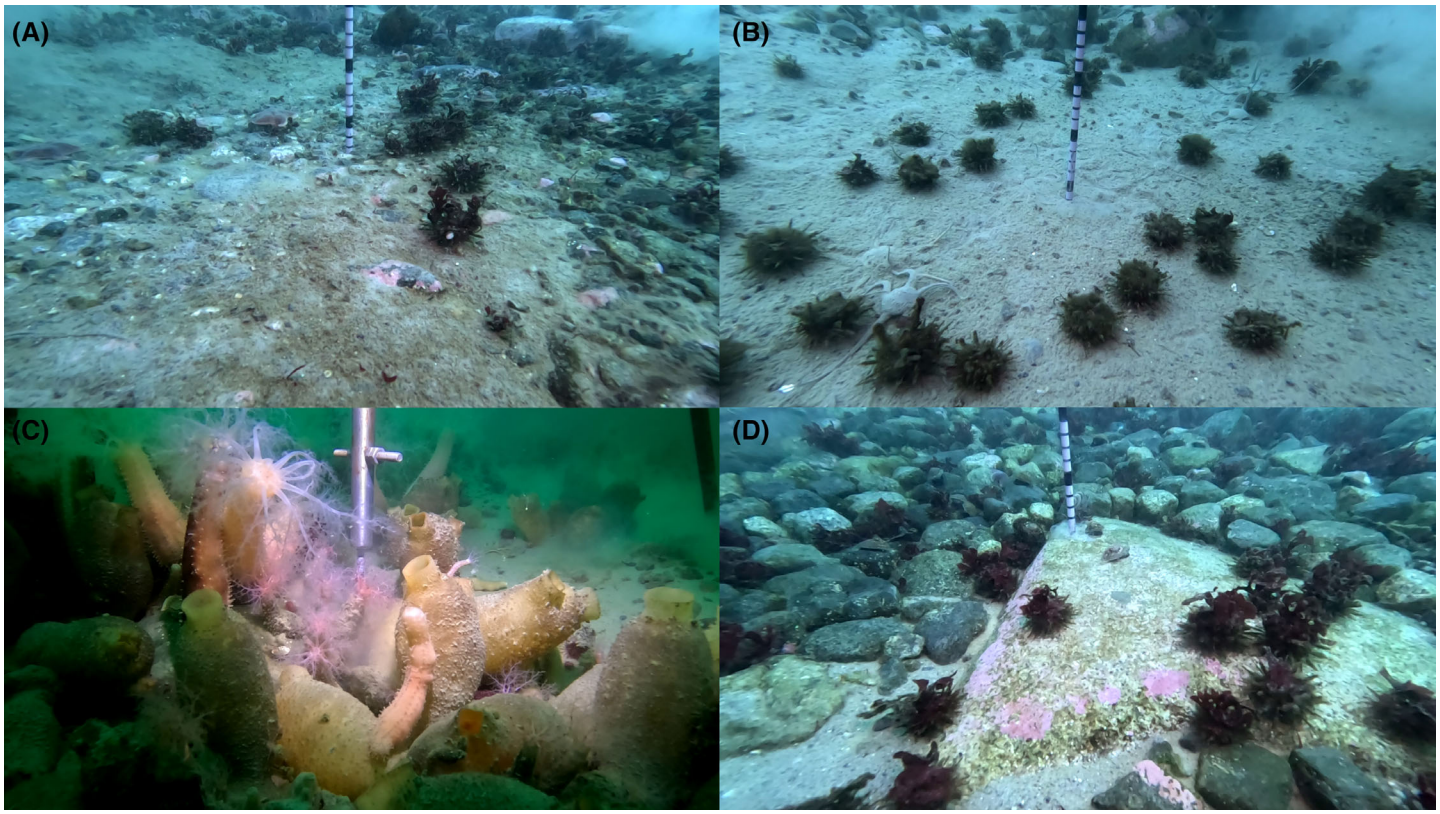


Fig. 3. Example images of SeaPen drops. The top images show penetration depths of (**A**) 7 cm and (**B**) 4 cm. The lower images show (**C**), an obscured view that was not included in the analyses, and (**D**) a penetration depth of 0 cm.

the heterogeneous nature of the substratum, with pockets of fine sediment within a matrix of boulders, cobbles and pebbles.

The additional separation of primary substratum type by secondary substratum type did not improve the discrimination of penetration depths (Fig. 7).

SeaPen performance and improvements

The major benefit of this device is its ability to take repeat measurements in a single deployment, and its rapid redeployment between sites. It can take a couple of minutes to remove the GoPro camera to replace the battery and SD card, and a further few minutes to replace the spindle if necessary. The video records the whole deployment; therefore, it allows a reviewer to accept or reject each drop. Rejection criteria can include (A) the spindle obscured from view. This can be caused by biota or substrate in the frame between the spindle and camera or sediment disturbed when the frame lands. (B) The bar not free-falling. This can be caused by friction between the nylon rings and the bar if the device landed on a slope, or any other obstruction not allowing the bar to move freely. (C) Spindle not being allowed to fully penetrate the substratum can be caused by the frame falling over if positioned on a slope or movement of the vessel causing tension on the rope.

It is hypothesized that strong water currents may also affect successful deployment, but they were not encountered during this study. Operating the device does not require technical skill or experience. Deployment and recovery can be completed with two people, thus reducing the chance of injury, damage to the boat or device and making it easier to handle due to its weight. Operating the device requires one person to lower and "feel" for the right position to drop. This is easy to achieve, and, during this study, multiple different operators were used. On occasion the frame was lifted off the seabed prior to the drop, but these drops were removed from the analyses after review of the video. It was more common for this to occur during rougher sea states, when it was also more difficult for the operator to feel the lifting pin hit the frame. It is therefore suggested that to work in rougher sea states some prior experience is necessary to get the feel for an accurate drop.

The SeaPen's weight and size make it easy to deploy from small boats. In this study, the vessel used was an Island RIBs 7 m rigid inflatable boat (RIB). The deck space behind the console measured 180 × 130 cm. This was

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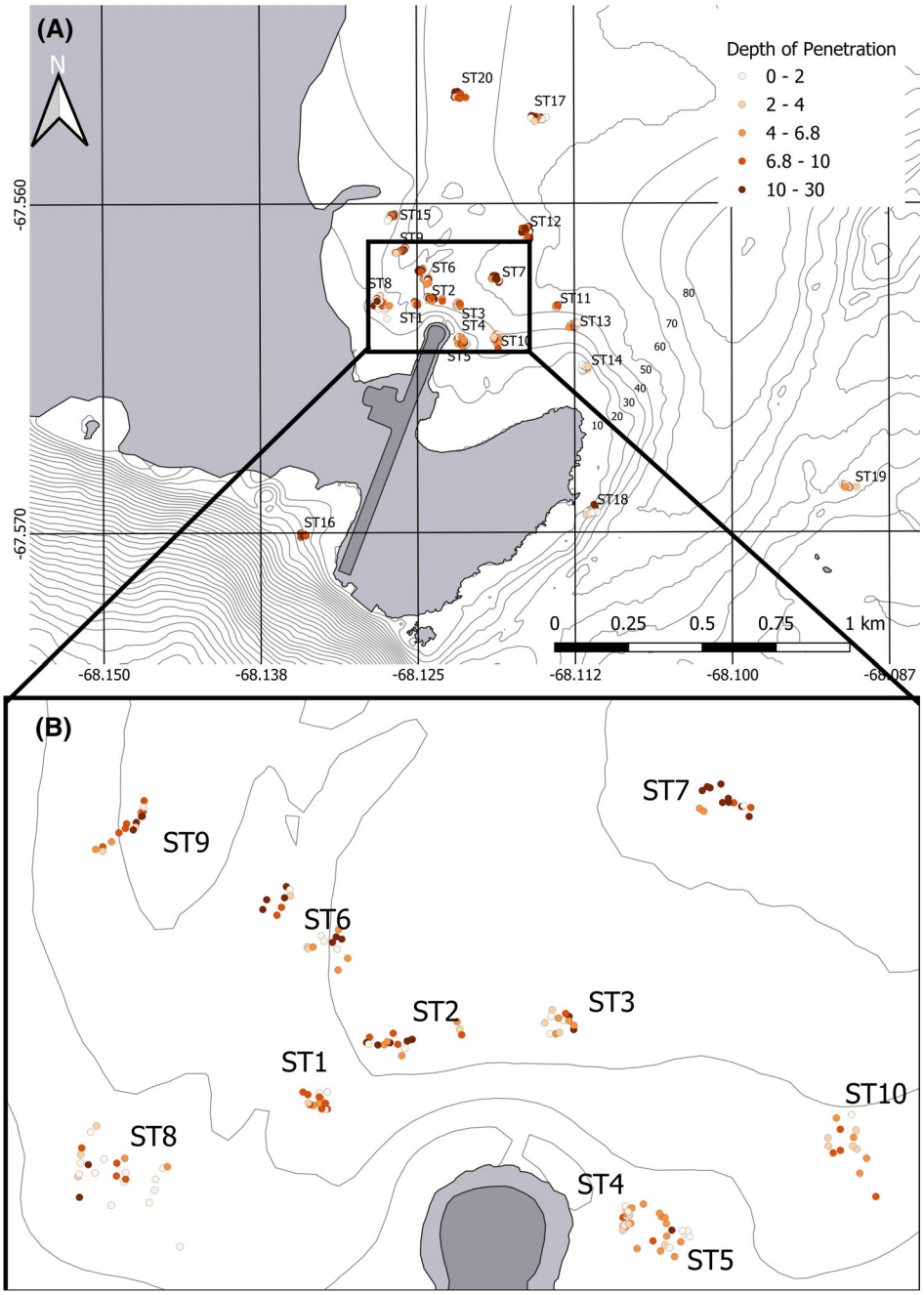


Fig. 4. (**A**) SeaPen drop locations with site labels. Each site has between 12 and 23 sample points clustered within 30 m of a central point. GPS coordinate position are labeled on the outside. (**B**) Map zoomed in selection of sites close to the end of the runway, to highlight the heterogeneity of penetration depth within each site. The darker the color the deeper the spindle penetrated the sediment.

adequate for the SeaPen, hauling rope, spares box, data sheets and up to 3 passengers. The legs on the SeaPen are telescopic and if necessary, could be shortened for transit. Due to the nature of working in a cold polar environment, it was deemed to be ineffective to try to extend the legs at sea as the use of spanners to tighten nuts and bolts is difficult when wearing insulated gloves, but in warmer climates this will be a feasible option. A simple tripod frame can be easily built to the specification here, or alternatively built to match the space available on any vessel. A larger vessel which accommodates winches can be used to haul the SeaPen to and from the seabed, although an operator or sophisticated equipment will have to handle the final approaches and determine the drop. Using winches will reduce fatigue and save time, thus allowing more deployments in any given day.

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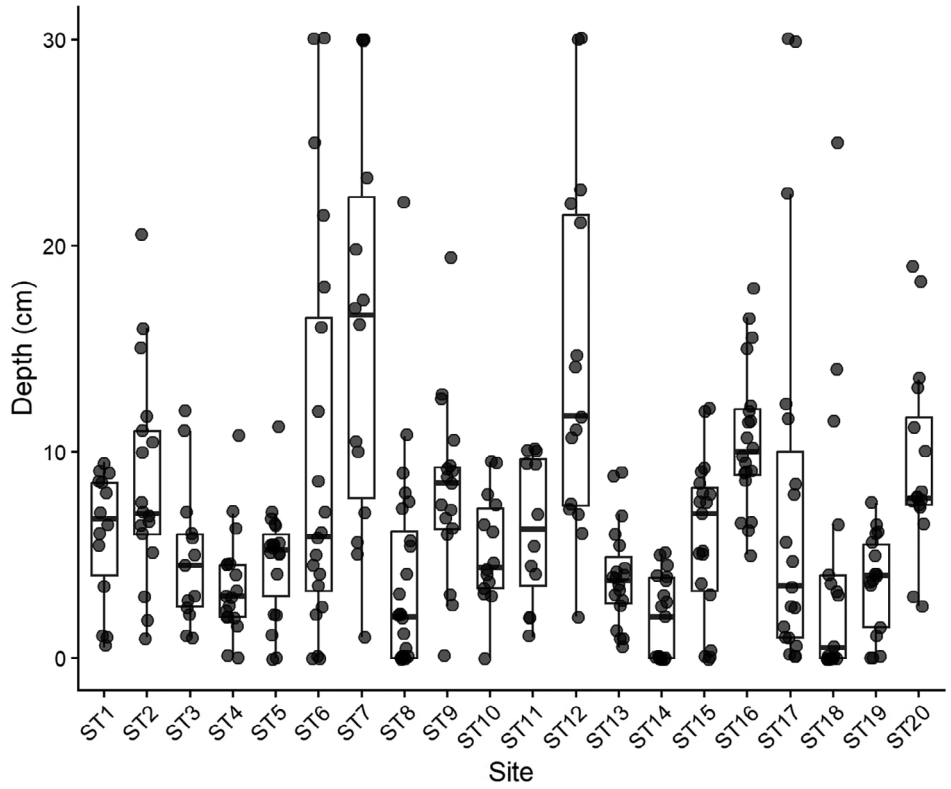


Fig. 5. Penetration depths from all sites. Boxplot shows median values and interquartile ranges. Vertical lines outside the boxplots show the smallest and largest values within 1.5× interquartile range. Data points are superimposed.

Furthermore, this method has relied upon sediment grain size to be determined using the imagery obtained. While Image J software was useful in determining the size difference between boulder, cobble and pebble, it proved to be difficult with smaller grain sizes. Further calibration of images from the SeaPen to sediment samples will allow the development of more robust substratum classifications to the Wentworth scale. A Summary of the positives and negatives of the SeaPen are shown in Table 2.

Discussion

The SeaPen provides the powerful combination of penetration depth and video during rapid deployments. This is crucial in habitats that are categorized by small scale heterogeneity, where, for example, a shallow penetration depth could be caused by hard substrata, like pebbles, or from highly sorted and compacted finer sediments. As these substratum types provide different habitats, it is ecologically important to determine the difference in substratum type, which a single depth measurement may not do. Previous devices, such as that of Parada (2024) is smaller and lighter in weight than the SeaPen described here, but it is only able to take a single measurement during each deployment and unable to determine these subtle differences in substratum type. To our knowledge, and apart from acoustic techniques which require specialist experience and equipment, most other techniques that sample the sediment characteristics from a vessel are only able to obtain single measurements on each deployment. Multicore equipment can obtain repeat measurements; however, they are collected alongside one another during a single deployment and are ineffective in mixed substratum, such as that being surveyed here. The ability to take continuous repeat measurements allows for a greater assessment of heterogeneity within the habitat, at multiple spatial scales. The small to medium (tens of meters) scale heterogeneity is often overlooked as existing methods require recovery of equipment and thus tend to move greater distances between deployments. The SeaPen will be a particularly powerful tool if it is dropped in areas in which broad scale habitat has already been surveyed using acoustics.

To date, traditional methods for measuring substratum characteristics work well if certain conditions are met, for example, coring works in soft sediments, acoustics require technical skills and equipment, and SCUBA diving is labor intensive and logistically challenging. The SeaPen used in this study has successfully measured sediment characteristics in a heterogeneous environment across a range of depths, in a timely manner, and off a small vessel with limited space and no winch system. The addition of the Go-Pro to the SeaPen has markedly improved its operation, particularly the ability

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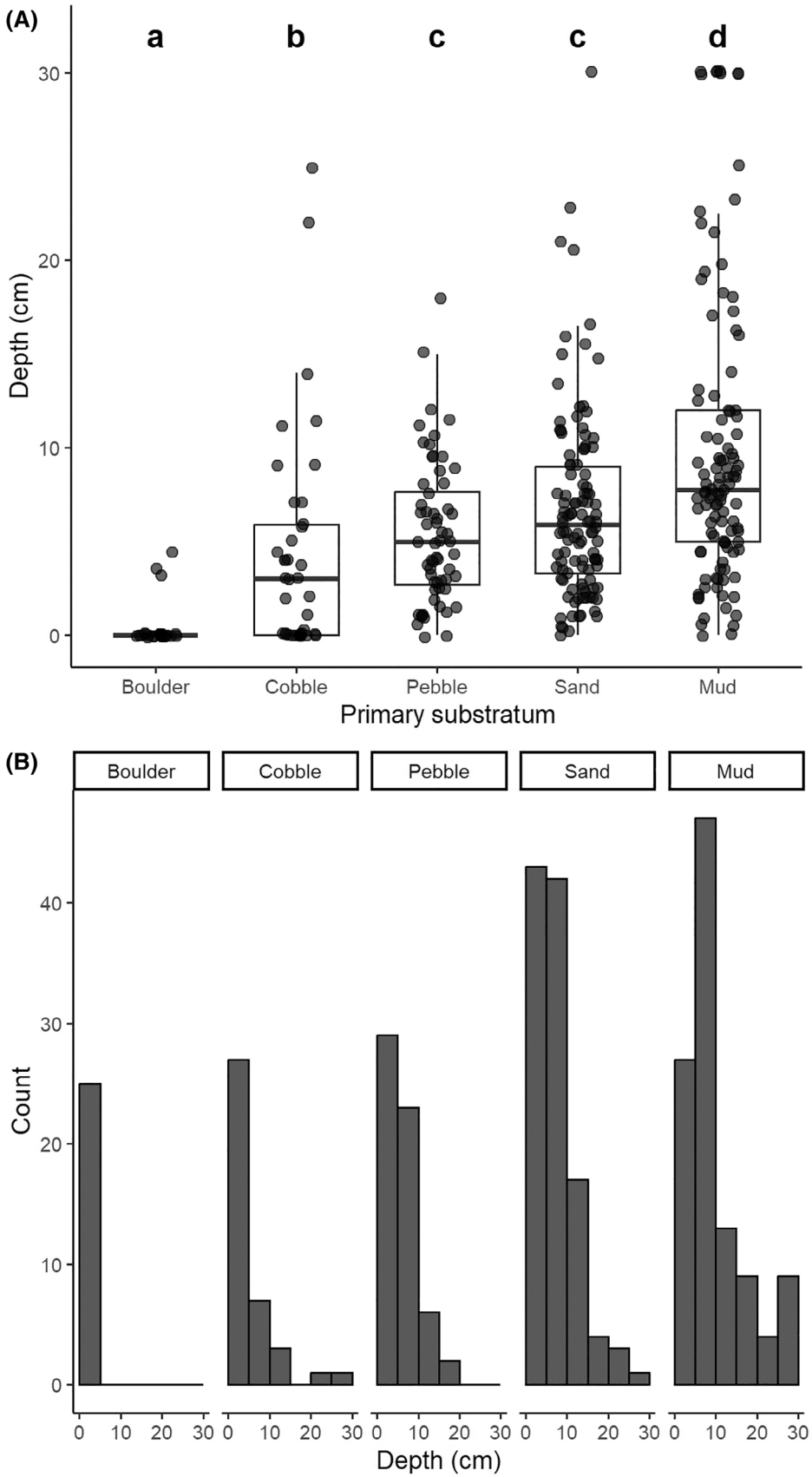


Fig. 6. Legend on next page.

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for multiple penetration measurements that can be compared with images of the seafloor will greatly improve comparability with and between future studies, thus aiding marine biodiversity management.

The data obtained with the SeaPen can be used to quantify habitat heterogeneity on a small scale (meters) through to larger scales (kilometers). Measuring habitat heterogeneity is difficult, and previous studies have tried with varying degrees of success (Lapointe and Bourget 1999; Ismail et al. 2019; Romoth et al. 2023).

Depth of sediment, substratum type and its compaction will determine the biota present (Li et al. 2016; Martins et al. 2013). No ecological or geospatial patterns were distinguished from the SeaPen substratum measurements, but the SeaPen provided measurements of the heterogeneity within and between sites. The study area is exposed to many icebergs which drift through the sound between Adelaide Island and the mainland WAP on the northerly winds, often getting grounded and bouncing around the study area for months at a time (all authors' personal observations). These icebergs create a highly heterogeneous seabed habitat. The substratum determination showed sand and mud as the majority of primary and pebbles and sand as the secondary substratum; however, shallow depths of penetration showed that these finer sediment areas were either (A) thin sediment layers on top of harder substratum or (B) highly compacted sediments. The few measurements (of the current study) of 30+ cm showed that this area does experience some sediment accumulation in small pockets, or lenses, likely created by iceberg scours, an important consideration when assessing biodiversity in each area. The generally shallow sediment depth, however, could be a consequence of the consistent impact and scour rate which occurs at the study site, which results in the regular resuspension of sediments. Any resuspended sediments would likely be carried away from the survey area by the prevalent water currents into deeper water. This study found a predominantly thin layer of finer

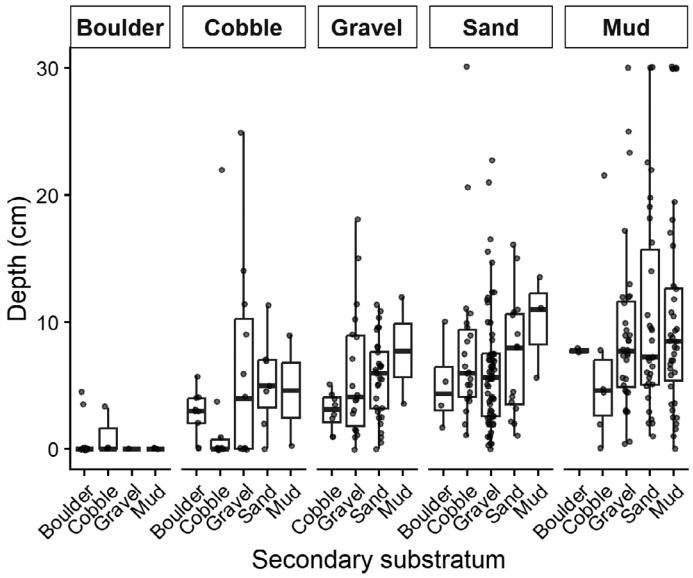


Fig. 7. Depth of penetration grouped by secondary substratum type, grouped within primary substratum type (labels above figure). Boxplot shows median values and interquartile ranges, with points superimposed. Vertical lines outside the boxplots show the smallest and largest values within 1.5× interquartile range. Significant differences are provided in Supporting Information Table S1.

Table 2. Table of the positive and negatives of the SeaPen.

Benefits	Negatives
Can be used on small boats	Spindle can get damaged during drop/deployment
Repeat measurements in single deployment	If on a slope bar may not slide freely/same force
Rapid redeployment between sites	Physically exhausting if hand hauled
No technical experience needed to operate	The force of the drop needs to be the same to compare across different studies
Applied force should be the same on each drop	Need to attribute force applied and depth of penetration to a defined classified description of substrates
Light enough to be hand hauled or used on a winch system if available	Identifying sediment grain size in an image is not as accurate as validating with physical samples
Can measure over small–medium spatial scales to assess patchiness	
Easy method to monitor sedimentation rates	
Cheap and easy to build	
Easily validate the quality of drops via video review	
Allow simultaneous measurement of substratum type and hardness from video review	

Fig. 6. (**A**) Primary substratum type with depth of penetration. Boxplot show median values and interquartile ranges. Vertical lines outside the boxplots show the smallest and largest values within 1.5× interquartile range. Data points are superimposed. Significant differences are shown above—substratum types with different letters are significantly different (Kruskal–Wallis followed by probability adjusted Wilcoxon rank sum paired test). (**B**) Histograms to show the distribution of penetration depths within each Wentworth category.

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sediments (sand and mud) over coarser grain (pebbles and cobbles) and/or bedrock.

The substratum vs. penetration depth analyses showed that the SeaPen penetration measurement was strongly correlated with seabed hardness. There were only minor differences between the primary and secondary substratum types therefore, showing that the SeaPen penetration depth was representative of the wider seabed structure which seemed to accurately represent the habitat. The ability to make multiple, quick measurements on a single site allows sufficient replication to reduce estimated error and in especially heterogeneous environments the number of drops per site can be increased. The video can be used to assess heterogeneity or habitat complexity and can be used to decide how many drops are required. The consistency of each drop, and therefore penetration depth measurements, allows comparison between drops and sites. It is important to note here that these measurements by themselves cannot determine substratum type. Physical samples, such as cores, from the drop location would aid interpretation and further the understanding of sediment characteristics, including the vertical structure.

Habitat heterogeneity is an important driver of β and γ diversity as increased heterogeneity supports greater species richness by providing more niches compared with more homogenous habitats (MacArthur and MacArthur 1961; Gutt et al. 2019; Mestdagh et al. 2020; Gallucci et al. 2020; Romoth et al. 2023). Quantifying sediment characteristics at a site where there are long term measurements of oceanographic variables (Venables et al. 2020), ice scour and marine biodiversity recruitment (Barnes et al. 2025) could add considerable interpretative power. This complexity can be difficult to measure and quantify, which is why previous studies have used video techniques (Romoth et al. 2023). Although video can obtain a continuous measurement, only the surface sediment characteristics are in view, whereas the SeaPen is able to obtain a measure of the surface layer in a quantifiable and more objective manner. This makes it much more useful for comparisons between locations and studies. The method presented here provides a substantially quicker and easier way of measuring seabed habitat heterogeneity on multiple spatial scales than previous and more traditional methods, especially where finances, vessel size, power source and lifting capacity may be a limiting factor. A question that is rarely asked but would be invaluable is at what scale does heterogeneity impact biodiversity? As the SeaPen can easily be deployed on multiple spatial scales within a survey day or field campaign, it can help to answer questions like these.

Understanding habitat heterogeneity will help decide survey areas/number of samples required to better inform Marine management including where and how to designate MPA's. As previously stated, habitat heterogeneity is an important factor which increases biodiversity in any given area. A comprehensive study of marine substrata can be logistically difficult, expensive and require specialist skills and equipment. Yet, to date few quantifiable methods have been described to enable assessment of habitat heterogeneity. This novel instrument will allow new insights into marine substrata and contribute toward ecological assessments. The ease of use, cost of building and its unique ability to provide repeat measurements makes the SeaPen a device that could become a standard worldwide in benthic habitat and biodiversity surveys.

Author Contributions

Gareth Flint designed and built the drop camera which became the base of the latter SeaPen frame. Ryan J. W. Mathews designed and built the modifications to the Dropcam frame. Data collection was captured by Ryan J. W. Mathews, David K. A. Barnes, and Simon A. Morley. Ryan J. W. Mathews undertook the data analyses and manuscript preparations. David K. A. Barnes and Simon A. Morley have edited and provided substantial oversight. Lloyd S. Peck has edited latter versions of the manuscript.

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Conflicts of Interest

None declared.

Data Availability Statement

The data that supports the findings of this study are available in the Supporting Information of this article.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

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