**Title:** Geomorphological evidence of large vertebrates interacting with the seafloor at abyssal depths in a region designated for deep-sea mining.

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**Abstract:** Exploration licences for seafloor mineral deposits have been granted across large areas of the world’s oceans, with the abyssal Pacific Ocean being the primary target for polymetallic nodules – a potentially valuable source of minerals. These nodule-bearing areas support a large diversity of deep-sea life and, although studies have begun to characterize the benthic fauna within the region, the ecological interactions between large bathypelagic vertebrates of the open ocean and the abyssal seafloor remain largely unknown. Here we report seafloor geomorphological alterations observed by autonomous underwater vehicle that suggest large vertebrates could have interacted with the seafloor to a maximum depth of 4258m in the recent geological past. Patterns of disturbance on the seafloor are broadly comparable to those recorded in other regions of the world’s oceans attributed to beaked whales. These observations have important implications for baseline ecological assessments and the environmental management of potential future mining activities within this region of the Pacific.

**Keywords:** marine mammals, deep-sea mining, autonomous underwater vehicle, deep-diving mammals, Clarion Clipperton Zone, ichnology

**Introduction**

The abyssal seafloor represents approximately 85% of the global seafloor (1), yet many of the ecosystems and species that it sustains are largely unknown because of the difficulties in studying such a vast and remote environment. Advances in deep-submergence technologies have allowed abyssal research to be conducted at spatially confined environments such as hydrothermal vents (2), trenches (3) and submarine canyons (4). However, studies at the scale necessary to understand the ecology and importance of sediment-hosted abyssal plains are still rare (5).

The Clarion Clipperton Zone (CCZ) in the Northeast Pacific covers around 6 million km2 and ranges from 3000-6000 m in depth (6). This region has received significant interest over the past decade owing to the presence of polymetallic nodules – a targeted mineral resource of cobalt, copper and rare earth elements in the deep sea. The International Seabed Authority (ISA) is the organisation established by the 1982 UN Convention on the Law of the Sea (UNCLOS) to manage seabed mining beyond the areas of national jurisdiction (ABNJ) and, as of January 2018, the ISA had granted 16 exploration contracts within the CCZ (Figure 1).

It is widely accepted that nodules provide a home for a wide variety of suspension feeders and specialised invertebrate megafauna, which are dependent on the hard substratum provided by the nodules in an otherwise sediment dominated environment (7). To quantify the ecological importance of these areas, under their contractual arrangements with the ISA, exploration contractors are obliged to undertake environmental baseline biological studies. Researchers have begun to understand the structure of benthic faunal assemblages in the CCZ (7,8) however, the ecological interactions between bathypelagic vertebrates of the open ocean and the abyssal seafloor remain largely unknown. Therefore, serendipitous observations during industry-led deep-submergence work can be of significant interest (9).

This paper suggests that large vertebrates have utilised the abyssal seafloor in the CCZ in the recent geological past. We demonstrate that sequential depressions represented by acoustic shadows from AUV (autonomous underwater vehicle) geophysical surveys observed in the CCZ are spatially comparable and, from limited seafloor imagery, represent a morphology akin to those inferred from beaked whales in the Atlantic (10) and Mediterranean (11,12).

**Materials and Methods**

MIDAS (Managing Impacts of Deep-sea reSource exploitation) is an EU-funded project aimed at building the knowledge base to underpin sound environmental policies in relation to deep-sea mining. As part of this project, the RRS *James Cook* visited the CCZ in April to May 2015 (expedition JC120; (13)), focussing on the UK Seabed Resources Ltd. claim zone and the north easternmost Area of Particular Environmental Importance (APEI) defined by the ISA (14). This expedition used the *Autosub6000* AUV (15) along with a suite of other data collection methods to form an environmental baseline for this area.

Operations were constrained within approx. 5,500 km2 area of seafloor within the APEI and within approx. 1,100 km2 of the UK Seabed Resources Ltd. claim. Shipboard EM120 multibeam echosounder data acquired and gridded at 100 m resolution were used to create bathymetric derivatives for survey planning. In the bathymetric data, several morphological features were clearly visible in the region. To try and capture this variation, a stratified random survey was designed using objective criteria (13) . High-resolution acoustic mapping data (multibeam echosounder and sidescan sonar data) from defined strata were recorded using *Autosub6000* (Figure 1).

*Autosub6000* is equipped with an Edgetech FS2200-M dual-frequency sidescan sonar and sub-bottom profiler (16). The high-frequency setting (410 kHz) of the Edgetech sidescan sonar was used both for short dedicated transects (15 m altitude) and during photo-transects (3 m altitude) carried out by the AUV. The extremely low incidence angles at ~3 m altitude allowed the sonar to image very shallow depressions (represented as acoustic shadows), which could also be seen faintly in the 15m altitude data (Figure 2). However, the depressions were not visible in lower frequency, or higher altitude data.

In total, four *Autosub6000* missions (M79, M81, M83 within the APEI and M85 within the UK claim zone) were achieved at the optimal altitude (3m) and frequency (410kHz) to allow seafloor depressions to be resolved. Processing of the high-frequency sidescan sonar data was completed using the NOC-developed PRISM software package (17). Results were collated in ERDAS Imagine and compiled into a single image mosaic. All resolvable depressions were digitized in ArcGIS 10.3 as a point file. From this shapefile, a series of ‘tracks’ (curvilinear strings of sequential depressions) were selected for further analysis. As the detection of depressions varies with the quality of the sidescan, not all depressions were easily resolved. Therefore, objective criteria were designed to assess the spatial patterns of the depressions within a given track. For M83 and M85, only 1 and 2 tracks were detected respectively. Both of these sets of tracks had a minimum number of 6 depressions (i.e. 5 mid-point to mid-point distances). As a result, 6 sequential depressions was set as the minimum number of detectable depressions for M79 and M80. Additionally, the tracks were not counted if they crossed the nadir (the centre region of the sidescan data, which represents the transit of the sonar signal through the water column) of the geophysical survey. If a track crosses the nadir, a depression may not have been detected in the region of the seafloor in which the nadir occurs, which would result in an incorrect distance between depressions being calculated. Depression length and width was measured directly from the raw sidescan data using Edgetech DISCOVER 4200 software, and the distance between consecutive depressions within a given track was determined using the analysis toolbox in ArcGIS 10.3. For comparison, the distance between depressions was also calculated from the high-resolution photomosaic published in (12).

Seabed imagery was successfully collected in a zig-zag survey design randomly located within the acoustic survey areas of M79, M81 and M83 within the APEI. Photographic data were obtained using two Point Gray Research Inc. Grasshopper 2 cameras on the AUV, one mounted vertically and the other obliquely looking forward (5). The field of view from the vertically-mounted camera was ~2.4 m2. AUV photography and high-frequency sidescan surveys were acquired simultaneously at 3m altitude. As a result, the photographs provided by the vertically-mounted camera run through the nadir (~1.5 m width) of the geophysical data, preventing simultaneous assessment of features in both the photographs and sidescan data.

Seabed photographs from the successful AUV photography missions were reviewed. Owing to the perpendicular angle of the camera to the seafloor of the vertically-mounted camera, any depressions or relief in the seafloor topography is difficult to resolve. Only limited occurrences of the depressions were observed in the forward-facing camera, and no laser scaling is provided in the oblique view images. Therefore, no further morphometric data could be obtained.

**Results and Discussion**

AUV acoustic seabed surveys of an area within the Clarion Clipperton Zone (CCZ; Figure 1) revealed elongated depressions across the seafloor fabric (Figure 3). A total of 3539 depressions were counted over sidescan sonar data covering 21.8 km2 at water depths from 3999 m to 4258 m in the north-eastern CCZ (Table 1). These depressions formed curvilinear tracks along the seafloor, consisting of up to 21 depressions spaced between 6 and 13 m apart. The seafloor depressions followed variable paths, with distinct tracks spaced irregularly over much of the area surveyed and occasionally crossing (Figure 3). Depressions consisted of irregular furrows on the seafloor (mean 0.97 m wide and 2.57 m long) approximately 0.13 m deep (data provided from Figure 3). Limited observations of individual depressions were also visible on seafloor imagery (Figure 4) with these observations broadly corresponding in morphology to those inferred from the sidescan data.

The CCZ has an extremely low food supply (particulate organic carbon flux ~1 gCm-2y-1; (18), bottom-currents (1-9 cms-1) (19), sedimentation (0.35cm kyr-1) (20) and bioturbation rates (3-6 cm2yr-1) (21), suggesting tracks may be preserved for long periods of time. Based on the sedimentation rate alone, a maximum age for these tracks in the CCZ can be estimated, with it taking approximately 28 kyr to fill a typical trace depression (0.1m deep). The geophysical data presented here appear to show tracks of various ages based on their acoustic shadows; shadows with sharp edges are inferred to be from more recent depressions, while shadows with lower reflective contrast are inferred to correspond to older depressions, having experienced infilling by sedimentation, bioturbation and erosion by bottom currents (Figure 3).

There is no direct evidence for the cause of the depressions. No known geological mechanism exists for the formation of curvilinear sequences of shallow depressions in deep water low permeability sediments with no advective seabed fluid flow expected (22). The size and frequency of depressions suggests that only a large organism could be responsible. The largest fish species (<1.02m) known to inhabit these water depths in the Pacific are *Coryphaenoides armatus* and *Coryphaenoides yaquinae* (23). These species of abyssal fish have reduced locomotory capacity (24) and slow swimming speeds (<0.15 ms-1) (25) and are unlikely to be able to create relatively deep, sequential depressions in clay sediments (20) several times longer than their body lengths. Complex behaviours associated with nesting (26) have not been observed in deep-sea fishes and would be energetically extremely costly to make in this environment.

Geomorphic alterations of the seafloor caused by marine tetrapods have been recognized in both modern (27) and paleontological records (28). In modern oceans, these seabed alterations (e.g. gouges, pits, tracks etc.) have been well-documented from narwhals and beluga whales in fjords (29), to walruses and humpback whales on the shallow continental shelf (30). The characteristic patterns observed within this study and the distance between the mid-points of consecutive depressions within a given track are similar to seafloor modifications identified from ROV (remotely operated vehicle) video in the Mediterranean (separation distance 5-10 m (9); separation distance 6-10 m (12)) with their occurrence being attributed to foraging beaked whales. From limited imagery, the depressions are also of similar morphology to those presented in previous studies (9,10). However, it is important to note that some inconsistencies are observed, specifically when compared to those from (9), where a narrow central groove is observed superimposed on a larger seafloor depression. These differences could be attributed to either (a) the methodologies obtaining the size and morphology of depression - sidescan sonar can be used only to provide approximate measurements based on acoustic shadows and may not resolve subtleties in the morphology (i.e. a groove feature within a depression), while measurements from oblique ROV videography can again only provide an estimate of size, but will give greater visual resolution; (b) the relative age of the depression, which may result in altered morphology (owing to seafloor processes) and/or finally; (c) different species are responsible for making the depressions.

Despite being the most speciose family of the cetaceans, deep-diving beaked whales of the Family Ziphiidae represent the most elusive whales in the world’s oceans, with species new to science still being discovered (31). Unlike shallow-water counterparts (e.g. Delphinidae), or large filter feeding relatives (e.g. Balaenidae), deep-diving whales are challenging to study owing to their open-ocean pelagic nature, small fin with a low-surface profile and inconspicuous surface blows (32). To date, five extant species of beaked whale (Ziphiidae) and the deep-diving sperm whale (*Physeter microcephalus*) are likely to occur in the waters of the Pacific Ocean within the CCZ region (33). While it is not possible to identify which species (extinct or extant) could be responsible, our observations of seafloor modifications within the 4258 m contour exceed the deepest known dive (34) by any species of whale by over 1200 m.

Throughout the CCZ, there is a high incidence of fossil whale bones from the Family Ziphiidae (35). Furthermore, a recent “whale-fall” of a small odontocete has been observed at 4142 m depth (36). Although the presence of extinct fossilized whale bones and the observation of a recently deceased odontocete does not demonstrate that these animals were (or are) capable of diving to these abyssal depths, it does confirm their presence over geological timescales within the CCZ region. When we consider the maximum eustatic sea-level amplitude, we would suggest that even if these marks were made during the last glacial maximum, when water depths in the Pacific Ocean were 125-135m lower (37), the species responsible would still have been capable of diving to depths of nearly 4000 m. Anatomical studies suggest that cranial air spaces in Cuvier's beaked whales could withstand a dive to depths of 5000 m (38), and although the physiological limits of diving are unknown, it is conceivable that a whale capable of diving to these depths exists in our oceans today.

Several hypotheses have been proposed as to why whales may cause such indentations on the seafloor. These include (a) removing parasites or dead skin (11), behaviour that is known from other odontocetes in shallow water (39–41); (b) foraging in the sediments for prey items (benthic or infaunal invertebrates) (9) or; (c) trying to catch motile bentho-pelagic species such as cephalopods and fish (10). As a result of (b) and (c), it has been suggested that individuals may be ingesting debris accidently (42). However, there are examples where other marine tetrapods are known to (d) intentionally ingest coarse material to regulate buoyancy (43).

The characteristic curvilinear pattern observed here would suggest that an individual would come in to contact with the seafloor multiple times during one dive. Therefore, it appears that the individual is actively excavating the sediment. Invertebrate benthic biomass in abyssal plains is reported to be low (~4 g m-2)(44) – unlike the large shallow-water feeding mysticetes on the continental shelf (which filter-feed on sediments containing ~170 g m-2 of ampeliscid amphipods) (30) this bentho-abyssal approach for a species of whale would represent an energetically-costly mode of foraging for such parsimonious feeding.

Some species of beaked whale are known to feed in close proximity to the seafloor (*Mesoplodon densirostris*) (45), while other species (*Ziphius cavirostris*) in the east (46,47) and west North Pacific (*Berardius bairdii*) (48) are reported to feed on abyssal bentho-pelagic fish, including the Macrouridae (or grenadiers). Maximum abundance of abyssal fish (including grenadiers) has recently been estimated at 723 individuals’ km-2 (49), which represents a significant food resource at depths beyond 4000 m. Although an efficient predatory method of echolocation (50) and suction feeding is employed by beaked whales (51) and other known species of odontocetes, this does not preclude a chase after escaping prey. Energetic foraging has been shown in the echolocating, suction-feeding, short-finned pilot whale (52), therefore it is plausible that sequential tracks could be a by-product of whale chasing prey (10).

Ingesting material (including nodules) for ballast - a hypothesis first postulated following the *Challenger* expedition(35) *-* is documented in both groups of fossil (53) and extant families of marine tetrapods (43,54,55) with the primary role inferred to regulate buoyancy in species that ‘fly’ or ‘glide’ underwater using hydrofoil fins (e.g. ottarids, penguins, pleisosaurs). To date, gastroliths (or “stomach stones”) have not been considered to play a major role in cetaceans that swim primarily utilizing a caudal fin (43). However, research suggests prolonged periods of ‘gliding’ are a behavioral response by caudal-fin swimming marine mammals to improve energetic efficiency during deep-dives (56) and that buoyancy (57,58) and biomechanical strategies (59) influence these different swimming gaits.

Species of beaked whale and the sperm whale are highly adapted for diving to extreme depths. These adaptations include significantly different body composition (60), a high oxygen storage capacity (reviewed by, 56) and for the beaked whales in particular, the use of a novel muscle composition (62) and unique stroke and glide pattern that suggest a neutral buoyancy for some species of beaked whale at depth (59). These adaptations would suggest that deep-diving species have the capability to forage at depth without the need ingest large quantities of sediment to add ballast. However, gastroliths have been reported in both individuals of Baird’s beaked whale (*Berardius bairdii*) (48) and the sperm whale (*Physeter microcephalus)* (63).

Although with the dataset available we cannot determine which species is responsible, or why they are creating these disturbances on the seafloor, the precautionary principle must be adhered to. Sperm whales and all the extant species of Ziphiidae are likely to occur within the CCZ and the literature would suggest that some of these deep-divers may be capable of utilising the seafloor within this region; this may have important implications for management of existing and planned marine industrial activities. All of these species are on the IUCN red list of Threatened Species (accessed 2018 http://www.iucnredlist.org/) and Article 120 of the 1982 UN Convention on the Law of the Sea (UNCLOS) puts in place measures for their conservation.

Monitoring of marine mammals in areas of industrial activity will be important, and current guidance from the International Seabed Authority (ISBA/19/LTC/8) requires contractors to record sightings of marine mammals to ascertain spatial and temporal variability of species within the region. For deep-diving whales that are renowned for their elusive lifestyle and sometimes inconspicuous identification at the surface, traditional vessel-based marine mammal observations may not be effective (32) and active management to avoid impacts to whales from underwater noise, to which they are particularly sensitive (66–68), will be necessary.

Whichever taxa maybe responsible for these seafloor interactions, this study highlights how the use of ultra-low altitude deep-submergence AUV’s will become invaluable in detecting these observations over large scales (kilometers) and deriving seafloor habitat utilization maps, while human-directed ROV observations will be key in visually examining and sampling these disturbances further. Deep-diving whales can be found throughout our global oceans - to what extent they are utilizing and altering the seafloor environment remains unknown. The observations presented in this study highlight the number of important discoveries yet to be made about our ocean and yet, we are already looking to exploit a habitat that we know very little about.

**Data accessibility**

The datasets supporting this article have been uploaded as part of the supplementary material.

**Competing interests**

The authors declare no competing interests.

**Author contributions**

D.O.B.J. was the NOC principal investigator on the MIDAS grant and conceived the study. D.O.B.J and V.A.I.H undertook the fieldwork. L.M. analysed the data and prepared the manuscript. All authors contributed to the manuscript and gave final approval for publication.

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**Figure Legends**

**Figure 1:**(A) Region targeted for polymetallic nodule mining in the Clarion Clipperton Fracture Zone (CCZ), Pacific Ocean. Exploration claims are delineated by coloured boxes. The Areas of Particular Environmental Interest (APEI) are shown in grey. (B) During expedition JC120, parts of the north easternmost APEI and the UK claim zone were surveyed. (Inset top) EM120 shipboard multibeam from the APEI with *Autosub6000* M79, M81 and M83 sidescan sonar missions. (Inset bottom) EM120 shipboard multibeam from the UK claim zone with *Autosub6000* M85 sidescan sonar missions.

**Figure 2:** Detail of feeding traces in independently-obtained high-frequency sidescan sonar at (A) 15m (traces faint) and (B) 3m (easily resolved) altitude, illustrating the occurrence of tracks of small elongated depressions.

**Figure 3:** *Autosub6000* Mission 81 (M81) within APEI (A) high-frequency (410kHz) sidescan sonar acquired at 3m altitude. Areas with high acoustic backscatter are represented in light grey, low acoustic backscatter in dark grey. Orange circles indicate depressions that have been digitized in ArcGIS 10.3. (B) Zoom of M81 indicating sequential depressions or ‘tracks’. (C) Single sequence of depressions (‘track’) from M81. Depth: 4023m (D) Overlapping tracks of differing ages. White tracks show high contrast and sharp edges indicating relatively younger tracks than those in orange with lower contrast and less definitive edges. Depth: 4041m

**Figure 4:** Image provided from the oblique camera from *Autosub6000* Mission 79 (M79) within the APEI shows two depressions, inferred to be those also observed from acoustic data. White dashed line indicates area where sediment from the excavation has subsequently covered nodules within the vicinity. Eroded edges would suggest that these particular depressions have not been made in recent years. Depth: 4153m

**Tables**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Vehicle** | **Data type** | **Location** | **Depth range (m)** | **Area covered (km2)** | **Total resolvable depressions** | **Density**  **(km-2)** | **Number of tracks (>6 sequential depressions)** | **Mean distance between depressions (± 1 s.d.)** | **Reference** |
| **AUV (M79)** | Sidescan | APEI CCZ, Pacific | 4195-4160 | 0.859 | 512 | 596 | 23 | 8.14 ± 2.83 | This study |
| **AUV (M81)** | Sidescan | APEI CCZ, Pacific | 4117-3999 | 11.277 | 2951 | 262 | 30 | 8.78 ± 2.88 | This study |
| **AUV (M83)** | Sidescan | APEI CCZ, Pacific | **4258**-4227 | 3.223 | 34 | 11 | 1 | 13.39 ± 1.19 | This study |
| **AUV (M85)** | Sidescan | UK Claim CCZ, Pacific | 4120-4111 | 6.490 | 42 | 3 | 2 | 6.44 ± 1.26 | This study |
| **ROV** | Photomosaic | Seamount, Mediterranean | 1000-800 | 0.00116 | 17 (identified within publication) | 14655\* | 1 | 8.09 ± 1.51 | Roman et al., (2012) |

**Table 1:** Summary of data on geomorphic alterations of the seafloor attributed to whales from high-frequency AUV sidescan (this study) and ROV photomosaic from Roman et al., (2012). Mean distance between depressions measured from centre point of each depression. The deepest observation is indicated in bold. (\*) likely an overestimate owing to targeted sampling using ROV.