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## **Shallow seafloor gas emissions near Heard and McDonald Islands on the Kerguelen Plateau, southern Indian Ocean**

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## Key Points:

1. Active submarine gas emission discovered around Heard and McDonald Islands on the Kerguelen Plateau, an intraplate Large Igneous Province in the southern Indian Ocean.
2. Gas release near the McDonald Islands possibly related to shallow diffuse hydrothermal venting, uncommon on an intraplate Large Igneous Province.
3. Gas release near Heard Island may indicate either or both a biogenic or thermogenic methane seep, the second reported location in the Southern Ocean to date.

## Abstract

Bubble emission mechanisms from submerged Large Igneous Provinces (LIPs) remains enigmatic. The Kerguelen Plateau, a LIP in the southern Indian Ocean, has a long-sustained history of active volcanism and glacial/interglacial cycles of sedimentation, both of which may cause seafloor bubble production. We present the results of hydroacoustic flare observations around the under-explored volcanically-active Heard Island and McDonald Islands on the Central Kerguelen Plateau. Flares were observed with a split-beam echosounder and characterized using multi-frequency decibel differencing. Deep-tow camera footage, water properties, water-column  $\delta^3\text{He}$ , sub-bottom profile, and sediment  $\delta^{13}\text{C}$  and  $\delta^{34}\text{S}$  data were analyzed to consider flare mechanisms. Excess  $\delta^3\text{He}$  near McDonald Islands seeps, indicating mantle-derived input, suggests proximal hydrothermal activity; McDonald Islands flares may thus indicate  $\text{CO}_2$ , methane, and other minor gas bubbles associated with shallow diffuse hydrothermal venting. The Heard Island seep environment, with sub-bottom acoustic blanking in thick sediment, muted  $^3\text{He}$  signal, and  $\delta^{13}\text{C}$  and  $\delta^{34}\text{S}$  fractionation factors, suggest Heard seeps may either be methane gas (possibly both shallow biogenic

methane and deeper-sourced thermogenic methane related to geothermal heat from onshore volcanism) or a combination of methane and CO<sub>2</sub>, such as seen in sediment-hosted geothermal systems (Procesi et al., 2019). These data provide the first evidence of submarine gas escape on the Central Kerguelen Plateau and expand our understanding of seafloor processes and carbon cycling in the data-poor southern Indian Ocean. Extensive sedimentation of the Kerguelen Plateau and additional zones of submarine volcanic activity mean additional seeps or vents may lie outside the small survey area proximal to the islands.

### **Plain language summary**

Bubbles are constantly escaping the seafloor, either from thick sediments with gas-producing bacteria or from volcanic gases escaping rocks deep beneath the seafloor. We use sonar to observe bubbles that appear as ‘hydroacoustic flares’ as they travel from the seafloor into the ocean. Our paper shows the results of the 2016 RV *Investigator* voyage to Heard and McDonald Islands, two of Australia’s most remote islands and home to its only active volcanoes. We observed hundreds of flares around the two islands and were able to examine bubbles in some of our camera footage. By examining the seafloor, the shallow sub-seafloor, and the chemistry of sediments and the water column, we suggest the bubbles may be composed of different gases. Around Heard Island, bubbles were associated with thick sediment that are likely rich with bacteria that produce methane gas; near the McDonald Islands, bubbles were not associated with sediments and possibly indicate shallow volcanic activity emitting gases, like CO<sub>2</sub>, originating from the mantle. Knowing where bubbles are escaping is crucial for understanding how much gas is contributed from the seafloor into the ocean and atmosphere.

## 1 Introduction

Bubble emission from the seafloor abounds in the global ocean. Predominantly hydrocarbon or hydrothermal in nature, gas seeps and vents are found in diverse geological settings and can aid our understanding of deep Earth and shallow seafloor processes (Rona et al., 1991; Murton et al., 1994; Riedel et al., 2001; Rona et al., 2002; De Beukelaer et al., 2003; Hovland et al., 2012; Gentz et al., 2014; Weber et al., 2014; Pérez et al., 2014; Nakamura et al., 2015; Passaro et al., 2016). Submarine gas emissions manifest as water column hydroacoustic ‘flares’ in shipboard echosounders as the impedance contrast bubbles create with the surrounding seawater makes them excellent acoustic scatterers (McCartney & Bary, 1965; Clift et al., 1978; McGinnis et al., 2006; Colbo et al., 2014).

The primary source of hydroacoustic flares is methane bubbles from cold methane seeps that are widespread on active and passive margins, where organic-rich sediment readily accumulates (Judd, 2003; Reeburgh, 2007; Kirschke et al., 2013; Suess, 2014). Methane seeps are the seafloor expression of: 1) methanogenesis, the microbial decomposition of organic matter in anoxic sediments; 2) thermogenesis, the thermo-catalytic breakdown of deep buried organic matter; or 3) dissolution of methane hydrates, which are stable in low-temperature, high-pressure settings, but dissociate above the Gas Hydrate Stability Zone.

Gas emissions adjacent to hydrothermal fluid venting can also produce hydroacoustic flares (Pérez et al., 2012; Passaro et al., 2014; Passaro et al., 2016; Hernández et al., 2017). Majority CO<sub>2</sub>, abiogenic methane, and other minor gas bubbles or CO<sub>2</sub> liquid droplets are commonly attributed to localized degassing along regional fracture systems from deeper mantle sources (Passaro et al., 2014). Only high frequency or close-range hydroacoustic systems would be able to identify fluid density changes caused by hot hydrothermal fluid venting or freshwater inputs from submarine groundwater discharge (Hay, 1984; Crawford &

Hay, 1993; Judd & Hovland, 2009; Colbo et al., 2014) although these signals are typically more subtle as the impedance contrast is lower.

Gas escape along continental margins is well understood (Judd, 2003; Hovland et al., 2012) yet in many remote and/or under-sampled locations seafloor gas emissions are both poorly mapped and poorly constrained. Heard Island and McDonald Islands (HIMI) are a sub-Antarctic island group in the southern Indian Ocean (Fig. 1a and 1b). HIMI, along with the Kerguelen Islands, are the currently subaerial portions of the Kerguelen Plateau, a predominantly Cretaceous Large Igneous Province (LIP) attributed to the Kerguelen hotspot or mantle plume (Coffin & Eldholm, 1994; Coffin et al., 2002) (Fig. 1a). HIMI have been constructed on the ~100 Myr Central Kerguelen Plateau and are both active hotspot volcanoes, forming since <1 Ma (Duncan et al., 2016) and <100 Ka (Quilty & Wheller, 2000) respectively (Fig. 1b). Both island groups are volcanically active making submarine extensions of subaerial geothermal systems probable. The current phase of volcanism began at ~400 to 200 Ka, with activity both pre- and post-dating the Last Glacial Maximum (LGM) when a large ice-cap covered the two islands (Hodgson et al., 2014; Duncan et al., 2016) (Fig. 1b). Around 70% of Heard Island's landmass remains obscured by glaciers. Glacial erosion dominates Heard Island and provides a constant source of glaciogenic material to the adjacent seafloor. Extensive submarine volcanism between 59 Ma and 21 Ka, with numerous examples <1 Ma, has also been documented across the broader Central Kerguelen Plateau (Weis et al., 2002).

We report the first scientific hydroacoustic, geochemical, geophysical, and video data from the water-column, seafloor, and sub-seafloor surrounding HIMI, collected during voyage IN2016\_V01 of Australia's Marine National Facility RV *Investigator* where 13 gas seeps were observed around the islands in water depths of <200 m. In the absence of direct gas samples from these remote seeps we analyze and interpret hydroacoustic flare

observations, combined with water column  $\delta^3\text{He}$ , sediment  $\delta^{13}\text{C}$  and  $\delta^{34}\text{S}$ , deep-tow camera footage, conductivity-temperature-depth (CTD), and sub-bottom profile data to understand the distribution of seeps and consider the origin and implications of the gas emissions.

## 2 Materials and methods

### 2.1 Hydroacoustics and sub-bottom profile

A Simrad EK60 multi-frequency split-beam echosounder recorded water column data at ship speeds  $\leq 10$  knots. We analyzed EK60 data collected at 38 and 120 kHz frequencies, both with a beam width of  $7^\circ$ . Pulse length was  $2.048 \text{ ms}^{-1}$  for 38 kHz and  $1.024 \text{ ms}^{-1}$  for 120 kHz. A sound velocity of  $1513.78 \text{ ms}^{-1}$  was applied to all EK60 data. The echosounder was calibrated prior to the voyage using the standard target method with a 20 mm tungsten-carbide sphere (Foote et al., 1987). For cogency, the term ‘acoustic anomalies’ will herein describe clusters of higher intensity water column backscatter that cover multiple pings in the time dimension and multiple samples in the depth dimension, the term ‘flare,’ ‘hydroacoustic flare,’ or ‘flare observation’ describes individual acoustic anomalies that characterize free gas bubble emission from the seafloor, and the term ‘seep’ describes locations where individual flares were surveyed multiple times over repeat survey passes and thus grouped together as a seep.

Acoustic anomalies were identified in the EK60 echograms, analyzed, and characterized using a processing methodology applied in the Echoview software package (version 7.0.90) (Supp. Text. 1). Acoustic anomalies attributable to fish schools, large biological scatterers (such as diving penguins and seals), seafloor reflections, interference from other hydroacoustic systems were manually removed, as were incomplete observations due to data gaps. The remaining anomalies were considered flare observations if they were

rooted to the seafloor and detected at least twice in the same approximate location during subsequent passes, following [Gentz et al. \(2014\)](#) and [Veloso et al. \(2015\)](#). Flare locations were georeferenced in Echoview by the GPS location of the middle ping of each flare in the split-beam data. Due to the spatial uncertainty associated with the location in the beam for aggregated backscatter in split-beam echosounder data, flares were not defined as individual flares but grouped as seeps for written clarity.

Flares were classified using a customized multi-frequency decibel-differencing technique (Supp. Fig. 1.f-i). Decibel-differencing compares water-column backscatter across two synchronized frequencies using a calibrated echosounder. Due to the nature of acoustic pressure waves backscatter recorded for different frequencies varies depending on bubble or target properties. Frequency differences can be exploited to classify biological water column scatterers due to the presence of a swim bladder ([Madureira et al., 1993](#); [Brierley & Watkins, 1996](#)) and we applied the technique here to water column gas bubbles. A mean volume backscatter strength (ratio of 120 – 38 kHz or  $\Delta MVBS$ ; acoustic intensity in decibels) frequency response filter of -20 to 1 dB was created using the acoustic response of the flares, where bubbles were observed in camera footage (see 2.2). The frequency response filter was then applied to all echograms, where no bubbles were visible in the limited camera footage or for which no footage was collected, to classify the remaining flares (Supp. Fig. 1.h and 1.i).

A Kongsberg SBP120 sub-bottom profiler, using linear chirp at 2 to 8 kHz, operated synchronously with the EK60. Raw SBP120 data were imported as SEG-Y files into the Fledermaus FM Midwater software package (version 7.7.4) for visualization. Files were merged with navigation data and converted to Generic Water Column (GWC) format. We interpreted sedimentary structures in the sub-bottom profiles, focusing on sedimentary horizons and acoustic blank zones beneath flares.

## 2.2 Water column and seafloor observations

A high-definition deep-tow camera system was deployed nine times over the three sites (Fig. 1c and 1d) where we observed strong persistent flares (Fig. 2a-c). The deep-tow camera system houses a Canon EOS-1DX still/video camera (34° angle of view; focal length = 70-200 mm; aperture = min f/2.8, max f/32; minimum focus distance = 1.5 m; exposure = 1/125) and a Canon C300 HD cinema video camera (~50° viewing angle). The Canon EOS-1DX was the primary system for both video and still camera footage. Track lengths and mean altitude values were calculated when the camera was within 10 m of seafloor. Visibility distance was estimated when the seafloor ceased being visible in the video footage (Supp. Table 1).

The deep-tow video and camera footage was examined to identify visible bubbles streams or evidence of seafloor emissions and thousands of high-resolution still images were examined for seafloor structures and benthic habitats. Bubbles sizes were determined by comparing their sizes at the seafloor with the camera laser sights (10 cm apart at the seafloor). Observed bubbles were georeferenced using the dedicated Ultra Short Base-Line (USBL) of the camera system.

The deep-tow camera system has a co-mounted SBE 37-SI MicroCAT CTD, located ~0.75 m aft of the camera system. CTD data was analyzed for any temperature/salinity anomalies present near flares. Sampling frequency of the CTD was 1.5 s, with an instrument resolution of 0.0001 mS cm<sup>1</sup> for conductivity, ± 0.0001 °C for temperature, and 0.002% of full-scale range for pressure.

## 2.3 Helium samples

We used helium isotopes from water samples to differentiate flares potentially related to hydrothermal activity. Hydrothermal fluids are enriched in light helium, <sup>3</sup>He, relative to

atmospheric helium,  $^4\text{He}$ , as their source is the mantle. The mantle is enriched in  $^3\text{He}$  making  $^3\text{He}/^4\text{He}$  isotope ratios therefore useful indicators for mantle input into the ocean. Volcanic rocks of Heard Island have high  $^3\text{He}/^4\text{He}$  ratios, up to 18 times the atmospheric ratio due to the involvement of a deep-seated mantle plume during its evolution ([Hilton et al., 1995](#)). Any hydrothermal input from the flanks of HIMI would therefore be expected to have comparably elevated  $^3\text{He}$ ; flares unrelated to hydrothermal activity (i.e., cold methane seeps) are expected to contain radiogenic helium with a lower  $^3\text{He}/^4\text{He}$  ratio.

During the voyage, 74 seawater samples were immediately drawn from Niskin bottles on the shipboard CTD rosette and hermetically sealed into copper tubes using a hydraulic crimping system ([Young & Lupton, 1983](#)). Samples were analyzed onshore for  $^3\text{He}$  and  $^4\text{He}$  concentrations and  $^3\text{He}/^4\text{He}$  ratios by mass spectrometry. Approximately half of the samples were reference samples collected in four vertical profiles spanning the Kerguelen Plateau north of HIMI to establish regional background  $^3\text{He}/^4\text{He}$  levels (Fig. 2d) and search for the presence of a  $^3\text{He}$  plume emanating from HIMI (Supp. Table 2). In addition to the Kerguelen Plateau profiles, another 32 samples were collected during shallow casts in the vicinity of flares with samples collected near the bottom of each CTD cast. The  $^3\text{He}/^4\text{He}$  is reported in units of  $\delta^3\text{He}$  (%), which is the percentage deviation from atmospheric  $^3\text{He}/^4\text{He}$ .

#### 2.4 Sediment samples

Two sediment samples from a Smith McIntyre grab (SMG) suitable for geochemical analyses were recovered from near Seep HRD1.2 (SMG-03 and SMG-08; Fig. 2c). No samples proximal to MCD1 seeps were viable for geochemical analyses as they were composed of pumice and sand. No samples were collected near MCD2 due to hard seafloor. Samples were split, freeze-dried, and sieved to separate the sediment from biogenic material (i.e., shell fragments). Weight % of bulk carbonate ( $^{13}\text{C}_{\text{carb}}$ ) and  $^{34}\text{S}$  were determined using an

Eltra CS-2000 elemental analyzer (Johnson et al., 2017 ; Durand et al., 2017). Each powdered sample was combusted at  $>1,500^{\circ}\text{C}$  in pure (99.99%) oxygen, causing carbon to form carbon dioxide ( $\text{CO}_2$ ) and sulfur to react to sulfur dioxide ( $\text{SO}_2$ ); reactions were measured on four infrared (IR) channels. The machine was calibrated to Eltra supplied standards, international standards (AR-4007, AR-4019, AR-4015, Choice Analytical), and internal standard (QLDSED). Data accuracy and reproducibility are better than 0.02% for S and 0.05% for C. Weight % of bulk organic carbon ( $^{13}\text{C}_{\text{org}}$ ) was determined using the same method; however, the samples (~500 mg) were pre-treated using an acid treatment of 6N HCl on a hotplate at  $70^{\circ}\text{C}$  for 8 hours to promote dissolution of inorganic carbon species. The samples were rinsed with distilled water and dried overnight and the dried residue analyzed using the aforementioned method.

Duplicate samples were sieved, powdered, and analyzed for carbon and sulfur isotopes at the Central Science Laboratory, University of Tasmania. The  $\delta^{13}\text{C}_{\text{carb}}$  component was derived by treating the powders with phosphoric acid (100%  $\text{H}_3\text{PO}_4$ ,  $50^{\circ}\text{C}$ , 24h). The evolved  $\text{CO}_2$  was purified by means of subsequent cold traps ( $\text{N}_2(\text{liq.}) -196^{\circ}\text{C}$  and acetone/ $\text{CO}_2 -94^{\circ}\text{C}$ ) to remove non-condensable reaction by-products, and analyzed using a dual inlet VG Optima. The  $\delta^{13}\text{C}_{\text{org}}$  component was derived using the same method as outlined for  $\text{C}_{\text{org}}\%$  to evolve inorganic carbon species, and analyzed using an Isoprime 100 PyroCube. Some samples (organic-rich sediments) yielded little  $\text{CO}_2$  and could not be analyzed. Sulfur isotope ( $\delta^{34}\text{S}$ ) analysis was conducted also using the Isoprime 100 PyroCube. Analytical uncertainty is less than 0.05‰; reproducibility based on full duplicate analyses and internal and international standards was better than 0.3‰ for all analyses

### 3 Results

#### 3.1 Flare identification and classification

We identified 13 distinct seeps at three sites (composed of >200 individual hydroacoustic flare observations) (Fig. 1c and 1d) originating from the seafloor in water depths of 55-150 m (Fig. 3): seven seeps at Site MCD1 (Fig. 2a), two seeps at Site MCD2 (Fig. 2b), and four seeps at Site HRD1 (Fig. 2c). All flare observations are listed in Supp. Table 3 with each seep composed of multiple flare observations.

The seven seeps at MCD1 occur on sloping seafloor northeast of the McDonald Islands (mean water depth ~130 m) (Fig. 2a). Many MCD1 seeps were not persistent during multiple passes nor maintained a consistent morphology (Fig. 3). Some flares were observed to be ellipsoid-shaped, sometimes slanting; other flares were observed as weak, diffuse scattering near the seafloor (Fig. 3; Supp. Table 3). MCD1 flares averaged 28 m height from the seafloor, with a maximum height of 74 m (Fig. 3).

The two seeps at MCD2 occur on top of a shallow sea knoll south of the McDonald Islands (mean water depths ~60 m) (Fig. 2b). Seeps were persistent in the water column during multiple survey passes, with vertically elongated ellipsoid-shapes. MCD2 flares averaged 31 m in height from the seafloor, with a maximum height of 48 m; the tallest flares were within 15 m of the sea surface (Fig. 3; Supp. Table 3).

The four seeps at HRD1 occur on flat seafloor northeast of Heard Island (mean water depths ~90 m) (Fig. 2c). Seeps were persistent in the water column over multiple survey passes, with tall vertically elongated shapes. HRD1 flares averaged 33 m in height from the seafloor, with a maximum height of 79 m (Fig. 3); the tallest flares were within 15 m of the sea surface (Fig. 3; Supp. Table 3). The flares of seep HRD1.2 (a tight cluster of four discrete flares) were repeatedly observed, however due to the spatial uncertainty associated with each flare's origin in the split-beam echosounder beam, we grouped them as one seep for clarity.

### 3.2 Flare classification

All HRD1 flares were classified by the  $\Delta$ MVBS filter of -20 to 1 dB. The broad decibel range reflects a broad distribution of bubble sizes. A higher intensity response in the lower 38 kHz echogram (Supp. Fig. 1.h) is consistent with gas-filled resonant sphere models, where the relative frequency response peaks in lower frequencies (18 or 38 kHz) and diminishes in higher frequencies (Madureira et al., 1993; Everson et al., 1993; Brierley & Watkins, 1996). HRD1 flare intensity varied little during multiple passes, allowing the filter to work consistently, suggesting continuous seep activity. All MCD2 flares were also captured by the HRD1  $\Delta$ MVBS filter of -20 to 1 dB, confirming the flares are caused by gas emission from the seafloor with a similar broad distribution of bubble sizes to HRD1 flares, with a higher intensity response in the lower 38 kHz frequency. The flares did not vary intensity during multiple passes, suggesting continuous activity.

Few MCD1 flares were captured by the HRD1  $\Delta$ MVBS filter of -20 to 1 dB (Supp. Fig. 1.h). More MCD1 flares were captured using a second frequency response filter ( $\Delta$ MVBS = 1 to 20 dB; Supp. Fig. 1.i) demonstrating a dominant response in the higher 120 kHz echogram, though flares varied in intensity over multiple survey passes. As MCD1 flares were captured in both the HRD1 video-verified  $\Delta$ MVBS classification (-20 to 1 dB) and the non-verified  $\Delta$ MVBS classification (1 to 20 dB), a much broader bubble size distribution than both HRD1 and MCD2 is expected though dominant target sizes are smaller than HRD1 and MCD2.

### 3.3 Sub-bottom profile assessment

At MCD1 (Fig. 4a) the sub-bottom data reveal a strong seafloor and sub-seafloor reflection, of varying relief (Fig. 4d). A thin (~5 m) layer of sediment accumulation is

observed beneath two seep locations, MCD1.5 and MCD1.6 (Fig. 4a), with the acoustic signal obscured below. No distinct horizons or acoustically transparent lenses were imaged. At MCD2 (Fig. 4b), the sub-bottom data reveal a strong seafloor reflection, associated with the shallow sea knoll (Fig. 4e). The sea knoll has gentle relief on its summit and steep relief on its flanks. No sediment accumulation was imaged at MCD2.

At HRD1 (Fig. 4c), the sub-bottom data reveal gentle seafloor relief, with continuous reflections delineating stratigraphic units beneath the seafloor to depths of ~20 m (Fig. 4f and 4g), with alternating strong and weak reflections. Sub-surface acoustically transparent lenses were imaged both beneath observed flares (Fig. 4f and g) and in the vicinity of and to the northeast of HRD1 without any observed coincident water column flares (Fig. 4c). Most acoustic lenses sit beneath the same undulating horizon marked by a strong reflection that sits a few meters below the seafloor (Fig. 4f and 4g). Acoustic blanking of the signal occurs beneath these lenses and beneath a strong acoustic reflector, with the signal lost ~20 m beneath the seafloor.

### 3.4 Water column and seafloor assessments

#### 3.4.1 Temperature and salinity

CTD measurements collected coincidentally with the towed camera did not record any near-seafloor temperature or salinity perturbations at any sites where towed camera footage was collected (Supp. Fig. 2). No water column stratification was observed indicating a mixed layer from sea surface to seafloor ([Holmes et al., 2019](#)). The near-seafloor water around HRD1 was ~0.3°C warmer than both MCD1 and MCD2, likely due to its shallower depths. Salinity showed regional variation, with a lower median of 33.87 PSU for HRD1, compared

to 33.91 PSU for both MCD1 and MCD2 (Supp. Fig. 2). The CTD was located ~0.5 m above and ~0.75 m aft of the camera, with a mean altitude range of 2.5 and 4.0 m.

### 3.4.2 Seafloor camera observations

Gas bubbles were observed originating from the seafloor at HRD1 (Fig. 5), coinciding with all four seeps (Fig. 2c). Variations in estimated bubble diameters (~5 to 15 mm) coincide with the broad size distribution expected from the  $\Delta$ MVBS classification. Bubble sizes were consistent with those observed at other global seeps (~4 to 20 mm) (Greinert & Nützel, 2004). Bubble flow rates varied visibly from fast flowing small bubble streams (Fig. 5a-f) to slow-rising, larger bubbles of an oblate wobbly character (Fig. 5c and 5d).

Seeps HRD1.1, HRD1.2, and HRD1.3 (Fig. 5a-d) host patchy accumulations of dense yellow matter of varying morphology from a ~5 cm diameter ring (Fig. 5b) to an elongated ~40 cm feature (Fig. 5d). Most observable bubble streams originate from the yellow matter, with three bubble streams expressed from distinct ~2 cm diameter openings (Fig. 5a-d). Some bubbles observed near HRD1.2 and the observable bubble streams of HRD1.4 (Fig. 5f) exit the seafloor from sediment with no associated yellow matter. The seafloor surrounding HRD1 seeps is composed of unconsolidated sediment and coral rubble (Fig. 6a-e) with a variety of epibenthic invertebrates, primarily echinoderms (feather stars - Fig. 6a and 6e; sun stars - Fig. 6b; brittle stars - Fig. 6c and 6d; sea stars - Fig. 6d and 6e; and basket stars), along with fish, crinoids, rays, and skates (not shown). A patch of relict tubeworms was also observed (Fig. 6c).

No bubbles were observed in footage from any MCD1 camera deployments (these covered Seeps MCD1.1, and MCD1.7) although visibility was poor due to the turbid water column (estimated to be < 2 m). Any bubbles present would likely be indistinguishable from water column particulate matter. The seafloor at Seep MCD1.1 is covered in extensive ripples

(Fig. 6f and 6g). Large (>1 m long, ~1 m wide) defined trenches in the surficial sediment are bare and contain no ripples (Fig. 6f and 6g). MCD1.1 hosts echinoderms, though scarcer and less diverse than at HRD1, with yellow brittle stars the dominant visible seafloor biota (Fig. 6f and 6g). The seafloor at MCD1.4 was more difficult to observe due to a higher camera altitude; however large boulders, anemones, and ripples were present (Fig. 6h and 6i). The flares were located on the flanks of a seafloor mound, with seep locations barren within disturbed sediment patches. No yellow material was observed at either site or any obvious location of bubble release.

No bubbles, ripples, seafloor matter, or visible biota were observed at Site MCD2, although visibility was extremely poor due to the turbid water column (estimated to be < 2 m). The seafloor at Site MCD2 consists of cream to light grey coarse-grained sediment demarcated by prominent lines of darker, fine-grained sediment (Fig. 6j-m). The lines correspond to flare locations and consist of centimeter-wide central channels, some infilled with white material, with ~10 cm wide fine-grained darker material berms on either side (Fig. 6j-m).

### 3.5 Helium analyses

Background helium profiles taken across the Kerguelen Plateau (Fig. 2d) increase smoothly to  $\delta^3\text{He}$  values of ~9‰ at depths greater than 1000 m (Fig. 7a), consistent with previous measurements of  $^3\text{He}/^4\text{He}$  in the southern Indian Ocean ([Hilton et al., 1995](#)) thereby showing no evidence for local input from HIMI in the reference samples.

Twenty-four of thirty-two water samples near flares show  $\delta^3\text{He}$  exceeding background levels, ranging 0.29 to 10.09  $\delta^3\text{He}\%$  (Fig. 7b). Two values are greater than typical  $\delta^3\text{He}$  values of ~8‰ from mid-ocean ridge basalts (MORB): 8.22‰ (CTD-20) and

10.09% (CTD-36), both from CTD casts near MCD1 seeps (MCD1.1 and MCD1.5, respectively; Fig. 7b and c). The next highest values, 6.0% (CTD-32), 4.5% (CTD-38), and 3.6% (CTD-39) were also proximal to MCD1. The CTD casts nearest HRD1 flares are CTD-51 and CTD-52, ~550 and 600 m respectively from the large quadruple flare. CTD-51 had  $\delta^3\text{He}\%$  of 1.69; CTD-52 had  $\delta^3\text{He}\%$  of 3.27.

### 3.6 Geochemistry of seep sediments

Sediments sampled from both HRD1 grabs (SMG-03 and SMG-05; Fig. 2c) comprised fine basaltic silty mud, with <2 mm grain sizes (Fig. 8a). Despite the similarity of grain sizes, the two HRD grabs exhibit highly different isotopic values. SMG-03 showed the most positive and widest range  $\delta^{34}\text{S}$  values (range 3.5‰ to 19.1‰, mean 10.6‰, n=14) when compared to the far more negative SMG-08  $\delta^{34}\text{S}$  values (range -12.0‰ to 9.5‰, mean -2.62‰, n=6) (Fig. 8b; Supp. Table 4). SMG-03 exhibited more negative  $\delta^{13}\text{C}_{\text{org}}$  values (range -29.9‰ to -24.5‰, mean -27.1‰, n=14) when compared with SMG-08  $\delta^{13}\text{C}_{\text{org}}$  values (range -23.9‰ to -16.3‰, mean -21.2‰, n=6), leading to a smaller fractionation factor between the two carbon phases (~25%, compared to >30%) (Fig. 8b). Carbon isotopic values for carbonate within the sediments were lacking in some samples due to low yield for analysis.

## 4 Discussion

We observed 13 submarine gas seeps near HIMI, the first scientific evidence for submarine gas emission on the  $\sim 1.8 \times 10^6 \text{ km}^2$  Kerguelen Plateau. The Kerguelen Plateau LIP in the remote southern Indian Ocean has a long-sustained history of active subaerial volcanism and glacial/interglacial cycles of sedimentation, both of which make the area a likely candidate for submarine gas emissions. Our multi-frequency analysis of the observed hydroacoustic flares confirm gas release near both island groups; this analysis also allowed us

to approximate relative bubble sizes of the seeps. In the absence of direct gas samples being obtained from these remote seeps we examine hydroacoustic, water-column, geochemical, geological, and biological indicators to consider the possible mechanism(s) of the HIMI flares.

The shallow (<150 m) marine setting of these sites excludes methane hydrate dissociation as the necessary high pressure and low temperature conditions for hydrate formation are not met ([Peckmann et al., 2001](#)). Likewise, liquid CO<sub>2</sub> droplets associated with hydrothermal vents occur beneath the CO<sub>2</sub> phase transition boundary so are thus confined to deeper (>500 meters below sea level (MBSL)) sites ([Konno et al., 2006](#); [Alendal et al., 2013](#); [Nakamura et al., 2013](#); [Linke et al., 2014](#)). After excluding the above, we explore possible mechanisms for the flares that fit the depth, temperature, and salinity conditions of the two islands: 1) methane bubbles associated with biogenic cold seeps; 2) methane bubbles associated with thermogenic gas release; 3) CO<sub>2</sub>, abiotic methane, and other minor gas bubbles associated with shallow diffuse hydrothermalism; or a combination of the three, such as a sediment-hosted geothermal system.

At Heard Island (HRD1) the lack of >MORB <sup>3</sup>He/<sup>4</sup>He ratios (expected for hydrothermal venting) may suggest gas release either unrelated to hydrothermal activity or predominantly related to a different gas release mechanism. The helium samples nearest HRD1 flares however were >500 m from the largest flare thus any potential weak signal may not be captured. Seafloor sediment sulfides formed at MORB hydrothermal systems typically have δ<sup>34</sup>S values in the narrow range of 0 to +5 ‰, similar to magmatic sulfur ([Herzig et al., 1998](#)). The HRD sediment grab samples show two distinctly different <sup>34</sup>S values: SMG-03 sediments show positive <sup>34</sup>S and negative <sup>13</sup>C<sub>org</sub>; SMG-08 shows a de-coupled carbon and sulfur isotope trend (increasing positive <sup>13</sup>C<sub>org</sub> values with much more negative <sup>34</sup>S values; Fig. 8c) consistent with biogenic sulfide and pyrite formation associated with microbial

reduction of marine sulfate in surface sediments, typical for marine sediments (Jørgensen et al., 2004). The combined sulfur isotopic values for both grabs exhibit a much larger range (-12.0‰ to +19.1‰) than those expected from a pure volcanic/hydrothermal source (+0 to 5‰), barite formation (+4 to 27‰), or water column source (~+20‰) (Herzig et al., 1998; Orphan et al., 2004). The negative  $^{13}\text{C}$  results from both samples may be explained by the expulsion of thermogenic gas (deep buried organic matter warmed by a shallow heat source) causing a depletion in  $^{13}\text{C}$  organic carbon, though we cannot determine if the  $^{13}\text{C}$  organic values represent the influence of water column biomass on surface sediments (Scott et al., 1994; Lorant et al., 1998). The combined negative and positive  $^{34}\text{S}$  of the two grabs may suggest both strong methane production and weak hydrothermal expulsion, although we cannot determine the source for the positive values (whether hydrothermal sulfur or water column sulfate).

The yellow accumulations observed at HRD1 may either be: a) dense pigmented bacterial mats or, b) inorganic mineral precipitate. If the accumulations observed are pigmented mats (as opposed to unpigmented or white bacterial mats), similar to yellow-orange *Beggiatoa* mats observed at Hydrate Ridge (Tryon et al., 2002; Boetius & Suess, 2004), these commonly have little to no  $\text{CO}_2$  incorporation ability and are considered heterotrophic or methanotrophic, with methane and  $\text{H}_2\text{S}$  instead serving as the energy source for the microbial communities (Sassen et al., 1998; Nikolaus et al., 2003). Alternatively, if the accumulations are instead evidence of mineral precipitation, such as Fe-oxyhydroxides crusts observed but also unsampled at Hook Ridge, Antarctica (Bohrmann et al., 1999; Petersen et al., 2004), a relict or extremely low magnitude hydrothermal source may be suggested. Physical samples of the accumulations would be required to confirm their origin. No high reflective signals in the seafloor bathymetry backscatter (not shown) were observed; high backscatter signals usually indicate slabs of authigenic carbonate and are diagnostic of

high magnitude seeps ([Hovland et al., 2012](#)). HRD1 also hosts a flourishing ecosystem of echinoderms, anemones, skates, rays, and fish, with no indication of localized acidification or reduced biodiversity that would typically accompany shallow diffuse hydrothermal venting with associated CO<sub>2</sub> and other minor gas release.

More broadly, offshore conditions around Heard Island are optimal for cold methane seeps: a large supply of sediment from glaciers, relatively sheltered coastal shelf, and an intraplate setting has allowed thick deposits of organic matter to accumulate over time ([Reeburgh, 2007](#); [Hovland et al., 2012](#)). The alternating lithologies in the sub-bottom data at HRD1 suggest strongly reflective volcanogenic material overlain by weakly reflective hemipelagic sediment (see 3.5). We suggest the acoustic blanking observed beneath HRD1 flares evidence of shallow gas reservoirs and possible gas conduits, rising from the base of the imaged sediments to the yellow horizon (Fig. 4f and 4g). Unlike water and sediment, gas absorbs acoustic energy thus blanking in sub-seafloor sediments is commonly interpreted as pooling gas ([Davies et al., 1997](#); [Fleischer et al., 2001](#); [Tóth et al., 2014](#); [Tóth et al., 2015](#)). The sub-surface acoustic lenses beneath HRD1 (Fig. 4f and 4g), and farther northeast of Heard Island, may be related to paleo-glacial conditions, such as meltwater channels and associated eskers formed by sub-glacial hydrological flow when glaciers extended farther from HIMI onto the Central Kerguelen Plateau.

At the McDonald Islands elevated <sup>3</sup>He levels (>MORB) (Fig. 7) observed in the water column suggest some form of primitive source material nearby (e.g. hydrothermal venting) ([Craig & Lupton, 1976](#)). High <sup>3</sup>He ratios (>MORB (mid-ocean ridge basalt) levels of ~8%), as observed in the two samples proximal to MCD1 seeps, provide definitive evidence of deep mantle input into the water column such as diffuse hydrothermal venting undetectable to our echo-sounders. Samples with <sup>3</sup>He/<sup>4</sup>He ratios ≤MORB however, such as the remaining samples around both islands, are less definitive proof of mantle input ([Poreda et al., 1992](#);

Hilton et al., 1995). Hydrothermal fluid venting (or other fluid escape) would not provide sufficient acoustic contrast to form flares; CO<sub>2</sub>, abiotic methane, and other minor gas bubbles associated with shallow diffuse hydrothermal venting however could provide such a contrast. Shallow hydrothermal vents are unique due to the presence of a gas phase, absent at deep-sea vents (Tarasov et al., 2005) and often have no detectable difference in seawater temperatures as the gases cool rapidly as they rise (Passaro et al., 2014; Passaro et al., 2016). Shallow diffuse hydrothermal gas are usually dominated by CO<sub>2</sub> due to degassing slab or magma, with abiotic CH<sub>4</sub>, H<sub>2</sub>S, and H<sub>2</sub> also important components (Dando, 2010).

In areas of shallow CO<sub>2</sub> (and other minor gas) venting reduced biodiversity is expected as localized acidification results in fewer taxa with acidification-tolerant species dominating (Hall-Spencer et al., 2008; Dando, 2010; Kroeker et al., 2011). At MCD1 we observe few to no benthic communities and low biodiversity, and at MCD2 a complete absence of visible biota. The gas escape causing the flares we observed might reasonably be expected to be composed of CO<sub>2</sub>, H<sub>2</sub>S, abiotic CH<sub>4</sub>, and other minor gases. Offshore conditions around the McDonald Islands are less amenable to hosting cold methane seeps: the McDonald Islands host no glaciers to deliver large volumes of sediment offshore; the islands also bear the brunt of the eastward flowing Antarctic Circumpolar Current, inhibiting most sediment from accumulating. The sub-bottom profile across both MCD1 and MCD2 seeps is interpreted as a hard surface covered in a thin layer of reflective volcanogenic sediments (see 3.5). The thin (<10 m) sediment accumulation observed in the sub-bottom at MCD1 may host methanogens however the flare intensity appears out of proportion to the amount of sediment potentially detected. Sediment accumulation also appears minimal at MCD2, but strong, persistent flares are still observed indicating a point source of gas release. Without core samples however, true sediment extent cannot be determined. The presence of acoustically reflective volcanogenic sediment may have inhibited signal penetration and as such, sediment

may be present below the uppermost reflective layer but undetectable with our systems.

Seismic data collected northwest of McDonald Island ([Borissova et al., 2002](#)) however shows little to no sedimentation above hard, volcanic basement; low sedimentation rates may therefore be common around McDonald Islands.

Based on our observations, we speculate the Heard Island flares may result from either cold methane seepage or are indicators of a sediment-hosted geothermal system ([Procesi et al., 2019](#)). The nearby volcanism of Heard Island, and related geothermal heat, may be enhancing the maturation potential of methanogens or thermally degrading organic matter in the thick seafloor sediments resulting in a possible dual biogenic-thermogenic methane source for seafloor gas at HRD1, alongside volcanic gas emissions, as observed at sediment-hosted geothermal systems (SHGS) ([Procesi et al., 2019](#)). The lack of a high  $^3\text{He}$  excess ( $>\text{MORB}$ ) near Heard Island suggests the bubbles observed are primarily methanogenic in origin. Two, possibly dual, mechanisms remain: sedimentary biogenic methane from near-surface anoxic sediments, or  $\delta^{13}\text{C}$  enriched methane from thermogenic processes. The presence of possible gas conduits observed as acoustic blanking in deeper sediments (Fig. 4e and 4f), the isotopic depletion of  $^{13}\text{C}$  organic carbon (Fig. 8a), and nearby active volcanism contributing geothermal heat, suggest a possible dual biogenic-thermogenic methane source for the gas emissions. The lower  $^3\text{He}$  ratios ( $\leq\text{MORB}$ ) and possible Fe-oxyhydroxide precipitation could suggest a relict or extremely low magnitude hydrothermal venting proximal to, but not a primary cause of, flares.

In contrast, we speculate the McDonald Islands flares at MCD1 and MCD2 may be locations of diffuse and point-source gas release respectively, related to shallow  $\text{CO}_2$ , abiotic methane, and other minor gas emissions. As onshore regions of HIMI are volcanically active ([Duncan et al., 2016](#)), observable as subaerial gas emissions, submarine volcanic gas emissions are probable thus providing an alternate gas source to methane gas escape. The

high  $^3\text{He}/^4\text{He}$  ratios ( $>\text{MORB}$ ) at MCD1 suggest these flares may result from gas emissions analogous to those observed coincident with hydrothermalism at shallow convergent plate margins or hotspot volcanoes ([Monecke et al., 2012](#); [Passaro et al., 2014](#); [Pérez et al., 2014](#); [Ingrassia et al., 2015](#); [Passaro et al., 2016](#)). The scarcity of sediments containing organic matter proximal to the McDonald Islands seeps, and thus the non-viability for sampling, suggests a biogenic source is not primarily responsible for the flares observed. The McDonald Islands emissions may be linked to either faults or submarine extensions of subaerial geothermal systems, such as those observed subaerially on the islands ([Quilty & Wheller, 2000](#); [Stephenson et al., 2005](#); [McIvor, 2007](#)). Active fumaroles were observed degassing on the McDonald Islands during data collection for this study.

#### 4.1 Implications for McDonald Islands flares

The McDonald Islands seeps may represent one of very few known shallow intraplate gas vents. Though shallow-water hydrothermal venting is common at convergent margins ([Tarasov et al., 2005](#); [Passaro et al., 2014](#); [Passaro et al., 2016](#)), few examples of shallow-water venting in intraplate circumstances have been observed globally. Of more than 600 identified submarine gas vents in a recent review ([Beaulieu et al., 2013](#)), 61 (~10%) are found in shallow (<200 m) waters. Of the 61 shallow sites reported by Beaulieu et al. (2013) only two are found in intraplate settings. The two examples of shallow intraplate vent sites are within the Azores Archipelago in the North Atlantic, associated with the Azores hotspot, and the basaltic Macdonald Seamount in the South Pacific, associated with the Macdonald hotspot. The Azores Archipelago hosts nine vents degassing bubbles composed ~90%  $\text{CO}_2$  ([Couto et al., 2015](#); [Aguiar & Costa, 2010](#); [Rajasabapathy et al., 2015](#)), including shallow (~35 m depth) low temperature bubble emissions ([Munaro et al., 2010](#)). The Macdonald

Seamount also has extensive shallow gas (methane, CO<sub>2</sub>, and SO<sub>4</sub>) release observed exiting shallow (156 m) seafloor sediments ([Cheminée et al., 1991](#)).

Subsequent to the [Beaulieu et al. \(2013\)](#) review, work on El Hierro Island in the North Atlantic, associated with the Canary hotspot, suggests that it may be another relevant analogue. Evidence for gas venting has been observed in water 88 to 350 m deep around El Hierro ([Pérez et al., 2012](#); [Beaulieu et al., 2013](#); [Pérez et al., 2014](#); [Somoza et al., 2017](#)). Flares were recorded along with CO<sub>2</sub> and H<sub>2</sub>S degassing and pyroclastic plumes during the 2011-2012 eruption ([Pérez et al., 2012](#); [Pérez et al., 2014](#)), with significant discharge of CO<sub>2</sub> continuing after the eruption ([Santana-Casiano et al., 2016](#)). El Hierro, thought to be above the present Canary hotspot location, is composed primarily of alkali picrite and basanite though it hosts some phonolitic lava ([Stroncik et al., 2008](#)). The Canary Islands more broadly are largely phonolitic, like the McDonald Islands.

Shallow hydrothermal systems directly affect ecosystem development due to localized acidification and are valuable proxies for how increased ocean acidity may affect benthic communities ([Hall-Spencer et al., 2008](#); [Kroeker et al., 2011](#)). Additionally, hydrothermal venting along mid-ocean ridges plays a large part in the ocean energy budget and elemental cycling ([Winckler et al., 2010](#)), however the contribution from shallow water hydrothermal systems to the global CO<sub>2</sub> budget is, like submarine methane contributions, not well constrained.

#### 4.2 Implications for Heard Island flares

The Heard Island flares may represent the first cold methane seep observed on the Kerguelen Plateau, and the second active methane seep discovered in the Southern Ocean to date ([Römer et al., 2014](#)). Unlike most other shallow cold methane seeps ([Dupré et al., 2014](#); [Gentz et al., 2014](#); [Römer et al., 2014](#); [Sahling et al., 2014](#)) the water column above the

Heard Island sites has persistent strong vertical mixing ([Park et al., 2008](#)) which could remove the usual biological and physical filters, without which methane gas may escape into the atmosphere. Greater depths and the presence of a pycnocline usually inhibits methane escape to the atmosphere (rising bubbles dissolve in the under-saturated water column or are consumed by methanotrophs) ([Gentz et al., 2014](#); [James et al., 2016](#)). In the presence of a consistent well-mixed water column for HRD1 ([Holmes et al., 2019](#)), assume the flares are dominantly methane, and assume that the gas rises higher than our sounders can observe, we can calculate a maximum estimate of possible methane contribution to the atmosphere. If we assume only ~10% of methane contained in a bubble will reach the surface from depths <100 m ([Leifer & Patro, 2002](#)), and assume an average rate of bubble release of one bubble sec<sup>-1</sup>, with seven discrete bubble release points (three seep groups and a quadruple seep), we estimate ~70 kg year<sup>-1</sup> of methane reaching the surface (methane density (3°C at 90 MBSL) = 7.07 kg m<sup>-3</sup> ([Medwin & Clay, 1997](#)), average bubble radius = 5 mm, initial mass of methane per bubble (≥ 90% methane) = 3.3 x 10<sup>-6</sup> kg ([Leifer & Patro, 2002](#)).

An extensive ice cap covered Heard Island, possibly the McDonald Islands, and some of the Central Kerguelen Plateau during LGM (Fig. 1b) ([Siddall et al., 2003](#); [Balco, 2007](#); [Hall, 2009](#); [Hodgson et al., 2014](#)). Under the thick grounded ice cap conditions favor the formation of methane hydrates. When deglaciation began after LGM, exposed hydrates would begin dissociating if above the gas hydrate stability zone (GHSZ). All of the reconstructed palaeo ice sheet margin sits at, or higher, than the ~300 m deep GHSZ thus we would expect to find evidence of methane hydrate dissociation over the ~9,600 km<sup>2</sup> inside the palaeo ice sheet margin ([Hodgson et al., 2014](#)). If we assume the same density of seeps as HIMI (seven discrete methane seeps in the hydroacoustically observed ~1,278 km<sup>2</sup>), as many as 50 additional sites may exist with the potential to contribute >500 kg year<sup>-1</sup>. While this low flux would not significantly influence the global carbon cycle, for example in comparison to

the East Siberian Arctic Shelf (0.9 Tg year<sup>-1</sup> Shakhova et al., 2014), the HRD seeps may have localized effects on atmospheric CO<sub>2</sub> drawdown or benthic habitat composition.

## 5 Conclusions

We observed 13 discrete seeps, observed as flares, at three sites proximal to the remote HIMI. This is the first scientific hydroacoustic survey of the region and the first indication of submarine gas emission on the Kerguelen Plateau. Based on hydroacoustic, geophysical, geochemical, and video results we conjecture that:

- (1) Heard Island flares potentially represent a previously unknown cold methane seep of possible combined biogenic and thermogenic origin, originating from thick sediment packages northeast of the island, with nearby onshore volcanism of Heard Island may be enhancing the maturation potential of sediment-hosted methanogens;
- (2) McDonald Islands flares potentially show evidence of submarine gas emissions associated with unconfirmed shallow diffuse hydrothermal venting, related to active intraplate hotspot volcanism on the island.

The Heard Island seeps may represent the second cold methane seep so far observed in the Southern Ocean. As the methane may not be readily confined within the water column, the Heard seeps may contribute a globally negligible, though locally significant, source of methane. If the McDonald Islands seeps represent hydrothermal-related gas venting, our dataset provides the first evidence of active submarine volcanism on the Kerguelen Plateau. The data expands our limited understanding of the submarine environment of HIMI and adds to the limited number of hot vents observed in shallow intraplate settings and on LIPs (Beaulieu et al., 2013).

Our study highlights the value of water-column hydroacoustic data for understanding seafloor processes and carbon cycling in the data-poor Southern Ocean and other unmapped or remote regions. Additional seeps may also be present elsewhere within the reconstructed ice sheet margin that covered HIMI and a portion of the Central Kerguelen Plateau during LGM. Extensive sedimentation and other zones of potential submarine volcanic activity on the Kerguelen Plateau means additional seeps or vents may lie outside the small survey zone proximal to the islands, warranting further study into the nature of gas/fluid exchange on the Kerguelen Plateau and LIPs generally. Future sampling efforts with a remotely operated vehicle (ROV) to obtain suitable gas tight samples, physical samples of yellow seafloor accumulations, or direct dissolved gas sampling with a towed vehicle or autonomous underwater vehicle would allow us to fully constrain gas composition, bubble release mechanisms, and quantify possible interaction with the atmosphere.

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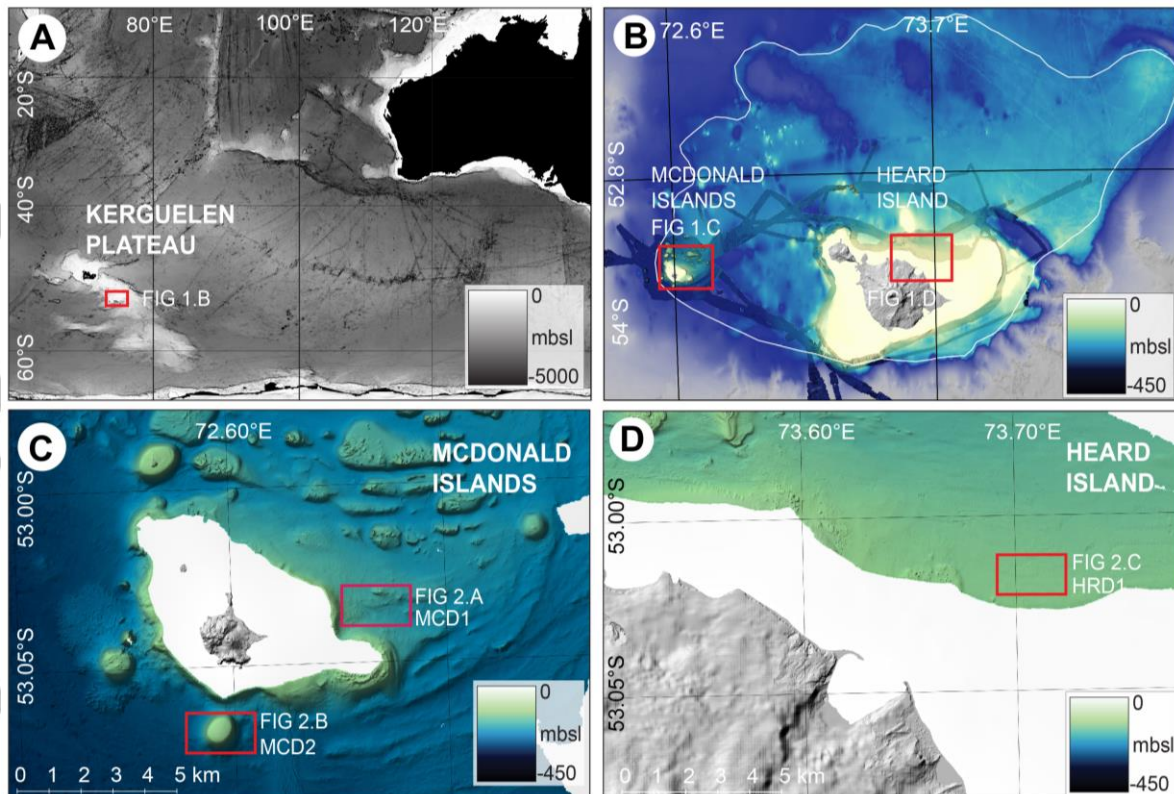
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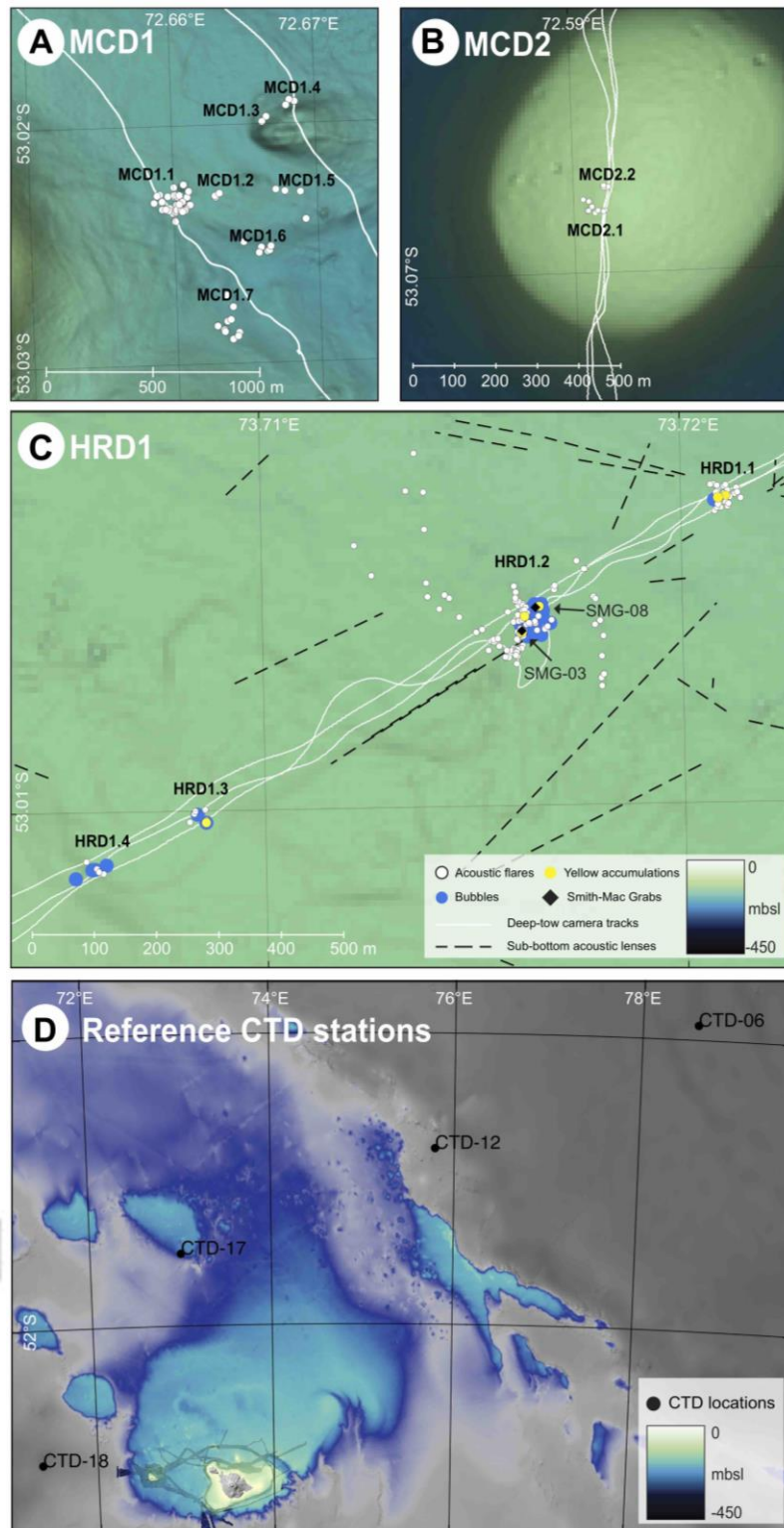
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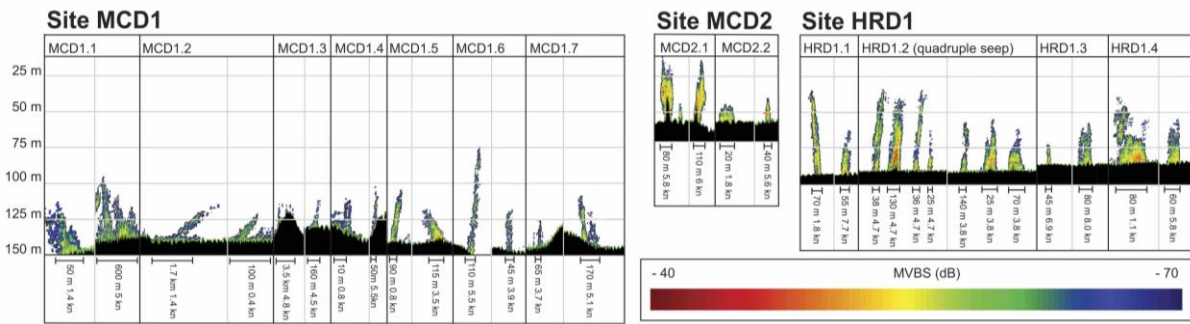


**Figure 1.** Maps of (a) the Kerguelen Plateau (30 arc-sec bathymetry *GEBCO\_2014*); (b) Central Kerguelen Plateau, with Heard Island and McDonald Islands (HIMI) showing palaeo-ice sheet margin (white line) (100 m bathymetry (*Beaman & O'Brien, 2011*)); (c) McDonald Islands study sites MCD1 and MCD2; (d) Heard Island study site HRD1. (c) and (d) 10 m bathymetry from *IN2016\_V01 EM710* multibeam echosounder.

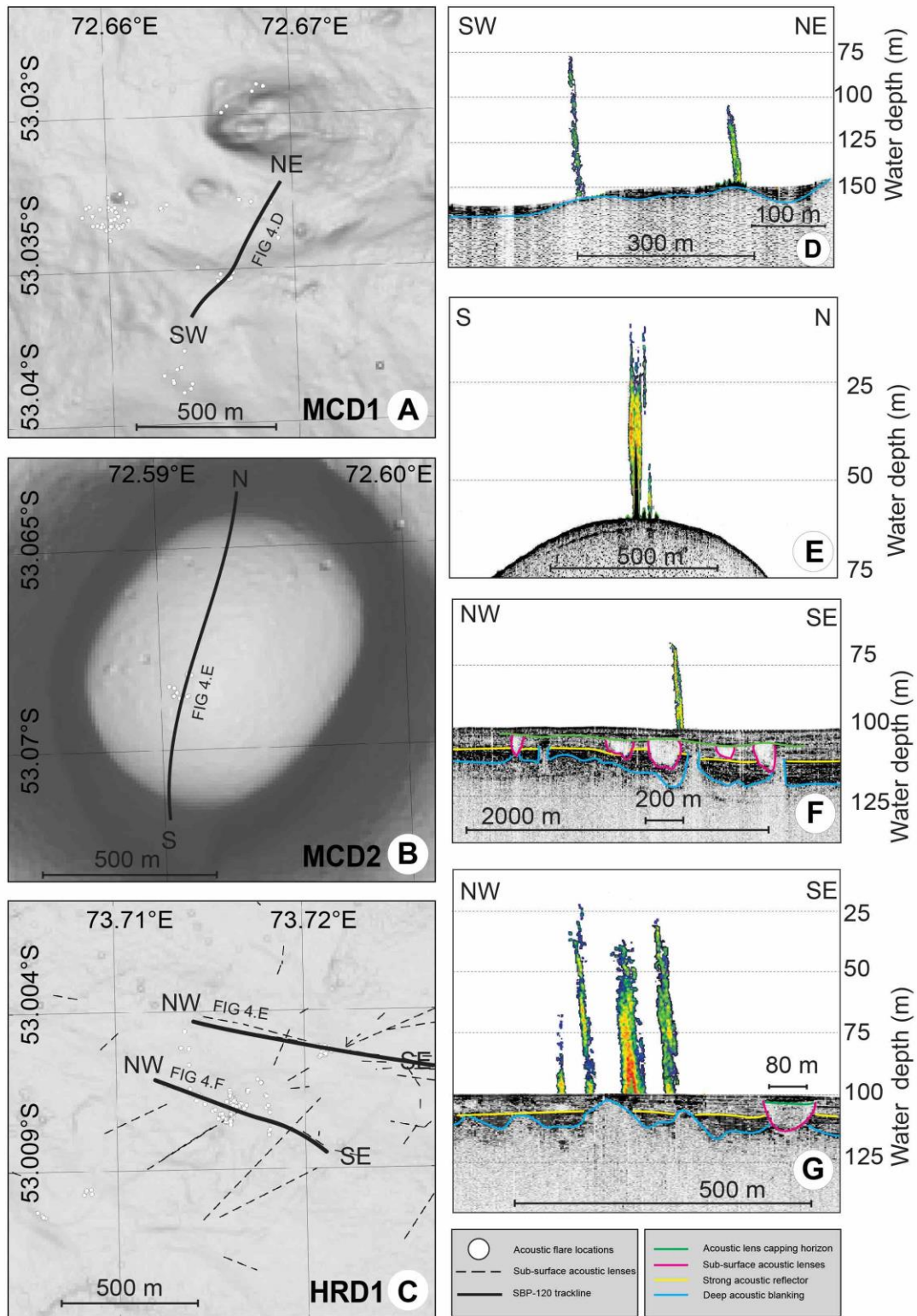
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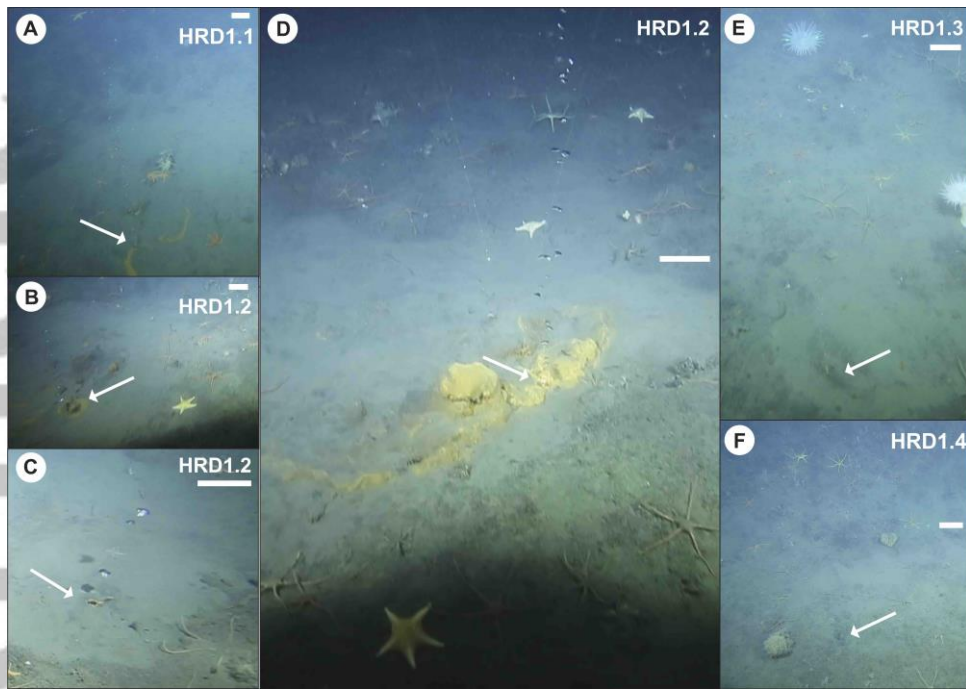
**Figure 2.** Sample locations (a) MCD1, (b) MCD2, (c) HRD1, with observed flares, bubbles, yellow matter, and SMG sample sites. (d) map of 4 CTD casts analyzed for background helium isotopes spanning the Kerguelen Plateau north of HIMI. Color bar applies to all maps.



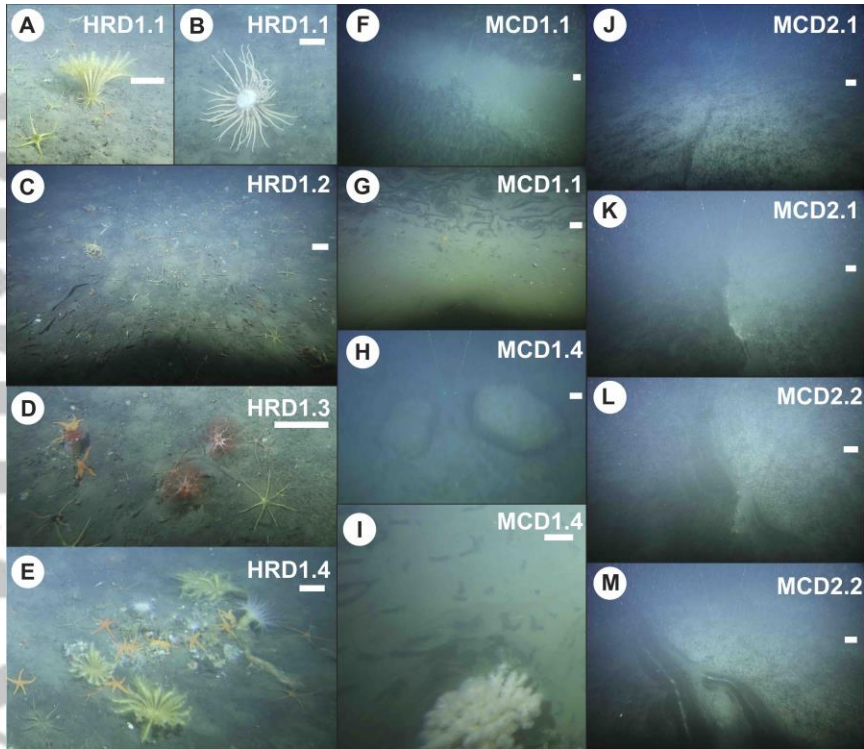
**Figure 3.** Compilation of flares observed at the three sites (MCD1, MCD2, and HRD1). Vertical axis is water depth, 25 m intervals; horizontal axis is calculated from time (UTC) and average ship speed. Top 10 m of water and all data below the seafloor are removed (black areas). Flares are colored by mean volume backscatter strength (MVBS; acoustic intensity, dB), red the highest (-40 dB) and blue the lowest (-70 dB). All flares have been cleaned, threshold filtered, and resampled in Echoview.



**Figure 4.** Plan view of three sub-bottom profile lines at (a) MCD1, (b) MCD2, and (c) HRD1. Sub-bottom shown in (d) MCD1, (e) MCD2, (f) and (g) HRD1, with EK60 flares overlain. Vertical axis is depth, calculated from two-way travel time (assuming constant sound speed of  $1500 \text{ m s}^{-1}$  applied to the SBP120).

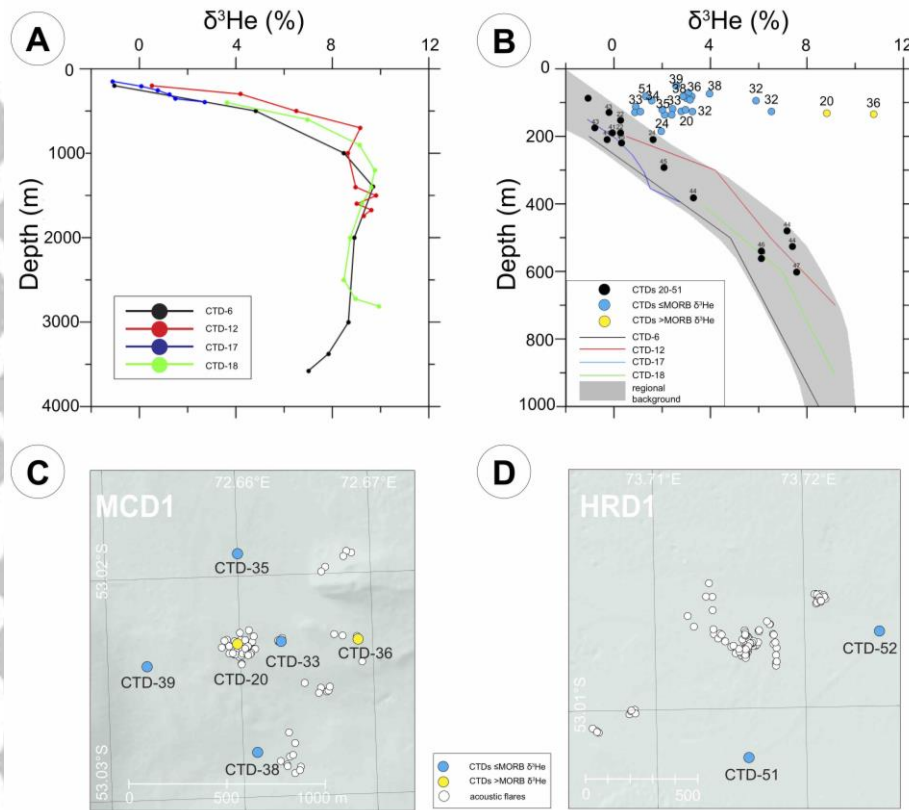


**Figure 5.** Photographs from HRD1; (a) and (b) have consistent bubble streams; (c) a small seep, with larger (~1.5 cm) wobbly, oblate bubbles; (d) the largest extent of yellow accumulations, ~40 cm long; (e) and (f) are thinner streams, with no obvious yellow matter. White scale bars are 10 cm long at the seafloor. Camera tows and observed bubble locations are shown in Fig. 2.

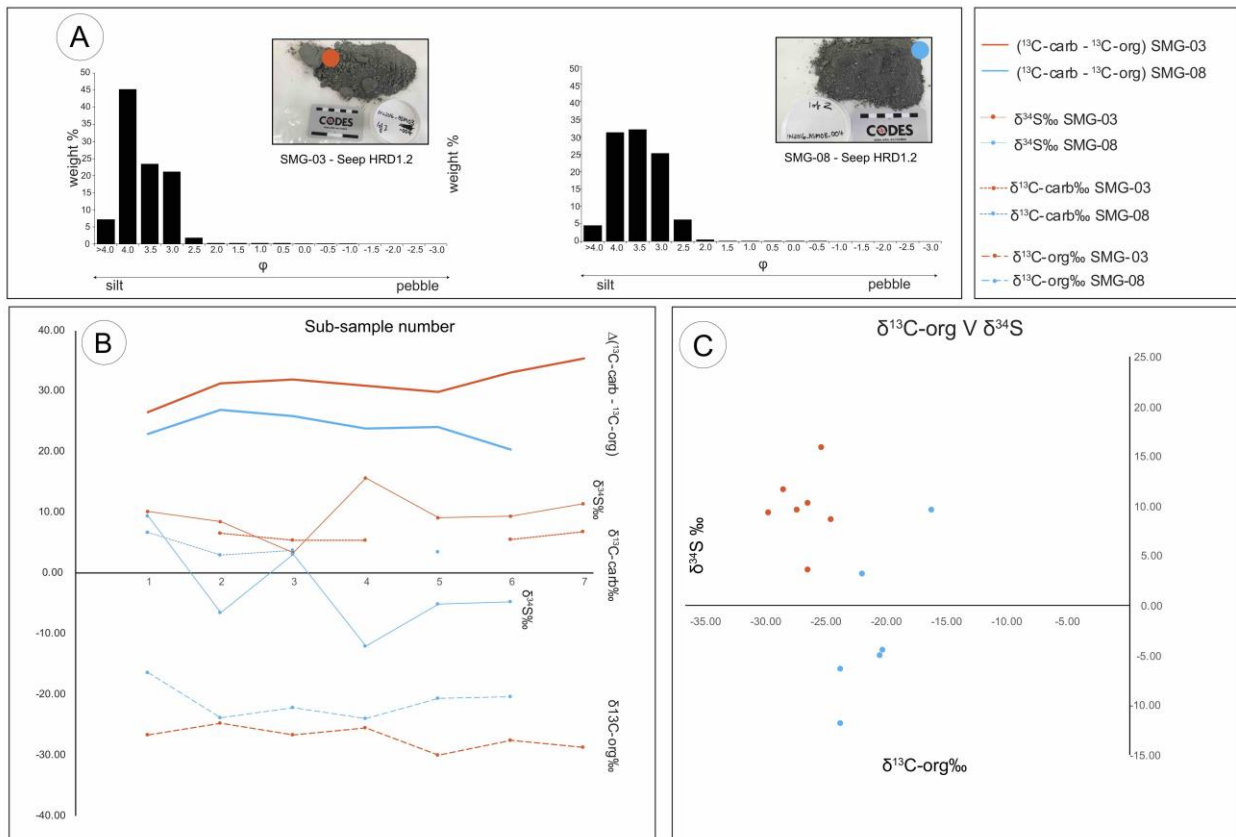


**Figure 6.** Photographs from HRD1 (a-e) show a variety of benthic species; MCD1 (f-i) shows disturbed sediment, ripples and limited benthic species; and, MCD2 (j-m) show -20 cm wide and tens of meters long marks on the seafloor, with no benthic species. White scale bars are 10 cm long at the seafloor. Camera tows are shown in Fig. 2.

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**Figure 7.** (a) Profiles of background  $\delta^3\text{He}$  vs. depth at four locations on the Central Kerguelen Plateau (see Fig. 2d). The four profiles are similar to those found throughout the southern Indian Ocean; (b) Plot of  $\delta^3\text{He}$  vs. depth for shallow samples collected at flare sites on the flanks of HIMI. Small numbers are the ship CTD casts. Solid lines are  $\delta^3\text{He}$  profiles from the Kerguelen Plateau (Fig. 2d and Fig. 7a). Shaded area shows regional background based on the Kerguelen Plateau profiles. Several shallow samples show  $\delta^3\text{He}$  in excess of regional background and  $\leq$ MORB (blue dots); two samples show  $\delta^3\text{He} >$ MORB (yellow dots), unambiguous evidence for local input of  $^3\text{He}$ -rich fluid or gas. (c) Map of MCD samples with  $\delta^3\text{He}$  above regional background (blue dots), samples with  $\delta^3\text{He} >$ MORB (yellow dots), and flare bases (white dots). (d) Map of HRD samples with  $\delta^3\text{He}$  above regional background (blue dots) and flare bases (white dots).



**Figure 8.** (a) Grain size analysis and photographs showing different seafloor sediments for SMG-03 (orange) and SMG-08 (blue) sites. CODES scale bar, top: 1 cm increments; bottom: 1-inch increments; (b) seven sub-sample analyses comparison showing discrete values: SMG-03 and SMG-08 for  $\delta^{34}\text{S-CDT}\text{‰}$  (Cañon Diablo Troilite standard),  $\delta^{13}\text{Ccarb-PDB}$  (Pee-Dee Belemnite standard), and  $\delta^{13}\text{Corg-PDB}$  (Pee-Dee Belemnite standard); (c) Plot of  $\delta^{13}\text{Corg}\text{‰}$  versus  $\delta^{34}\text{S}\text{‰}$ .

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