RV *Investigator* Voyage Plan

Voyage #:	**IN2016_V01**		
Voyage title:	HEOBI: Heard Earth-Ocean-Biosphere Interactions		
Mobilisation:	Fremantle, Wednesday, 6 January- Thursday, 7 January 2016		
Depart:	Fremantle, 0800 Friday, 8 January 2016		
Return:	Hobart, 0800 Saturday, 5 March 2016		
Demobilisation:	Hobart, Sunday, 6 March 2016		
Voyage Manager:	Brett Muir	**Contact details:**	brett.muir@csiro.au
Chief Scientist:	Professor Millard (Mike) Coffin		
Affiliation:	Institute for Marine & Antarctic Studies, University of Tasmania		
Contact details:	mike.coffin@utas.edu.au		

Scientific objectives

Iron supply limits oceanic primary production in the Southern Ocean as well as elsewhere in the global ocean. We aim to test the hypothesis that hydrothermal activity driven by active submarine magmatism fertilises surface waters with iron thereby enhancing biological productivity. Heard and McDonald Islands on the Kerguelen Plateau are among the world's most active hotspot volcanoes, and are type examples sourced from a particular geochemical component in the Earth's mantle (enriched mantle 1, or EM1). Existing data indicate that fields of submarine volcanoes extend for several hundred kilometres away from the islands.

We will produce three-dimensional, high-resolution bathymetric, backscatter, and sub-seafloor maps of the seafloor surrounding the islands in near-real time. From this mapping and data from geotagged seals indicating locations of anomalously warm bottom water, together with deep tow camera imaging and TRIAXUS sensor data, we will identify candidate active submarine volcanoes and hydrothermal systems, and sample these volcanoes and their surrounding shallow sediments. In the water column over and downstream of these active volcanoes/hydrothermal systems, we will measure temperatures and obtain water samples for geochemical and biogeochemical analyses that will indicate the presence or absence of associated hydrothermalism and iron and other elemental enrichment. We will also sample the deep boundary current that impinges on the eastern flank of the Plateau, to investigate the generation of internal waves that enhance mixing of surface and subsurface waters, providing a mechanism to deliver iron enriched waters to the surface downstream of the volcanoes. If hydrothermally derived iron and other micro-nutrients are ascending to surface waters, we will compare our data to contemporaneous shipboard and satellite-derived estimates of phytoplankton productivity and biomass to test for positive temporal and spatial correlations.

Should it be proven that hydrothermally derived iron exerts controls on the dynamics of plankton blooms, this will be the first demonstration of linkages between dynamic solid Earth processes (magmatism) and major biological processes (oceanic primary production). Plankton blooms, in turn, affect the biogeochemical cycles of carbon, nitrogen, silicon, and sulphur, and ultimately influence the Earth's climate system. Our results could therefore open significant new avenues of research in the solid Earth-Earth's biosphere domain, including investigations of both past (e.g., oceanic anoxic events) and future (e.g., high atmospheric CO_2) extreme Earth environments.

Voyage objectives

Seafloor and subseafloor mapping/geophysical characterisation

Continuous mapping will be carried out using the multibeam systems, multi-frequency split-beam echosounders, sub-bottom profiler, gravimeter, and (on long transits between ports and the study area) magnetometer to characterise bathymetric features and identify those most likely to include volcanic or hydrothermal activity. XBT or CTD data will be acquired at standard intervals for sound velocity corrections to the multibeam data. The data will be initially processed at sea to inform site selection for volcanic and hydrothermal sampling.

Nature of submarine volcanoes and hydrothermal systems

Dredges near fields of sea knolls have yielded volcanic rocks with ages as young as 30 ka, suggesting that the features are recently active or active volcanoes. Data from geotagged seals suggest that some of the volcanoes have active hydrothermal systems. These prospective active submarine volcanic fields are up to 300 km from active subaerial hotspot volcanoes (Heard and McDonald Islands). The suspected broad temporal and spatial distribution of active volcanism on the Plateau will be used to test current mantle plume or lithospheric convection models.

We will characterise the spatial distribution, morphology, and geology of active submarine volcanoes and hydrothermal systems. Initial characterisation will be undertaken using multibeam and multi-frequency split-beam echosounder data; prospective active hydrothermal systems identified from these data will be imaged using the deep tow and/or multicorer camera, and if active, we will sample the volcanic edifices hosting these systems by dredging/coring/sticky wax cores.

Detailed characterisation will involve sampling of:

- hydrothermal fluids and gases to illuminate the origin, nature, and chemistry of hydrothermal inputs to the ocean, and to determine the depths of volatile formation and release. Ideally, these fluids and gases will be sampled using gas tights.
- rocks from active volcanoes and near hydrothermal vents to reveal eruption type and process, geochemistry, and age. These rocks will be initially described on the ship and then archived for shore-based studies including petrology, geochemistry, and geochronology. If rocks prove challenging to dredge, sticky wax cores will be used to retrieve surficial glass from lavas.
- sediment cores (multicorer, box corer, gravity and piston cores) on volcaniclastic aprons to evaluate the timing and geochemical evolution of active submarine volcanic fields. The multicorer will have a payload that includes a down-looking camera. This camera will facilitate observing the seafloor prior to multicoring, box coring, and/or gravity/piston coring. The multicorer and box corer can be used for <1 m sediment cores, gravity and piston cores can penetrate deeper. For reconstructing past hydrothermal activity from sediment archives, it will be important to collect cores encircling any identified active hydrothermal systems, sampling all sectors. The cores will be split, stratigraphically logged, and smear sampled for volcanic ash layers, which will inform future environments/locations for coring operations. The split cores will then be stored in the refrigerators.

Detecting hydrothermal inputs to the ocean, and vertical water movements that deliver them to surface waters

On first approach to the Plateau, we will conduct a transect from ocean basin waters, onto the base of the Pleateau flank, and up onto the crest of the Plateau, repeating the KEOPS 'B' transect. This full-depth CTD/LADCP/TMR transect will capture cross-shore gradients in water properties and detect the export of hydrothermal minerals and elements in the Deep Western Boundary Current (DWBC) that scours the eastern side of the Plateau. The DWBC impinges on the rough bathymetry of the Plateau, generating internal waves that propagate upward and mix the water column when they break. We will determine whether this vertical transport mechanism plays a significant role in delivering enriched waters to the surface, to supply the high productivity seen northeast of the plateau in ocean colour images. This transect will also cross a high biomass, elongated feature to the north of Heard Island that may be stimulated with iron supplied by hydrothermal activity.

The cross-shore transect will also contribute to a four-ship, multi-national, simultaneous survey of the DWBC that carries Antarctic Bottom Water (AABW) northwards along the eastern flank of the Kerguelen Plateau to ventilate the bottom waters of the global ocean. This collaboration presents an extraordinary opportunity to measure the modification of AABW along its path between 142°E and Heard Island, and to determine the extent of warming and freshening of AABW since the last occupation in this region around 2003. *Aurora Australis* (K-axis) will sample east of Banzare Bank; the US will occupy the repeat hydrography line I8S, sampling across the Princess Elizabeth Trough; a Japanese vessel will sample near 110°E; *Aurora Australis* sampled the DWBC in the Australian occupation of the repeat line SR3 in January 2015.

Following the transect, a broad-scale survey over the platform containing Heard Island and McDonald Islands will be conducted. Simultaneous with multibeam mapping, multi-frequency split-beam echosounding, and sub-bottom profiling in the study area, we will 'fly' the TRIAXUS, either at approximately 100 m depth on the Heard Island-McDonald Islands platform (HIMIP) where water depths average 200 m, or at several hundred meters depth (below the ~200 m depth of the winter surface mixed layer to avoid convolving meteorological and biological effects on temperature, salinity, particle, and gas signatures). The minimum sensor configuration of pressure, salinity, temperature, oxygen (which has the strongest vertical gradient in the system), combined with shipboard ADCP observations to determine horizontal currents and detection of internal waves and mixing from a new analysis technique, will allow evidence of uplift or mixing driven by hydrothermalism or other processes (internal waves, bottom-stress, eddies) to be examined. This broad-scale survey will be placed in the context of the CTD/LADCP/TMR transect. The survey and transect together will deliver advances to physical and biogeochemical oceanographic understanding of deep-surface exchanges even if no hydrothermal features are found.

High-resolution model simulations, ~1 km spatial resolution, will be performed on board to assist in determining the path of iron-rich plumes from the hydrothermal vents. These simulations will be performed using the Regional Ocean Modeling System (ROMS) with realistic bathymetry, hydrography and forcing. Bathymetry will be taken from the multibeam observations on-board in addition to existing observations. Data from the shipboard ADCP, CTD, LADCP, TRIAXUS, underway data, and satellite imagery for the SST will be used for initial conditions. Mean currents, tides, and winds will be included for forcing, with the wind velocities taken from the ship meteorological data. This was previously done to a lesser extent on IN2015_v03. This is feasible, as the model has repeatedly performed well simulating tidal and mean currents in many domains. Information on the location, volume and temperature of a hydrothermal source can be incorporated into the simulations to predict dispersal of the associated hydrothermal plume. Since these values are not well known, multiple simulations will be performed to represent different strength plumes. A Linux computer will be brought along for this purpose. Better prediction of downstream plumes from hydrothermal vents will allow more efficient water column sampling.

The MNF particle backscatter sensor will allow particle fields such as those formed by hydrothermal vent 'smokers' and/or resuspended sediments to be localised. We will add additional sensors (including Eh meter, nephelometer, transmissometer) to bolster this capability to distinguish these two sources - on the towed body if it can accommodate the payload, or on the CTD. We are also working with NOAA-PMEL to deploy Oxidation Reduction Potential (ORP) sensors on the TRIAXUS and the CTD, reporting back in real-time, as well as a Miniature Autonomous Plume Recorder (MAPR) on *in situ* pumps and deep tow camera. MAPR is a self-contained instrument for recording light-backscattering (for suspended particle concentrations), oxidation-reduction potential (ORP, for detecting the presence of reduced chemical species such as H_2S and Fe^{2+}), temperature, and pressure (http://www.pmel.noaa.gov/eoi/PlumeStudies/mapr/). A miniaturized sampler (MINIMONE provided by Kochi University, Japan) will be used to collect samples from the TRIAXUS and deep tow camera for measurements of possible hydrothermal waters (both on-board – O, Si, Fe, Mn, and in Hobart – Mg/Ca).

Using a combination of CTD, a trace metal rosette (TMR), *in situ* particle (ISP) pumps, and sampling of the ship's trace-metal clean seawater supply, we will collect clean samples for shore-based analysis ($^3He/^4He$ anomalies, microscopic mineralogy, rare earth elements, macro-nutrients, Fe, Mn, dissolved and particulate elemental ratios, X-ray synchrotron mineralogy of particles, and other hydrothermal signatures). Dissolved Fe, Mn and Fe(II) will be determined at sea by flow injection analysis in samples taken from the TMR and the underway clean surface seawater intake (if shown to be clean on the transit to Heard). Samples will also be taken for Fe isotopic analysis (which is capable of distinguishing hydrothermal from background deep ocean Fe sources). Dissolved and particulate trace elemental subsamples will also be archived for ashore analysis by seaFAST-ICPMS. At sea measurements will also include microscopic examination of particles to look for hydrothermal minerals and volcanic glass fragments, and possibly dissolved gases indicative of high temperature water-rock interactions (CH_4, H_2S). We will also collect aerosol samples for trace elements to constrain the atmospheric delivery of iron and compare to sub-sea sources.

Detecting impacts on surface phytoplankton production

During the underway mapping we will continuously operate sensors to measure biological activity (fluorescence for phytoplankton abundance, fast-repetition-rate fluorescence for phytoplankton photosynthetic competence, transmission for total carbon biomass, and O_2/Ar ratio mass spectrometry for net community production). The sensors will be augmented by underway sampling for phytoplankton pigments, particulate organic and inorganic carbon, biogenic silica, heterotrophic bacterial responses, and microscopic phytoplankton identification to characterise community structures, and ^{15}N measurements to identify the extent of nitrate versus ammonium metabolism – a key indicator of ecosystem Fe stimulation capable of additional carbon sequestration. Above and downstream of active hydrothermal systems, we will obtain samples for further analyses ashore. We also intend to carry out deckboard micro-nutrient enrichment incubation experiments to ascertain the biological response of hydrothermal iron to surface phytoplankton communities. Deployment of a bio-optical sensor package after each CTD deployment will provide measurements to link these communities to satellite images.

Ocean circulation around Heard Island and across the eastern Indian Ocean sector of the Southern Ocean

The shipboard ADCP and all available underway systems (thermosalinograph, meteorology, and biogeochemical systems) will be run at all times. These data will add valuable *in situ* observations of the physical and biological structure of upper-ocean currents around Heard and between Heard Island and Australia, including the outgoing and return transits across the Antarctic Circumpolar Current fronts. *In situ* validation of satellite measurements in this region is rare and highly valuable. We will seek contributions of autonomous instruments to deploy on the voyage to provide more detailed sampling of the circulation. We have contacted the Global Surface Drifter Program run by NOAA, and the Australian office of the International Argo Program.

The lowered ADCP will be used at every CTD station to measure full water column velocity. New processing methods also allow the detection of internal waves and mixing using a shear-strain parameterisation, even in shallow waters. The shipboard ADCP will provide upper ocean currents, as well as detection of internal waves and mixing, in the upper ocean between stations. Thus we will be able to build a spatial view of the horizontal and vertical circulations across the Plateau that uplift hydrothermally-sourced fluid, mix it, and carry it away from the Plateau.

Microbial response and bacterial processes

Objective 1) What is the response of the microbial community to iron and organic carbon availability in different zones of the Southern Ocean, with focus on the possible impact of hydrothermal activity.

More specific question: How does iron and carbon limitation affect heterotrophic bacterial respiration and growth efficiency, and its diversity?

Methodologies:

a) Underway measurements (O_2/N_2) using a GTD gas tension device
b) Underway or CTD sampling for incubations for net community production and community respiration during 24 hour incubations.
c) Underway or CTD sampling for microbial diversity and dissolved organic matter (DOM) composition
d) Dose addition experiments (+Fe, +C) combined with bacterial respiration & production measurements.

Objective 2) What is the role of particle-attached bacteria in rendering iron bioavailable?

Methodology:

Incubation experiments with particles from ISP, incubated in dialysis bags, and natural bacterial communities.

Analyses planned at sea:

a) NCP net community production and CR community respiration
b) bacterial production
c) Analyses planned ashore:
d) flow cytometry (available mid-2016)
e) bacterial diversity (available 2017)
f) FT-ICR-MS (Fourier transform ion cyclotron resonance) on concentrated DOM (available 2017)
g) DOC dissolved organic carbon and DON dissolved organic nitrogen (available mid-2016)

Operational Risk Management

No potentially high risk operations have been identified to date.

Overall activity plan including details for first 24 hours of voyage

Outward transit from Fremantle to the Heard Island study area (1986 nm) is estimated to range from 6.9 days @ 12 kts to 8.3 days at 10 kts (Figure 1).

Return transit from the Heard Island study area to Hobart is estimated at 10.1 days at 12 kts.

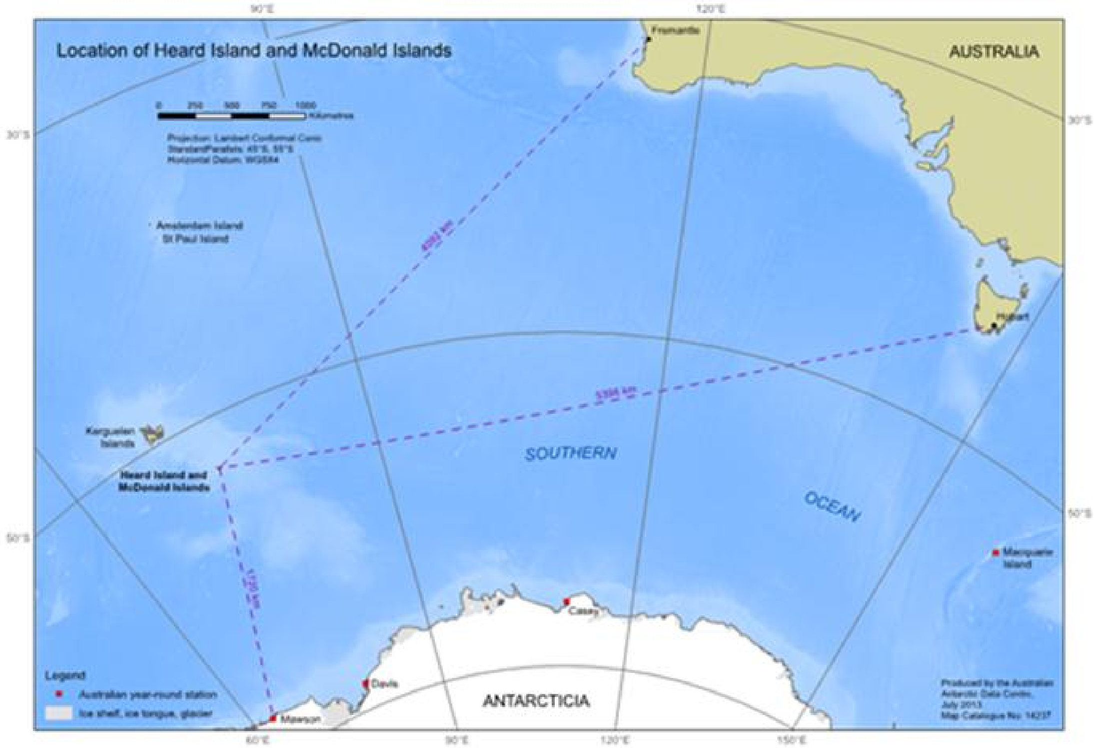


Figure 1. Great circle transits between Heard and McDonald Islands, and Hobart (5398 km) and Fremantle (4092 km).

Activities for the first 24 hours at sea will be limited to underway geophysics: multibeam sonar; multi-frequency split-beam echosounding; sub-bottom profiling; gravity; and magnetics. During the first 24 hours at sea we will transit over one of two approved 2017 International Ocean Discovery Program Expedition 369 drill sites, either MBAS-9A (33°16.1886'S, 114°19.3668'E) or MBAS-8A (33°04.9320'S, 113°04.8444'E), acquiring requisite multibeam sonar data.

After the first 24 hours along the transit, we will conduct two sets of operations, to test our equipment and to practice coordination across the project/MNF/ship's staff, by carrying out the following activities. The final locations of these two Test Sets, along or very close to the transit line, will be determined by satellite altimetry and ocean colour maps.

Test Set 1:

While still north of the Subtropical Front (STF) in preferably calm seas and clear skies

On ~Day 3 (~ 43°S, 90°E)

08:30am - 11:30 am: Deploy the CTD/LADCP to 2000 m: verify Niskin closures, and sensor logging and display (T, S, O_2, transmissometer, fluorometer, PAR photosynthetically active radiation). Verify LADCP data are collected and all heads are operating correctly. Collect samples for analysis by hydrochemistry (salts, O_2, nutrients), and for filtration by project team for pigments and particulate organic carbon (POC) and particulate biogenic silica (BSi). At same time collect these same samples from clean seawater supply for verification that underway pumping system is working correctly. Depending on results, possibly repeat.

11:30-12:30: Break

12:30-13:30: Deploy trace metal rosette (TMR) to 300 m to test operation and clean Niskin bottles.

14.00-15.30: Deploy one ISP to test deployment procedure.

15.30-16.00: Deploy the bio-optics instrument package (Hydroscat multi-frequency backscatter sensor; AC-9 multi-frequency absorption meter, and spectral radiometer) from the core boom to 150 m depth. These instruments provide a connection between the particulate fields (pigments, POC, BSi) and optical properties measured by satellite. That connection will allow the ship observations of potential hydrothermal influences on biological responses to be extended in time using satellite observations.

16:00: Deploy a Aus-India Bio-Argo float. Deploy a pair of NOAA Drifters.

16:15 Move the ship forward 1 nm to get away from the float, deploy the TRIAXUS, and begin oscillating flight surface to 200 m. Verify sensor logging and display (T,S, O_2, FIRe variable fluorescence, SUNA nitrate, PAR, possibly MAPR miniature autonomous plume recorder and MINIMONE units). Recover if modifications needed, otherwise tow for 24 hours at 9+ kts to verify mission and logging persists correctly.

Day 4:

1300 (or later) Recover TRIAXUS - after we have transited southward across the STF. This may require continuing to tow TRIAXUS until Day 5 depending on frontal structure at the time. We will optimize the start and end of the tow based on satellite data received before departure from Fremantle and updates from shore support at UTAS. This may require provision of additional email file transfers to the Chief and Co-chief scientists.

1330 Repeat 2000 m CTD, Repeat Bio-optical cast, Deploy another Aus-India Bio-Argo float. Continue transit. Deploy a pair of NOAA Drifters.

It is important to do Test Set 1 early in the transit so that any problems can be worked on before arrival in the study area. Doing it at the Subtropical Front provides synergies to the Aus-India Bio-Argo project. The hourly timings are designed to give both ship watches experience with the operations, (and to carry out the bio-optical cast close to the optimal time of local noon).

Test Set 2

On ~Day 8 (~ 48°S, 80°E)

In a region of high biomass near the Polar Front in the region east of the Kerguelen Isles (Figures 2a, 2b), to give us bio-optical and biogeochemical results for biological responses to the overall Fe inputs from the northern Kerguelen Plateau, for comparison to biological characteristics local to any hydrothermal inputs we encounter later.

Repeat all of Test Set 1. Deploy a SOCCOM float

Deploy trace metal rosette (TMR) (two hours) and 1-2 ISPs (two to three hours) to collect water for trace metal micronutrients in waters that receive elevated iron from the northern Kerguelen Plateau.

Then remove FIRe instrument (200 m rated) from TRIAXUS, and begin test oscillations to 350 m to get experience with deep flying for hydrothermal plume detection, including optimal ship speed.

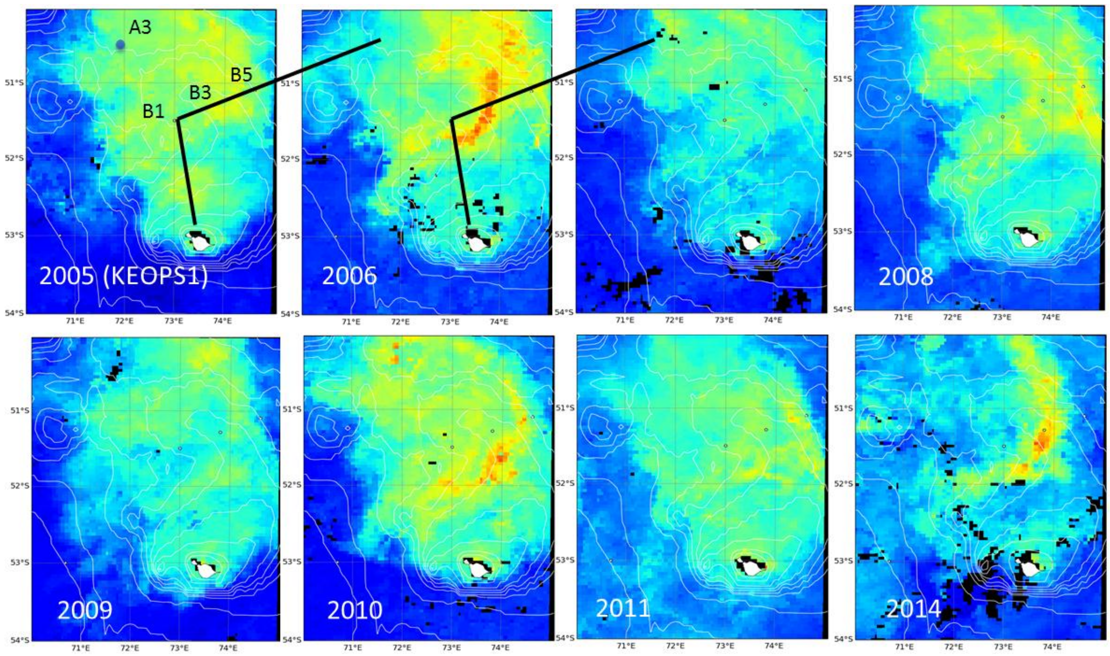


Figure 2a. Satellite images (MODIS 4 km resolution) of the region north of Heard Island between 25 January and 26 February over the past decade.

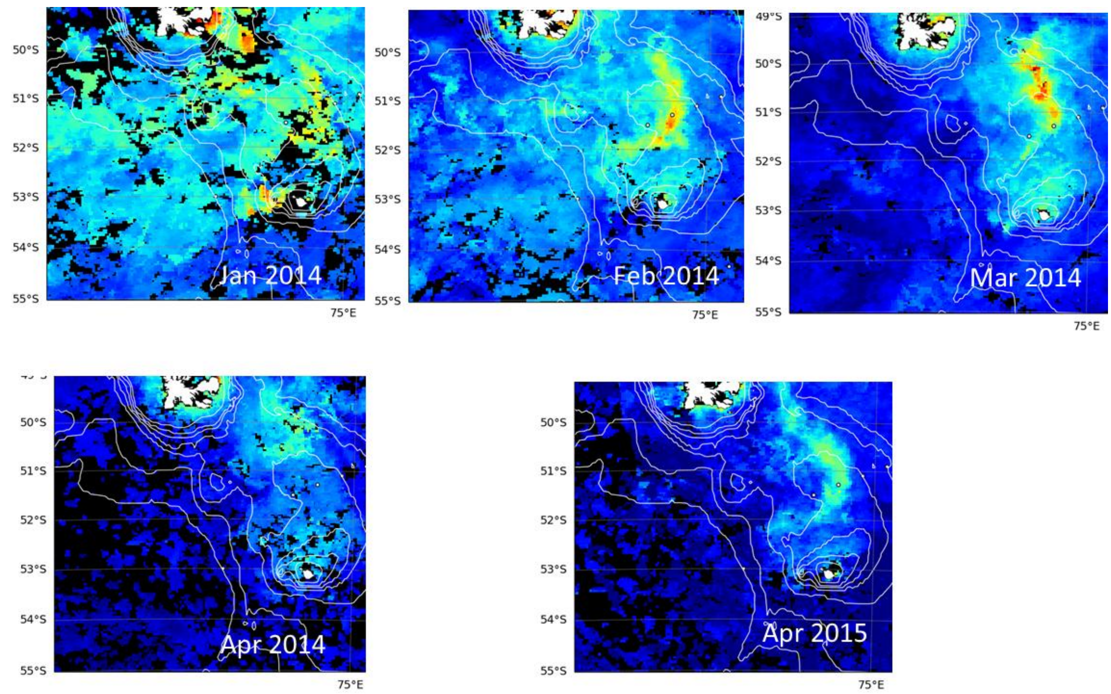


Figure 2b. Satellite images (MODIS 4 km resolution) of the region north of Heard Island between January and April 2014.

We require one “reference” station (0.5 days) in deep waters that are not fertilised with Fe from the Plateau or hydrothermal activity. Ideally this will be in high-nutrient, low-chlorophyll (HNLC) water upstream (west) of Heard Island, but due to the extra shiptime needed to achieve this, we may choose a reference station in deep HNLC waters far to the east of Heard Island. Stations ‘Hippies C1’ (49.9057 S, 78.5758 E) or ‘KEOPS B11’ (50.4983 S, 77.0017 E) on the transect onto the Plateau (see below) may be suitable locations, otherwise we will choose another site at sea. One TMR, CTD/LADCP and suite of ISPs will be deployed at this station (expected station time = 12 hours).

We will also deploy 20 NOAA surface drifters in pairs during the voyage. These drifters can be deployed over the side of the ship while the ship is moving at full speed. About half will be deployed along the transit to the Heard Island region and the other half over HIMIP to aid in understanding the currents in the region.

<u>Proposed plan in study region</u>

Phase 1: “TRANSECT”

Following transit to the study area (Figure 3), we will initially undertake the NE-SW cross-shore transect for physics/biogeochemistry (across the DWBC) from waters offshore and to the northeast of Shell Bank (~3500 m) onto the shelf-break (~1500 m) (Figures 4a, 4b and 4c). Station time required = 56 hours (2.5 days). This transect will continue along the southwesterly part of the KEOPS-1 ‘B’ transect and into shallow waters (~500 m) around Heard (Figure 4d). CTD/LADCP and TMRs will be deployed along the transect (CTDs at all stations and TMRs at the KEOPS ‘B’ stations plus Hippies ‘C1’). The TRIAXUS may be deployed between these transect stations, depending on the maximum towing speed of the TRIAXUS and steaming time between stations.

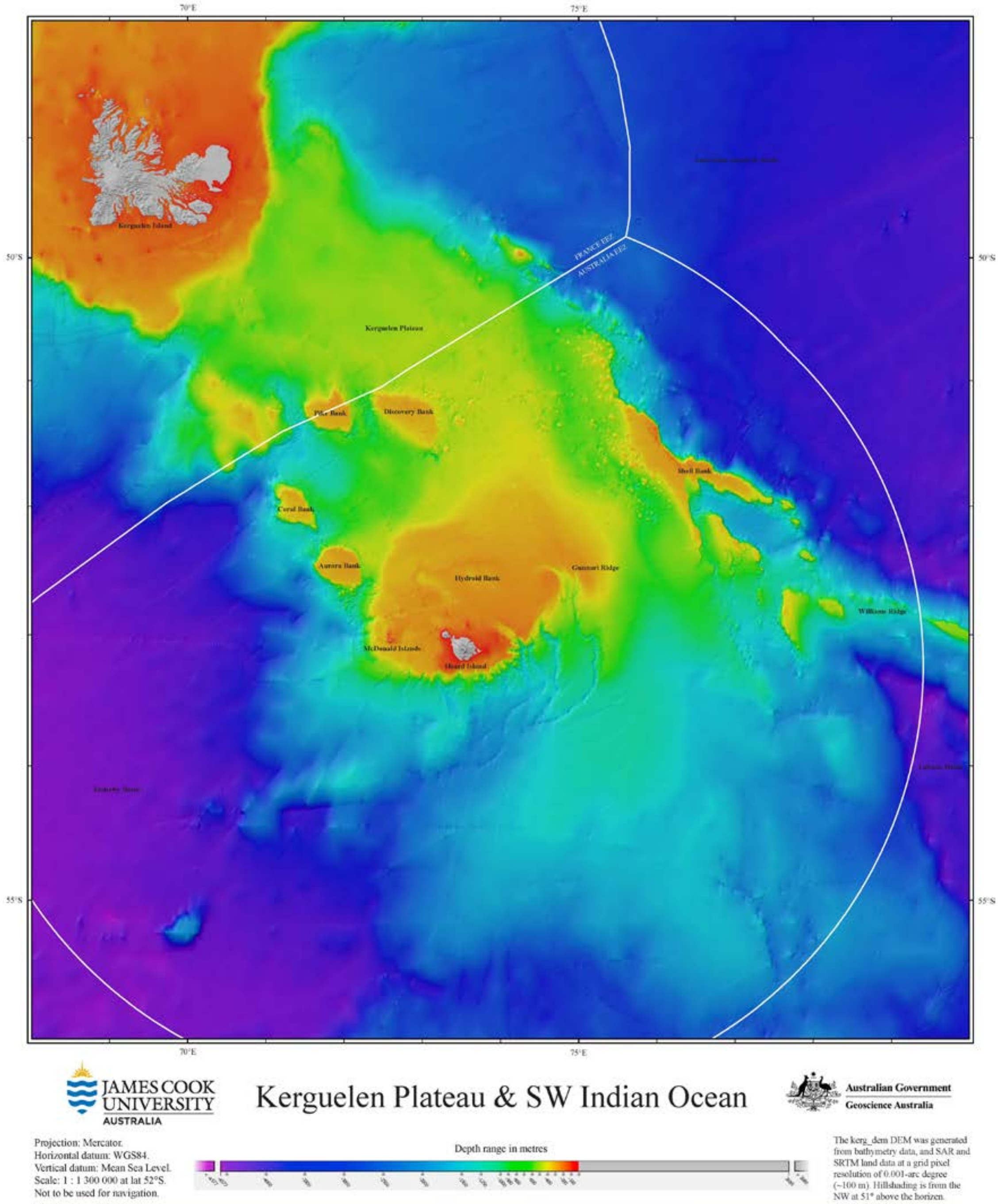


Figure 3. Highest resolution Kerguelen Plateau bathymetry currently available (Beaman and O'Brien, 2011).

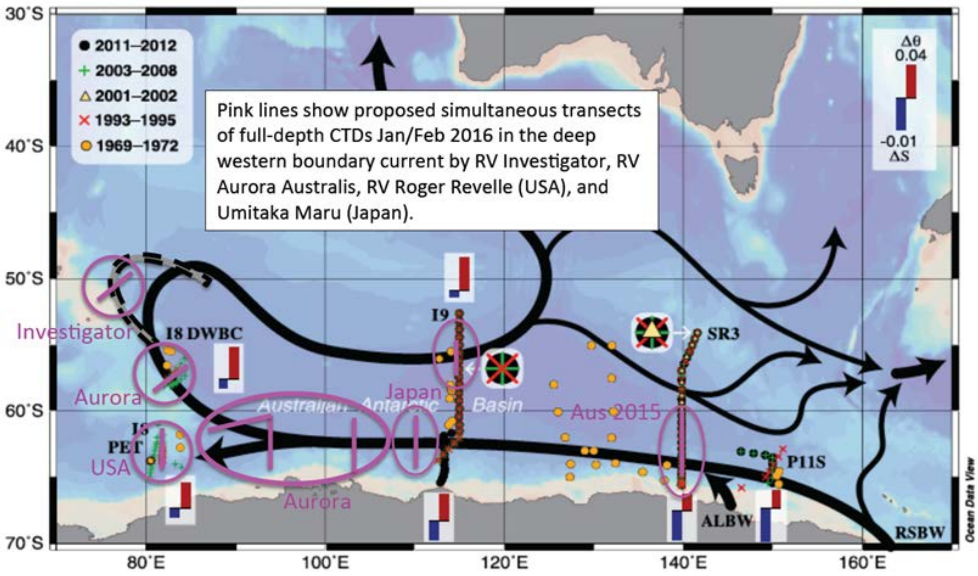


Figure 4a. Schematic of the Antarctic Bottom Water export pathways through the Australian-Antarctic Basin, with planned simultaneous transects of CTDs in early 2016 shown as pink lines.

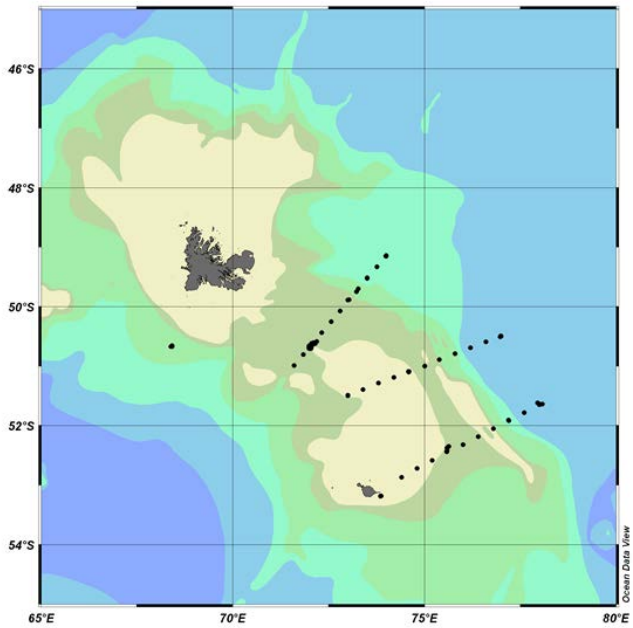


Figure 4b. Transects occupied during the KEOPS-1 voyage. We will repeat the middle line (transect B) as an extension of our transect across the DWBC (see Figure 4c).

Figure 4c. Transect for CTDs and TMRs on the approach to Heard Island on HEOBI plotted on predicted bathymetry (from Smith and Sandwell, 1997). Contours are every 200 m to 1000 m, and every 500 m in deeper waters. The two deep KEOPS positions overlap with the eight DWBC positions. This will enable us to cross the DWBC and trace the distributions of iron-enriched waters close to Heard Island towards the northeast (across Gunnari Ridge, the northern Shell Bank, and the shelf-break, and into open Southern Ocean waters). Colour coding is: KEOPS Line B stations (pink circles), Hippies Line C offshore station (green circle), and HEOBI transect stations (black dots).

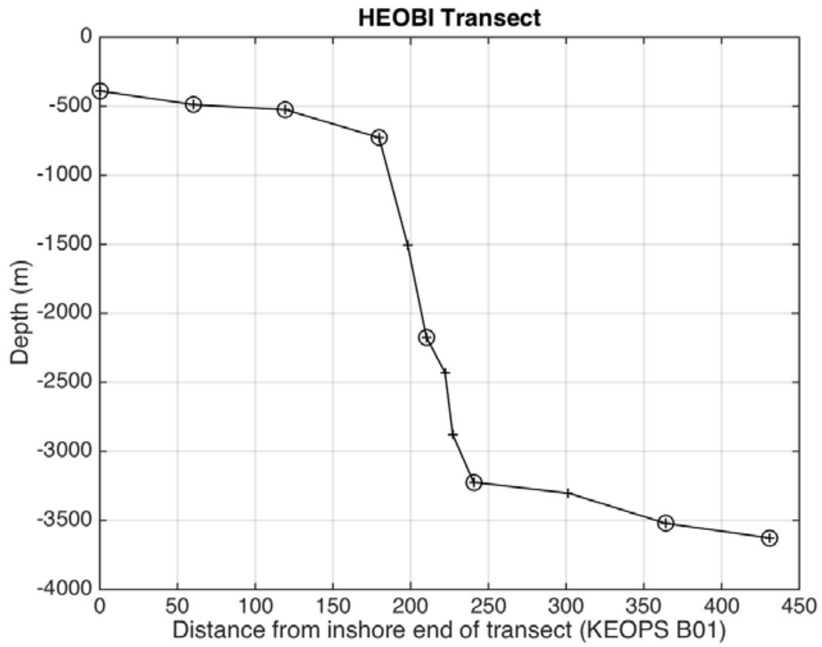


Figure 4d. Depth profile for the transect onto the Central Kerguelen Plateau. The KEOPS ‘B’ transect stations plus the Hippies ‘C1’ station are shown.

One SOCCOM float will be deployed at the NE end of the transect.

Geoscience: Along the transect from NE Shell Bank to Pike Bank (Figures 3, 4b, 4c), if hydrothermal activity or active volcanism is detected on the seafloor, we will dredge associated volcanic features. Locations of interest are approximately coincident with KEOPS B07-B05-B03, B01 water sampling locations (Figure 5). Seafloor depths of 380-620 m will require three hours for each of four dredge deployments and retrievals, i.e., 12 hours total including setup and contingency.

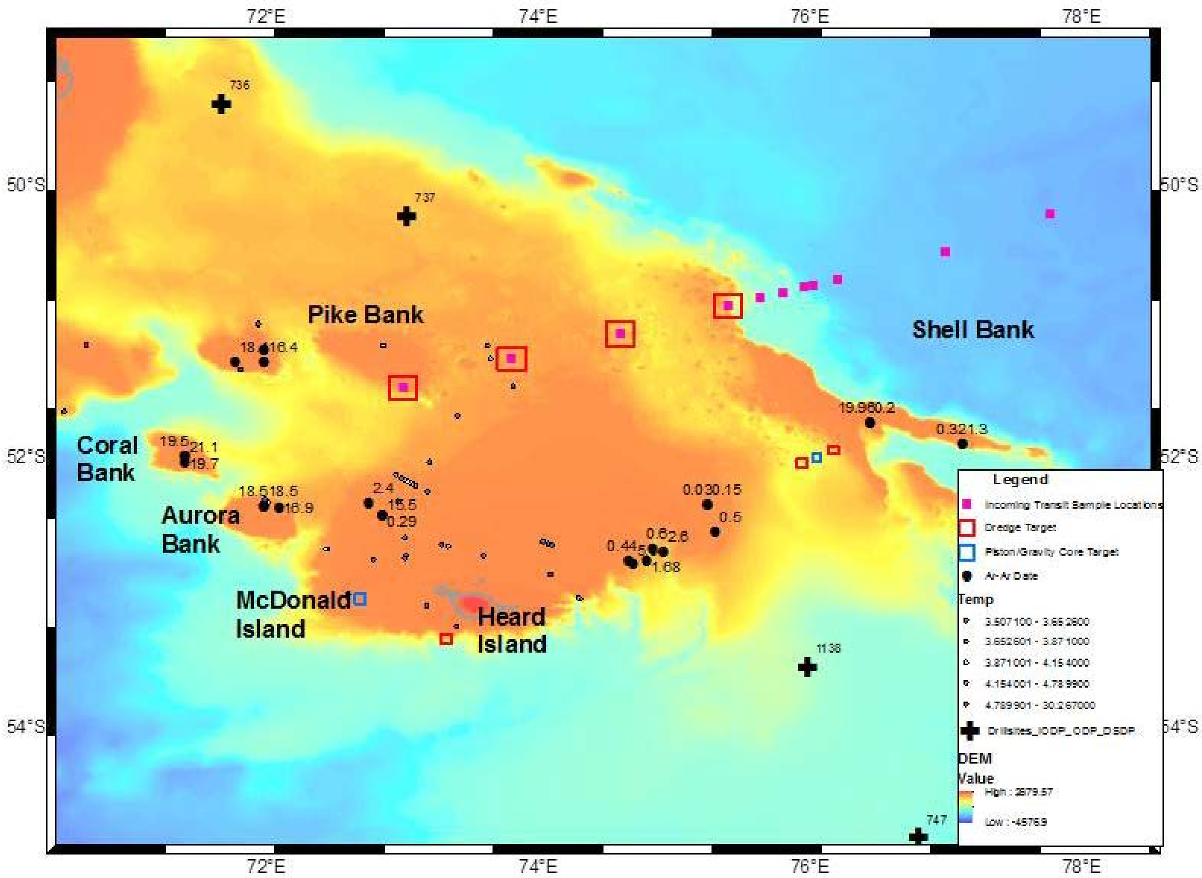


Figure 5. Bathymetry of the Central Kerguelen Plateau (Beaman and O'Brien, 2011). Black filled circles show locations of dredged lavas with $^{40}Ar/^{39}Ar$ ages in Ma (Duncan et al, in review; see also Table 1). Coloured dots show locations of anomalously warm water temperatures recorded by geotagged seals. KEOPS transit is shown by pink squares. Potential dredge locations are shown in red squares and are coincident with some KEOPS sites.

Time, sea state, and weather permitting, gravity or piston coring at a site south of the inferred paleo ice-sheet limit would help constrain the history of glaciation on Heard Island (see Figure 6 for potential core sites).

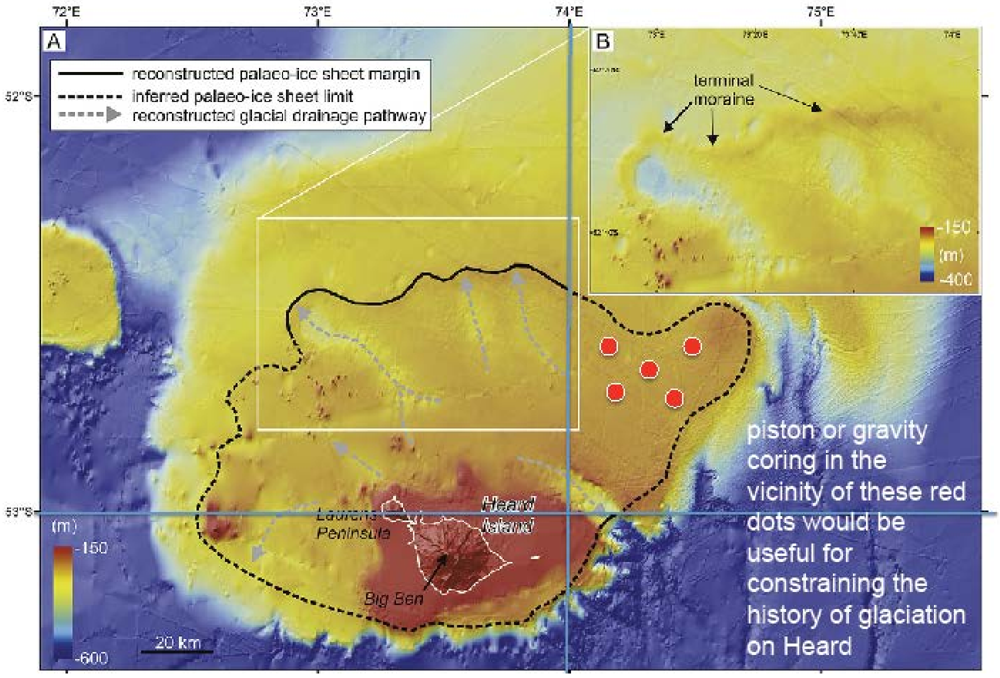


Figure 6. Terrestrial and submarine evidence for the extent and timing of the Last Glacial Maximum and onset of deglaciation around Heard and McDonald islands (Hodgson et al, 2014).

Nets for food web assessment will also be deployed after each CTD/TMR operation as the ship is leaving station. This will take minimal time for deployment.

Time for CTD is approximately two hours per operation and for TMR is approximately three hours per operation (or less depending on water depth).

Total time of Phase 1 = 72 hours (includes ~20 hours steaming and ~52 hours for operations)

Phase 2: "MAPPING"

We will then devote a minimum of 13 days to mapping the seafloor and shallow subseafloor using multibeam sonar; multi-frequency, split beam echosounding; sub-bottom profiling; and gravity (Figures 3, 7). This mapping will identify prospective active hydrothermal systems and volcanoes on the seafloor, guided by temperature anomalies recorded by geotagged seals and young $^{40}Ar/^{39}Ar$ ages (Figures 8a, 8b), and will focus on the HIMIP area between Gunnari Ridge and McDonald Islands (Figure 7). During this phase, to be undertaken steaming at 8 – 10knts, the TRIAXUS may be towed to assist in identifying active hydrothermal systems from particle backscatter, temperature, and ORP signatures. If no hydrothermal systems are detected on the seafloor in 13 days, we will extend the mapping phase, with phases 3 and 4 adjusted accordingly. Should extended mapping identify no active hydrothermal systems on the seafloor, we will move on to address secondary geoscientific and biogeochemical objectives.

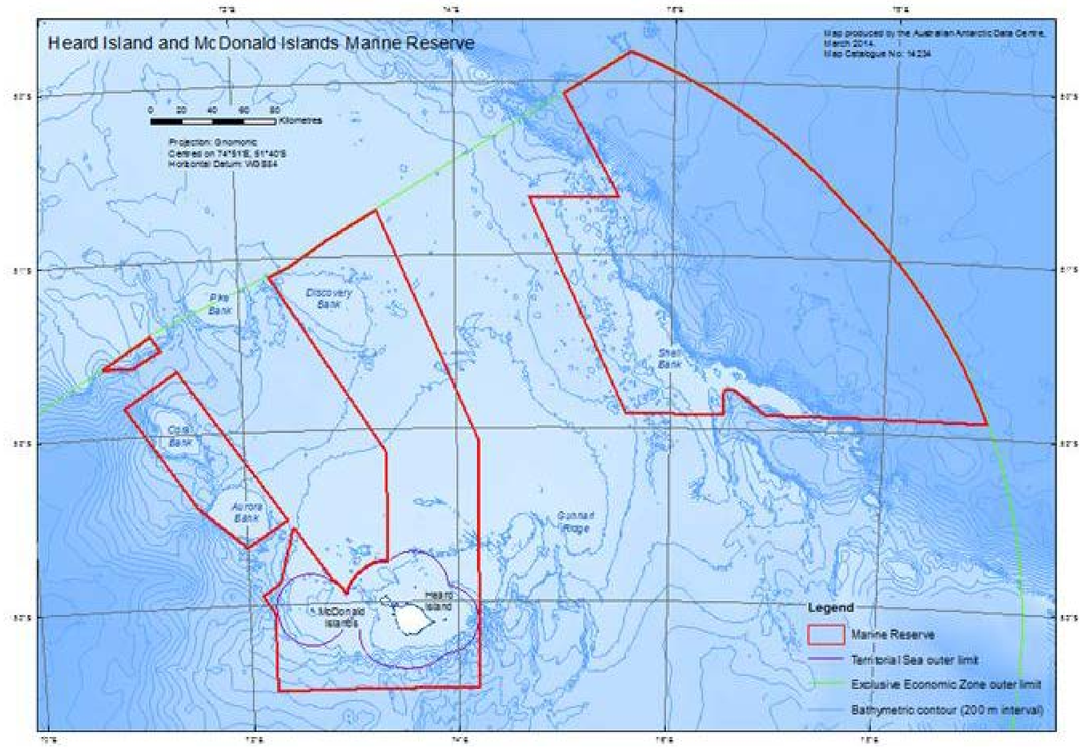


Figure 7. Mapping the seafloor, sampling the seafloor around active hydrothermal systems, and sampling the water column will be concentrated between Gunnari Ridge and McDonald Islands.

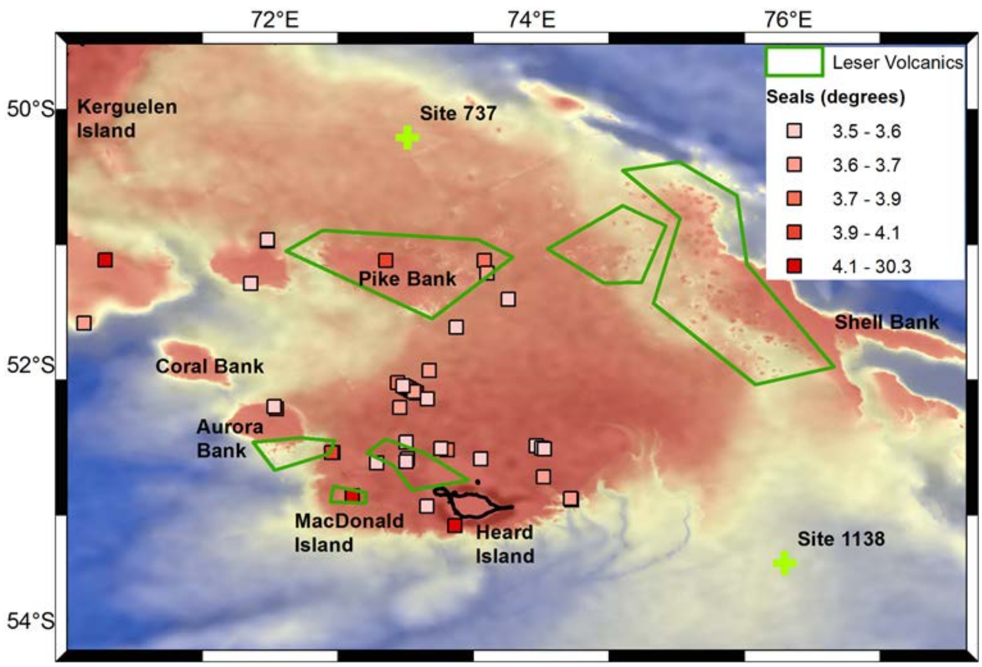


Figure 8a. Anomalously high temperature data points below 100 m (mixed layer) and within 250 m from seafloor of the Central Kerguelen Plateau (from N Polmear, UTAS Honour thesis, 2015). Fields of interpreted seafloor volcanoes are indicated by polygons outlined in green (from T Leser, UTAS 3rd year project, 2012).

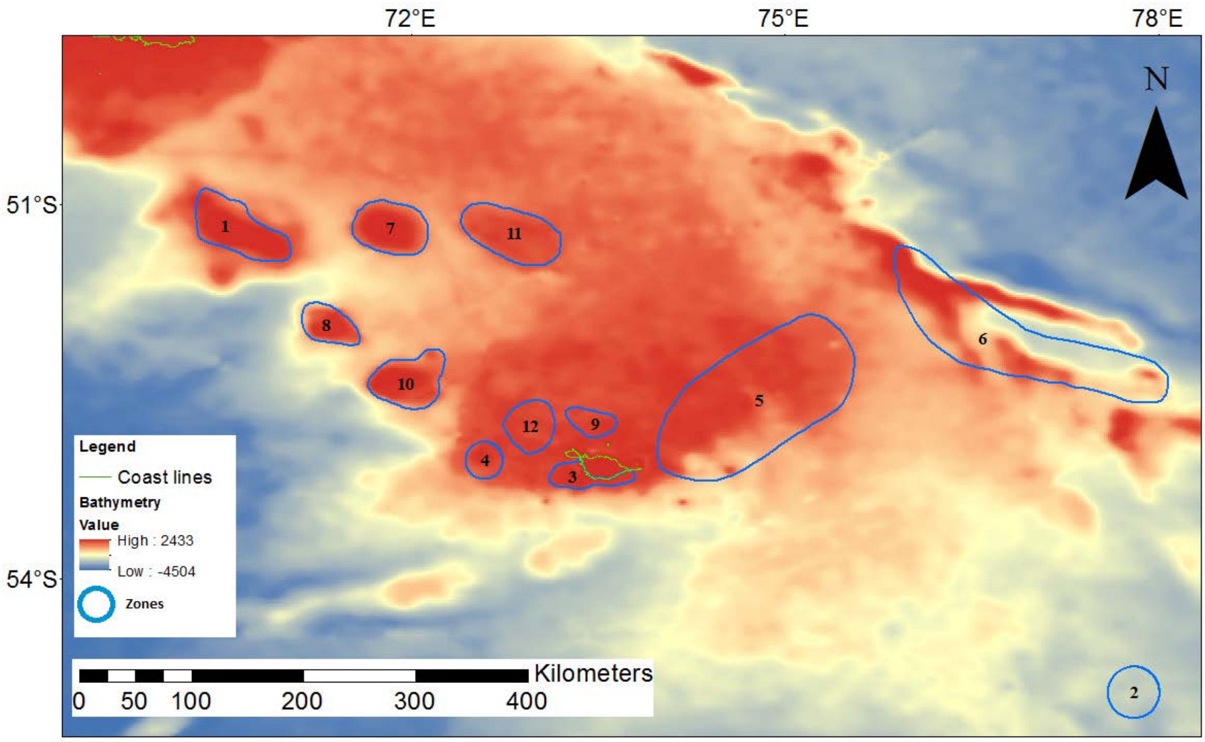


Figure 8b. Central Kerguelen Plateau bathymetry with regions of interest (outlined in blue) ordered from high (1) to low (12) potential for harbouring active hydrothermal systems (from N. Polmear, UTAS Honour thesis, 2015).

The area covered by mapping will depend on water depth, ship speed, and track spacing; below are examples for 200, 500, 1000, 2000, and 3000 m water depth at 8 kts and a track spacing of 3.5x water depth:

Water Depth	Line Spacing	Area Covered per Day (km^2)	Ship Speed
200	700	50	8
500	1800	330	8
1000	3500	1200	8
2000	7000	5000	8
3000	10000	10000	8

If a track spacing of 3.5x water depth produces excessive overlap, we will expand to 4x water depth.

Total time of Phase 2 = 312 hours

Phase 3: "HYDROTHERMAL VENT CHARACTERISATION"

After 13 or more days of mapping, assuming that we identify active hydrothermal systems, we will devote the next approximately 13 days to confirming active hydrothermal systems and volcanoes, and to characterise the water column above them using the TRIAXUS, deep tow camera, bio-optical casts, CTD/LADCPs, TMRs, and ISPs (all three for also sampling hydrothermal fluids), and sampling volcanic rock and sediment near the active systems, but not active vents themselves, using rock dredging, sediment piston/gravity coring, and sediment multicorer/box coring. Nets for food web assessment will also be deployed after each CTD/TMR operation as the ship is leaving station. This will take minimal time for deployment.

We anticipate that six days (144 hours) will be devoted to CTD/LADCP, TMR, ISP, TRIAXUS and Bio-optical deployments.

We anticipate that seven days (168 hours) of Phase 3 will be used for dredging/coring operations. Seafloor depths in the region of interest are typically 200 m but no greater than 450 m, unless no hydrothermal systems are identified in the HIMIP region and some are located in deeper regions to the east. Dredges require 1.5x the depth of wire out. Coring operation wire out equals seafloor depths.

In addition to sampling active volcanoes, we will undertake dredging south of Heard Island, sampling the collapse of Big Ben rock fall deposits (Figure 5). Total time for the dredge deployment will be two hours in water depths of 800 m. One piston core will be acquired east of McDonald Islands (Figure 5), a total of two hours at water depths of 250 m is required. Total time for these deployments is four hours, not including transits to/from the sites.

<u>Dredging operations:</u> Calculated wire times at a conservative 50 m/min require a maximum of 30 minutes (up and down), plus one hour to prepare the operation. Dredge seafloor bottom times of <30 minutes = total dredge time of two hours. This is a maximum number driven by calculations using seafloor depths of 450 m.

<u>Coring operations:</u> The box corer or multicorer can only retrieve cores <1 m long. The gravity corer lengths can in theory be as long as piston coring (24 m: same system), however the gravity corer is likely to break with lengths >5 meters. The coring technologies that will be employed will depend on a) science question and b) sea conditions. The box corer can be deployed in higher sea states than the multicorer, gravity, or piston corer. The multicorer will be instrumented with a camera, and can be used to capture images of the seafloor, which will facilitate more efficient coring operations. Calculated wire times at a conservative 50 m/min require a maximum of 18 minutes (up and down). Coring operations are expected to take one hour per core. All coring operations will retrieve the surface sediment-water interface and, using the multicorer, pore waters (three hours per core); 12 cores in total = 36 hours.

Contingency time for logistics extends the above estimates of timing, ie., total time of four hours/dredge and four hours/core.

We expect to conduct at least 30 dredge operations (120 hours) and 12 coring operations (48 hours). We expect to be doing mostly gravity/box coring operations (75%) piston coring (25%) and require a maximum of 500 m of PVC core liner.

Given the likely submarine geology of the Kerguelen Plateau, four chain dredges should be sufficient for the 30 dredge operations (MNFx2 (free) and MNFx2 (paid for if lost)).

Total time of Phase 3 = 312 hours

Phase 4: "BIOLOGICAL REPONSE TO IRON FLUX"

Following sampling of volcanic rock, sediment, hydrothermal fluids at their sources and the water column immediately above the vents, we will devote approximately 10 days to tracking hydrothermal fluids from their sources to surface waters and documenting any associated phytoplankton blooms. One primary objective of this is to constrain the iron flux from the hydrothermal vents along the plume into the surface bloom. The chosen target areas will be driven by satellite chlorophyll images, surface drifters, shipboard and lowered ADCP current vector data, and outputs from high resolution ROMS modelling of water parcel movements during the voyage. This will involve additional CTD/LADCP, bio-optical package, TMR, and ISP deployments, combined with TRIAXUS deployments between stations if we decide that will be useful.

Total time of Phase 4 = 240 hours

Total shiptime for HEOBI primary objectives:

Outward transit:	6.9 days (@ 12 kts)
Test Sets 1 and 2:	0.5 days
Return transit:	8.3 days (@ 12 kts)
Phase 1:	3 days
Phase 2:	13 days
Phase 3:	13 days
Phase 4:	10 days
Reference station:	0.5 days
Weather contingency:	2 days
TOTAL HEOBI :	**57.2**

(Total available shiptime = 58 days)

Total shiptime for piggyback projects:

Aus-India Floats:	0 days (integrated into main HEOBI voyage time)
SOCCOM floats:	0.4 days (integrated into main HEOBI voyage time)
Aerosol sampling:	0 days (integrated into main HEOBI voyage time)
UNCLOS shelf:	1.5 days (contingency)
K-axis:	2 days (contingency)
TOTAL PIGGYBACKS:	**3.9**

Proposed sampling plan

Number of CTDs: 49

(including two at the Test Sets, 12 on the cross-shore, four for SOCCOM deployments, and 31 for the remainder of the water column survey; 24 bottle rosette required but not all bottles will be fired in shallow waters; two hydrochemists should be adequate)

Number of TMRs: 43

(including two TMRs on the cross-shore transect, 35 for the remainder of the water column survey; many dips will be in shallow waters and not all Niskins used)

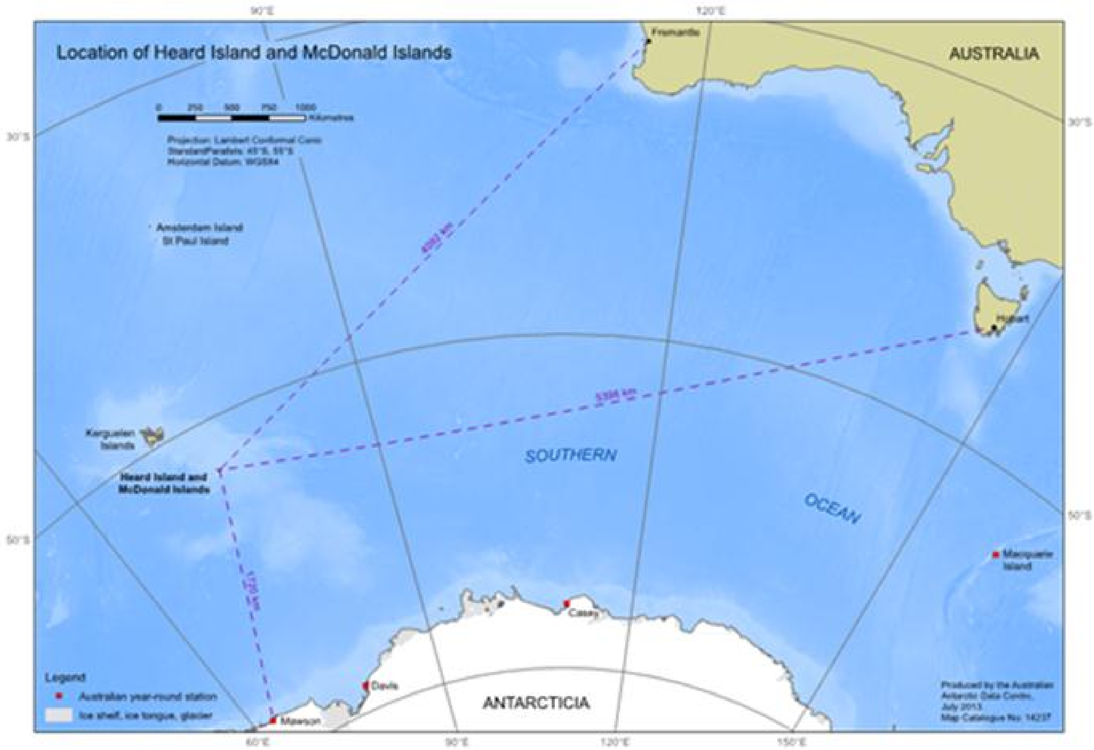
Number of ISPs: 20

(6-8 pumps per deployment on the wire)

Number of cores: eight gravity (8 m max) and four piston (24 m max)
(box cores will substitute if gravity and piston cores fail)

Number of dredges: four on transit and 30 in Phase 3.

Voyage track example



Great circle transits from Fremantle to Heard and McDonald Islands (4092 km) to Hobart (5398 km).

Waypoints and stations

	Decimal Latitude (°S)	Decimal Longitude (°E)	Distance (nm)	Total Distance (nm)	Steaming time (hrs)	Total Steam (hrs)
Fremantle	-32.06	115.74				
MBAS-9A or MBAS-8A	-33.27 or -33.08	114.32 or 113.08	102 or 148	102 or 148	8.5 or 12.3	
Test Set 1 (SOCCOM 1)	-43.0	90.0	1284 or 1239	1386 or 1387	107 or 103	115.4
Test Set 2 (SOCCOM 2)	-48.0	80.0	515	1900	42.9	158.3
DWBC 1 (Hippies C1) (SOCCOM 3)	-49.9057	78.5758	127	2161	0.8	180.1
DWBC 2	-50.2192	77.7722	48	2170	0.8	180.9
DWBC 3 (KEOPS B11)	-50.4983	77.0017	46	2152	1.6	179.3
DWBC 4 (KEOPS B09)	-50.6983	76.2017	48	2180	0.8	181.7
DWBC 5	-50.7455	76.0259	10	2189	0.8	182.5
DWBC 6	-50.7598	75.9594	4	2198	0.8	183.3
DWBC 7 (KEOPS B08)	-50.7990	75.8000	10	2208	0.8	184.1
DWBC 8	-50.8367	75.6382	10	2217	0.8	184.9
KEOPS B07	-50.8938	75.3928	15	2254	3.1	188.0
KEOPS B05	-51.1017	74.5983	48	2289	1.5	191.0
KEOPS B03	-51.2852	73.8025	48	2323	1.5	194.0
KEOPS B01	-51.5000	73.0017	48	2356	1.3	196.8
Phase 2: 13 days of mapping HIMIP; ship speed and track orientation will depend on sea state	TBD	TBD	TBD	2688	336	538.6
Phase 3: 13 days of sampling fluids from active hydrothermal systems and overlying water column, rocks from active volcanoes, and sediment from volcanic aprons	TBD	TBD	TBD	TBD	TBD	TBD

	Decimal Latitude (°S)	Decimal Longitude (°E)	Distance (nm)	Total Distance (nm)	Steaming time (hrs)	Total Steam (hrs)
Phase 4: 10 days of tracking hydrothermal fluids from their sources to surface waters and documenting any associated phytoplankton blooms	TBD	TBD	TBD	TBD	TBD	TBD
Heard Island	-53.0	73.5	TBD	TBD	TBD	TBD
SOCCOM 4	-54.3448	81.3252	291	TBD	24.3	TBD
SOCCOM 5	-55.1537	89.5702	291	TBD	24.3	TBD
SOCCOM 6	-55.3884	98.0329	291	TBD	24.3	TBD
SOCCOM 7	-55.0372	106.4708	291	TBD	24.3	TBD
Hobart	42.87	147.35	1742	TBD	145.2	TBD

Piggy-back projects

Five piggy-back projects are under consideration. Three are (in part) integrated into the voyage plan, totalling 10 hours (two involve no extra shiptime). Two contingency piggybacks, totalling 84 hours, will be considered if primary voyage objectives are achieved in less than the allocated time and/or catastrophic equipment loss or failure precludes addressing primary voyage objectives.

Integrated piggybacks:

Aus-India Bio-Argo Float deployments, Prof Tom Trull, CSIRO. Two bio-optical floats will be deployed along the early portion of the transit in the vicinity of the Subtropical front. In conjunction with a CTD/LADCP to 2000 m, a bio-optical sensor cast, and a TRIAXUS tow. This work is built into the operational Test Set 1 and correspondingly requires negligible additional time (even counting all those Test Set 1 events as a contribution to Aus-India only requires 12 hours: 6 hours for the CTDs and optical casts, plus 6 hours of time for the slower transit at 9 kts towing TRIAXUS for 30 hours).

Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM), Dr Zanna Chase, UTAS/IMAS. Seven biogeochemical floats (Argo floats with additional chemical and bio-optical sensors) will be deployed. The purpose is to increase the density of such observations in a rarely visited portion of the Southern Ocean. Each float deployment will be preceded by a 2000 m CTD/LADCP to collect calibration data, including nutrient and oxygen profiles. Total time for each float deployment and CTD will be approximately 2.5 hours. One each be deployed in conjunction with Test Sets 1 and 2 where 2000 m CTDs are already planned for Aus-India Bio-Argo program, and one will be made on the DWBC transect upon arrival into Heard, again where a CTD is already planned. The remaining four floats will be deployed on the return transit to Hobart, and require dedicated CTD casts. These deployments will be spaced about 10 degrees longitude along the transit. Therefore a total of 2.5 x 4 = 10 extra hours are anticipated for the entire piggy-back project.

Natural iron fertilisation of oceans around Australia: linking terrestrial aerosols to marine biogeochemistry, A/Prof Andrew Bowie, UTAS/IMAS/ACE CRC. We will install a simple pump and filtration system in the RV *Investigator* aerosol lab to sample trace metals in aerosols collected from the ship's air intake line. The equipment will be housed within a laminar flow hood to avoid contamination. Data will enable us to compare iron delivered from sub-sea sources with that from the atmosphere above. This system was successfully trialled during IN2015_E04 and will require no extra shiptime. Ideally, this system will be coupled to a trigger from the output of RV *Investigator* met data to enable autonomous sector control of air sampling (currently under investigation).

Contingency piggybacks:

United Nations Convention on the Law of the Sea (UNCLOS) Extended Continental Shelf, Dr Irina Borissova, Geoscience Australia. Six rock dredges would be conducted on William's Ridge between 52°-54°S, 77°-80°E. The purpose is to justify Australia's claim to William's Ridge as Extended Continental Shelf, which has not been accepted by the United Nations Commission on the Limits of the Continental Shelf. Dredges would be acquired during the transit back to Hobart from the Heard Island study area; each would take approximately 6 hours. Thus, a total of 36 hours would be anticipated for the entire piggy-back project.

Kerguelen Axis Ecology (K-axis), Dr Andrew Constable, AAD. One zonal transect in the Heard Island region would involve oceanographic, chemical, and biological sampling, including net deployments. The purpose would be to assess habitats, productivity, and food webs on the axis of the Kerguelen Plateau. A total of 48 hours would be anticipated for the entire piggyback project. The net deployments alone will take minimal extra shiptime as can be achieved after a CTD/TMR operation as the ship is leaving station and be deployed for ~1 hour.

Investigator equipment

(i) **Standard Laboratory and Facilities**

Name	Essential	Desirable
Aerosol Sampling Lab	X	
Air Chemistry Lab	X	
Constant Temperature Lab	X	
Underway Seawater Analysis Laboratory [O_2/Ar and pCO_2 systems]	X	
GP Wet Lab (dirty)	X	
GP Wet Lab (Clean)	X	
GP Dry Lab (Clean) [underway filtration system for surface water particles]	X	
Sheltered Science Area	X	
Monkey Island	X	
Walk in Freezer	X	
Clean Freezer	X	
Blast Freezer	X	
Ultra Low Temperature Freezer [pigment sample storage]	X	
Walk in Cool Room	X	

(ii) **Specialised Laboratory and Facilities**

Name	Essential	Desirable
Modular Radiation Laboratory [Blain/Obernosterer incubations]	X	
Modular Trace Metal Laboratory	X	
Modular biogeochemistry laboratory [older CSIRO clean van]	X	
Modular TMR storage container [smaller container]	X	
Stern Ramp	X	
Modular coring consumables container [Mark Lewis]	X	

(iii) **Standard Laboratory and Sampling Equipment**

Name	**Essential**	**Desirable**
CTD - Seabird 911 with 36 Bottle Rosette		X
CTD -Seabed 911 with 24 Bottle Rosette	X	
Lowered ADCP	X	
Sonardyne USBL System		X
XBT System	X	
Milli-Q System	X	
Laboratory Incubator [Blain/Obernosterer incubations]	X	
Heavy Duty Electronic Balance	X	
Surface Nets	X	
Bongo Nets	X	
Smith Mac grab	X	
Rock Dredges	X	
Dissecting Microscopes	X	

(iv) **Specialised Laboratory and Sampling Equipment**

Name	**Essential**	**Desirable**
TRIAXUS – Underway Profiling CTD	X	
Deep Tow Camera	X	
Deck Incubators [Blain/Obernosterer incubations]	X	
Short Sediment Coring System	X	
Long Sediment Coring System	X	
Multi Corer	X	
Box Corer	X	
Trace Metal Rosette and Bottles	X	
Trace metal *in situ* pumps (x6)	X	
Rock Saw	X	

(v) **Underway Systems**

Name	Essential	Desirable
75 KHz / 150 KHz ADCP	X	
Multi Beam Acoustics	X	
Sub-Bottom Profiler	X	
Scientific Echo Sounders	X	
Thermosalinograph	X	
Atmospheric Underway Sensors	X	
Biological Oceanography Underway Sensors	X	
Polarimetric Weather Radar		X
Gravity Meter	X	
Magnetometer	X	

User Equipment (responsible PIs are listed in parentheses)

Name	Essential	Desirable
Copper Tube Crimping Equipment [Arculus, ANU]	X	
Backup trace metal rosette (TMR) and wooden storage crate (Bowie, ANU)	X	
McLane *in situ* pumps (ISPs) (x2) (Bowie and Trull, ACE CRC)	X	
Flow injection analysers for trace elements (Fe, Mn, FeII) and associated consumables/chemicals (Bowie, ACE CRC)	X	
Trace metal clean sample processing equipment (filters, capsules, transfer lines, connectors, sample bottles, etc) (Bowie, ACE CRC)	X	
A trace metal clean aerosol filtration system to be installed in the aerosols lab (Bowie, CSIRO/Curtin)	X	
3 MAPR units (borrowed from NOAA-PMEL) for detecting particle backscatter, redox potential, temperature and pressure (Chase, IMAS)	X	
Spectrophotometer Cintra 2020	X	
SUNA-nitrate, PAR, and FIRe-variable fluorescence sensors and MINIMONE sampler for use on TRIAXUS and Deep Tow Camera (Trull, CSIRO)	X	
Bio-optical instrument package for deployment to 150 m from Coring Boom ~60 kg containing Hydroscat, AC-9, Radiometer, PAR sensors (Trull and Wojtasiewicz, CSIRO)	X	

Name	Essential	Desirable
pCO_2 system (Tilbrook for MNF ongoing use) O_2/Ar mass spectrometer (Tilbrook and Trull, CSIRO) Gas Tension Device (Blain, UPMC) Underway fluorometer (Trull, CSIRO) *All for installation in underway lab*	X	
Underway high volume size fractionation filtration system (Trull, ACE CRC, installed in forward inboard corner of General purpose dry lab during IN2015_v01)	X	
FlowCam microscopic imaging instrument (Wojtasiewicz and Trull, CSIRO)	X	
20' Laboratory Container (sediment trap van) with laminar flow bench for use on trawl deck as in-situ pump storage and preparation space. Requires monophase 30 amp supply. (Trull, CSIRO/ACE CRC)	X	
20 NOAA Drifter floats (Robertson, UNSW Canberra)	X	
7 SOCCOM Floats (Chase, IMAS and Rosso, Scripps)	X	

Special Requests

The following requests for underway instruments relate to scupper redesign on the RV *Investigator* and installation of new starboard side drains. Contact Tom Trull if any queries.

1. Operation of underway pCO_2 system (as installed by Tilbrook lab) in underway lab
2. Installation and operation of Tilbrook underway O_2/Ar spectrometer in underway lab
3. Re-installation and operation of Trull underway high volume size fractionation filtration systems in forward inboard corner of general purpose dry lab (as done during IN2015_v01).

Radioisotopes – application for approval for use on board needs to be submitted for participants Blain and Obernosterer (Marion Fourquez is coordinating)

Permits

An application for consent to conduct marine scientific research in areas under the national jurisdiction of France has been lodged with the MNF.

Work in the 71,200 km^2 Heard Island and McDonald Islands (HIMI) Marine Reserve requires permission from the Australian Antarctic Division (AAD). Two iterations of applications have been lodged with AAD following discussions and feedback on the first iteration.

Personnel List

1.	Brett Muir	Voyage Manager	CSIRO MNF
2.	Mark Rayner	Hydrochemist	CSIRO MNF
3.	Hugh Barker	DAP Support	CSIRO MNF
4.	Nicole Morgan	SIT Support	CSIRO MNF
5.	Aaron Tyndall	SIT Support	CSIRO MNF
6.	Tara Martin	GSM Support	CSIRO MNF
7.	Frances Cooke	GSM Support	CSIRO MNF
8.	Kendall Sherrin	Hydrochemist (Trainee)	MNF
9.	Mark Lewis	TRIAXUS/Camera/Coring support	MNF
10.	Dr Lloyd Fletcher	Doctor	ASPEN Medical
11.	Peter Harmsen	Cinematographer/Photographer/Editor	MNF
12.	Prof Millard (Mike) Coffin	Chief Scientist	UTAS/IMAS
13.	Prof Richard Arculus	Co-Chief Scientist	ANU
14.	A/Prof Andrew Bowie	Co-Chief Scientist/Lead PI (Biogeochemistry)	UTAS/IMAS/ACE CRC
15.	Charles Tambiah	Photographer/Videographer	ANU
16.	Dr Robin Robertson	Lead PI (Physical Oceanography)	UNSW
17.	Nicholas Polmear	Geologist	UTAS
18.	Jodi Fox	Geologist	UTAS/SET
19.	Sally Watson	Geophysicist	UTAS/IMAS
20.	Evan Draayers	Geologist	UTAS/SET
21.	Erica Spain	Geophysicist	UTAS/IMAS
22.	Anna Bradney	Water sampling/Cu tube crimping	ANU
23.	Prof Tom Trull	Biogeochemist (sensors)	CSIRO/ACE CRC
24.	Dr Pier van der Merwe	Biogeochemist (particulate trace elements)	UTAS/ACE CRC
25.	Prof Stephane Blain	Biogeochemist (incubations)	UPMC/LOMIC
26.	Dr Ingrid Obernosterer	Biogeochemist (incubations)	UPMC/LOMIC
27.	Dr Kathrin Wuttig	Biogeochemist (shipboard Mn)	CSIRO/ACE CRC
28.	Dr Zanna Chase	Biogeochemist (radiogenic isotopes)	UTAS/IMAS
29.	Thomas Holmes	Biogeochemist (shipboard Fe)	UTAS/IMAS/ACE CRC
30.	Lavenia Ratnarajah	Biogeochemist (iron recycling, net work)	UTAS/IMAS/ACE CRC
31.	Manon Tonnard	Organic iron speciation	UTAS/IMAS/ACE CRC/UBO/IUEM
32.	Habacuc Perez-Tribouillier	Radiogenic isotopes, sediment sampling program	UTAS/IMAS
33.	Bozena Wojtasiewicz	Bio-optics	CSIRO
34.	Hugh Doyle	TRIAXUS	UTAS/ACE CRC
35.	Paul Hartlipp	Physical Oceanographer	UNSW
36.	Isabella Rosso	Physical Oceanographer (SOCCOM)	Scripps
37.	Fernando Arce Gonzalez	Marine Mammal/Bird Obs	UTAS/IMAS
38.	Timothy Reid	Marine Mammal/Bird Obs	UTAS/IMAS
39.	James Batchelor	Artist	Australia Council
40.	Annalise Rees	Artist	UTAS/Australia Council

Signature

Your name	Mike Coffin	Chief Scientist
Date:	24 November 2015	

List of additional figures and documents

Table 1. $^{40}Ar/^{39}Ar$ Incremental Heating Ages for Dredged Rocks, Central Kerguelen Plateau (Duncan et al, in review).

Sample number	Location	Depth (m)	latitude	longitude	Total Fusion (Ma)	2s error (Ma)	Plateau Age (Ma)	2s error (Ma)	N	MSWD	Isochron Age (Ma)	2s error (Ma)	MSWD	40Ar/36Ar initial	2s error
1180010-2	Pike Bank	273	-51.309	71.769	17.98	0.19	18.07	0.20	18/38	0.96	17.49	0.93	0.94	346.6	93.2
1180011-2	Pike Bank	246	-51.217	71.980	17.49	0.25	17.56	0.19	8/8	0.71	17.56	0.2	0.78	294.2	3.8
Captains Sample	Pike Bank		-51.378	71.968	16.44	0.08	n/a	n/a	38/38	n/a	n/a	n/a	n/a	n/a	n/a
203-1	Coral Bank	294.5	-52.050	71.394	21.09	0.10	none		38/38	na	na			na	
205-1	Coral Bank	288	-52.000	71.394	20.29	0.16	19.66	0.13	6/8	1.43	19.62	0.13	0.42	298.0	2.2
205-2	Coral Bank	288	-52.000	71.394	19.79	0.24	19.54	0.21	6/8	0.42	19.50	0.29	0.49	295.7	0.9
177-1	Aurora Bank	221.5	-52.370	71.977	18.50	0.18	18.54	0.19	8/8	1.84	18.46	0.24	2.37	298.1	8.9
177-3	Aurora Bank	221.5	-52.370	71.977	18.59	0.27	18.51	0.24	8/8	1.93	18.38	0.32	1.87	297.6	3.7
189-1	Aurora Bank	229.5	-52.378	72.088	17.25	0.22	17.19	0.22	8/8	1.43	17.03	0.32	1.29	297.7	3.4
154-1	Plateau Shallow	282	-52.438	72.852	0.286	0.002	0.290	0.002	16/31	1.07	0.286	0.004	0.61	304.5	6.6
154-4	Plateau Shallow	282	-52.438	72.852	15.51	0.08	none		38/38	na	na			na	
156-3	Plateau Shallow	273	-52.345	72.747	2.96	0.20	2.41	0.28	6/8	1.77	1.83	1.05	1.66	297.9	4.1
253-12	Shell Bank	336.5	-51.910	77.116	1.39	0.19	1.46	0.19	8/8	1.4	0.92	0.66	1.10	297.4	2.3
253-14	Shell Bank	336.5	-51.910	77.116	0.319	0.003	0.320	0.010	15/31	1.12	0.321	0.007	1.13	293.4	4.9
274-2	Shell Bank	283.5	-51.757	76.436	0.188	0.095	0.168	0.090	8/8	0.58	0.081	0.217	0.54	300.7	12.6
274-3	Shell Bank	283.5	-51.757	76.436	66.06	0.24	19.96	0.78	13/31	13.08	13.17	1.93	2.30	334.1	10.8
1180180-2	Gunnari Ridge	334	-52.558	75.302	0.465	0.006	0.482	0.008	24/38	1.57	0.461	0.012	0.85	300.2	2.3
1180256-1	Gunnari Ridge	311	-52.365	75.246	0.153	0.003	0.152	0.003	31/31	0.77	0.150	0.005	0.75	296.4	1.6
1180256-2	Gunnari Ridge	311	-52.365	75.246	0.099	0.188	0.059	0.170	8/8	0.77	0.209	0.313	0.66	294.2	2.3
1180042-1	Plateau SE	381	-52.791	74.693	5.46	0.10	5.44	0.09	7/8	0.81	5.43	0.1	0.78	295.0	3.4
1180043-1a	Plateau SE	288	-52.772	74.657	0.447	0.006	0.436	0.009	7/31	1.62	0.422	0.056	1.86	297.8	9.0
1180044-1a	Plateau SE	532	-52.773	74.796	1.66	0.01	1.68	0.01	16/31	3.08	1.67	0.01	1.62	311.3	7.9
1180050-1a	Plateau Deep E	558	-52.708	74.916	2.59	0.01	2.60	0.01	27/40	2.67	2.60	0.01	2.74	295.1	1.7
1180051-2	Plateau Deep E	497	-52.682	74.841	0.439	0.103	0.562	0.105	7/8	1.15	0.609	0.329	1.35	295.1	2.9

Ages calculated using biotite monitor FCT-3 (28.201 Ma) and the total decay constant λ = 5.530E-10/yr. N is the number of heating steps (defining plateau/total);
MSWD is an F-statistic that compares the variance within step ages with the variance about the plateau age. J combines the neutron fluence with the monitor age.