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## **RV *Kronprins Haakon* (cruise no. 2021711)**

**Longyearbyen – Longyearbyen**

**28.09.2021 – 21.10.2021**



### **Hot Vents in an Ice-Covered Ocean HACON21 expedition**

Edited by

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Written by all HACON21 cruise participants

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## DEDICATION

The HACON21 cruise is dedicated to Prof Hans Tore Rapp, a world-recognised deep-sea biologist, colleague and good friend, who passed away in 2020. Hans Tore was a key person in the HACON project. Through his tireless and thorough work, openness to knowledge sharing, respect for other's work and his kindness, Hans Tore greatly contributed to the success of the project and the HACON19 cruise to the Aurora Vent Field. The achievements of the HACON21 cruise are also his.



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## PREFACE

The HACON21 cruise is a major component of the FRINATEK HACON project, funded by the Research Council of Norway. The project aims at investigating the role of the Gakkel Ridge and Arctic Ocean in biological connectivity amongst ocean basins and global biogeography of chemosynthetic ecosystems. The HACON study area is centered in the Aurora seamount and Aurora vent field. During the ChEss-Census of Marine Life programme (2000-2010), the Gakkel Ridge was identified as a key study area to contribute to the global biogeographic puzzle for hydrothermal vent communities (Ramirez-Llodra et al., 2007). Although the environmental, technological and economic challenges of working at great depths in complex topographic terrain under Arctic ice has constrained exploration and investigation of the Gakkel Ridge for decades, each research cruise to this remote region provides new information to better understand the composition and functioning of the Gakkel Ridge and its associated communities. The AMORE 2001 expedition located the Aurora vent field through the detection of the non-buoyant plume and the dredging of an extinct sulphide chimney (Edmonds et al., 2003). In 2014, the RV *Polarstern* (PS86) 2014 cruise observed the first black smoker in the Aurora vent field during an OFOS (Ocean Floor Observation System) transect conducted on the last day of a 5-week cruise. Only 1 image and less than 1 min of video of the black smoker could be gathered at the time (Boetius et al., 2014). In 2019, the HACON19 cruise returned to the Aurora vent field and obtained new high-resolution OFOBS data (video, sidescan and bathymetry) of multiple black smokers on the Aurora Vent Field (AVF) (Büenz & Ramirez-Llodra, 2019).

The FRINATEK programme provides the necessary funding framework from which to develop high-risk – high-gain projects that can greatly advance science and move forward the frontiers of science and knowledge in challenging deep-sea environments. It is in this framework that the HACON project (2018-2022) is being developed. In Sept-Oct 2019, the HACON19 cruise was the first HACON expedition to investigate the Aurora seamount and vent field situated at the western end of the Gakkel Ridge with the OFOBS towed system from the Alfred Wegener Institute (AWI), Germany. The HACON19 cruise provided additional data on the vent system and its communities (Büenz & Ramirez-Llodra, 2019). The 2019 expedition, as previous ones into the Arctic Ocean, faced many challenges. For reasons external to the project, the ROV *Ægir* was prevented from joining the cruise as originally planned. The WHOI NUI hybrid ROV/AUV was on board, but technical failures resulted in the vehicle not reaching the vent site on 3 occasions. This was followed by physical obstruction from sea ice to the study area, when a large ice floe remained stationary over the vent site, preventing a final NUI dive to sample the hydrothermal vents. The cruise was nevertheless a success. Four OFOBS dives recorded transects over the AVF, with 3 of the dives producing excellent images and data on 3 different black smokers. The systematic analysis of the video and stills data from the OFOBS transects is underway, providing new knowledge on the biological communities of the vent fauna. The imagery data, together with the water column and benthic samples, will increase our understanding of the composition and functioning of the Aurora seamount and vent field. In addition to the science conducted on board, the HACON cruise was a great success in terms of national and international collaboration amongst teams with different expertise, from physical oceanography to geology and geochemistry, ecology and engineering. The excellent collaborative atmosphere on board has facilitated the sharing of samples amongst groups and

the development of technological solutions on board to address some of the challenges. The expedition significantly strengthened existing collaborations, as well as establishing new ones amongst many of the diverse teams. The data from HACON19 and strong collaborations led to a new shiptime application for a second HACON cruise to the AVF on board RV *Kronprins Haakon*: the HACON21 cruise described in this cruise report.

The aim of the HACON21 expedition was to conduct the first ever ROV survey of the AVF, collecting samples for geochemistry, geology, physical oceanography, microbiology, meiofauna and macrofauna. The ROV *Aurora* from REV Ocean was on board, in addition to sampling equipment to be deployed from the side of the vessel (CTD, multicore, gravity core). In addition, the second part of the cruise aimed at mapping and surveying an area of the NE Greenland shelf where indications of cold seepage had been observed during previous investigations.

HACON21 was a phenomenal success. A full survey of the Aurora Vent Field was conducted, providing a wealth of new data and samples that will allow us to describe the functioning of this system and the composition and functioning of the associated fauna. In parallel, the cruise HACON21 was a technological and operations success, efficiently and safely using ROV *Aurora* on its maiden voyage to survey and sample, for the first time ever, deep hydrothermal vents under Arctic ice. The cruise also provided new bathymetric data of the NE Greenland shelf, contributing new knowledge of the shelf region under permanent ice cover.



## 1 PARTICIPANT LIST

|                    |                       |                             |
|--------------------|-----------------------|-----------------------------|
| Stefan Bünz        | CAGE, UiT             | Chief Scientist             |
| Eva Ramirez-Llodra | NIVA & REV Ocean      | Co-Chief Scientist          |
| Lisette Victorero  | NIVA/UAVR             | Deep-Sea Ecology            |
| Marie Stetzler     | CAGE, UiT             | Water Column, Oceanography  |
| Claudio Argentino  | CAGE, UiT             | Geochemistry                |
| Kate Waghorn       | CAGE, UiT             | Geophysics, data management |
| Frank Jakobsen     | CAGE, UiT             | Marine Geology              |
| Ida Helene Steen   | UiB                   | Microbiology                |
| Emily Denny        | UiB                   | Microbiology                |
| Eoghan Reeves      | UiB                   | Fluid Geochemistry          |
| Samuel Pereira     | UiB                   | Fluid Geochemistry          |
| Pedro Ribeiro      | UiB                   | Marine Ecology              |
| Ana Hilario        | UAVR                  | Marine Ecology              |
| Sofia Ramalho      | UAVR                  | Marine Ecology              |
| Carolina Costa     | UAVR                  | Marine Ecology              |
| Øystein Mikelborg  | REV Ocean             | ROV Operations              |
| Leighton Rolley    | REV Ocean             | ROV team/Instrumentation    |
| Lawrence Hislop    | REV Ocean             | Communications              |
| Cera McTavish      | REV Ocean             | Communications              |
| Tamara Ellis       | REV Ocean             | Sustainability              |
| Nils Baadnes       | REV Ocean             | Vessel Operations/Captain   |
| Stig Vågenes       | UiB                   | ROV team                    |
| Patrick Vågenes    | REV Ocean             | ROV team                    |
| Jörn Patrick Meyer | IMR                   | ROV team                    |
| Eivind Ernsten     | IMR                   | ROV team                    |
| Maria Baker        | UoS/DOSI, UK          | Marine Ecology              |
| John Jamieson      | Memorial Uni., Canada | Geology                     |
| Pascal Habault     | Independent           | Medical doctor              |
| Inka Cresswell     | Wild Space Prod. UK   | Filming                     |

CAGE/UiT: Centre for Arctic Gas Hydrate, Environment and Climate, UiT Arctic University of Norway

NIVA: Norsk Institutt for Vannforskning / Norwegian Institute for Water Research, Norway

UiB: University of Bergen, Norway

IMR: Institute of Marine Research, Norway

UAVR: University of Aveiro, Portugal

NORMAR, UiB: Norwegian Marine Robotics Facility, University of Bergen

UoS: University of Southampton, UK

DOSI: Deep Ocean Stewardship Initiative

Some participants were not able to join the HACON21 cruise for several reasons, including Covid travel restrictions. Nevertheless, they all provided input during the preparations phase and in this cruise report, and are thus included below.

|                    |               |  |
|--------------------|---------------|--|
| Tina Kutti         | IMR, NO       | Marine ecology                               |
| Christopher German | WHOI, USA     | Geochemistry                                 |
| Kevin Hand         | NASA-JPL, USA | Astrobiology                                 |
| Andrew Klesh       | NASA-JPL, USA | Engineer                                     |
| Autun Purser       | AWI, DE       | Habitat mapping                              |
| Monica Winsborrow  | UiT, NO       | Marine Geology, Glaciology                   |
| Mariana Esteves    | UiT, NO       | Marine Geology & Outreach,<br>Communications |

## 2 HACON21 IN THE CONTEXT OF THE CHALLENGER 150 PROGRAMME AND THE DECADE OF OCEAN SCIENCE

Maria Baker



The HACON21 expedition was affiliated with [Challenger 150](#), a new global scientific cooperative programme developed to respond to the needs of the [UN Decade of Ocean Science for Sustainable Development](#). This programme, active since January 2021, was one of the first to be endorsed by the Intergovernmental Oceanographic Commission as an action of the UN Ocean Decade. *Challenger 150* is an umbrella programme under which research projects can contribute to a global research effort coordinated towards a set of common objectives and standards. The objectives are set out by the UN Ocean Decade and for this programme, have been set in a deep-ocean research context (see [Howell et al. \(2020\)](#) for detail). The four main pillars of *Challenger 150* are to 1) Build capacity for deep-ocean research globally, supporting the development of people, facilities, technology and public understanding; 2) Expand deep-ocean biological observations and sampling in all ocean basins, specifically focusing on underexplored regions; 3) Build fundamental ecological understanding of deep-ocean ecosystems including ecosystem services delivered by the deep oceans, and flows of benefits to society and 4) Increase use of deep-ocean knowledge through development of effective ‘knowledge to end-user’ pathways, including use of decision-support tools in modelling deep-ocean management scenarios.

The Hacon21 expeditions ticked many of the objectives for the *Challenger 150* programme and the initial reporting and subsequent published research will be broadly communicated via the *Challenger 150* website, social media and network of deep-ocean scientists. With this new coordinated approach, *Challenger 150* aims to make the great leaps in knowledge needed to better manage our oceans. *Challenger 150* has close ties with the Deep-Ocean Stewardship Initiative (DOSI), a global network of ocean experts seeking to integrate science, technology, policy, law and economics to advise on ecosystem-based management of resource use in the deep ocean and strategies to maintain the integrity of deep-ocean ecosystems within and beyond national jurisdiction. International collaboration across disciplines and sectors is key to both broadening our knowledge of the deep ocean, and to make deep-ocean research more accessible to scientists, policy makers and other stakeholders from all nations. Given the inevitable interest in this ground-breaking project, it is important to maximise the reach of the research to all stakeholders. DOSI has also actively disseminated Hacon21 news and results to its network of over 2300 members from 103 different countries. A summary of the cruise and published results will appear in *Deep-Sea Life*, an informal publication to the deep-sea biology community and beyond.

HACON21 also provided an excellent opportunity for *Challenger 150* lead Ana Hilario and other programme members on board, and DOSI lead Maria Baker, to collaborate closely during this

expedition with scientists, technical and communications specialists from one of the *Challenger 150* partners, REV Ocean (Figure 1). In future, REV Ocean plans to support *Challenger 150* by contributing to the [Deep Ocean Training \(DOT\) initiative](#), offering 18 days ship time per year for capacity building in deep-ocean science.



Figure 1. The HACON21 team on the ice with the Challenger 150 banner.

### 3 INTRODUCTION AND OBJECTIVES OF THE HACON21 CRUISE

The HACON21/NE Greenland cruise on board RV Kronprins Haakon had three main objectives, each in a specific study area (Figure 2):

1. Conduct the first sea-trials of the Aurora Borealis ROV, including deep-water tests on the Molloy Deep.
2. Survey and sample for the first time the Aurora Vent Field and obtain additional samples of the Aurora seamount.
3. Conduct a multibeam survey of an area of the NE Greenland shelf exploring for cold seeps.

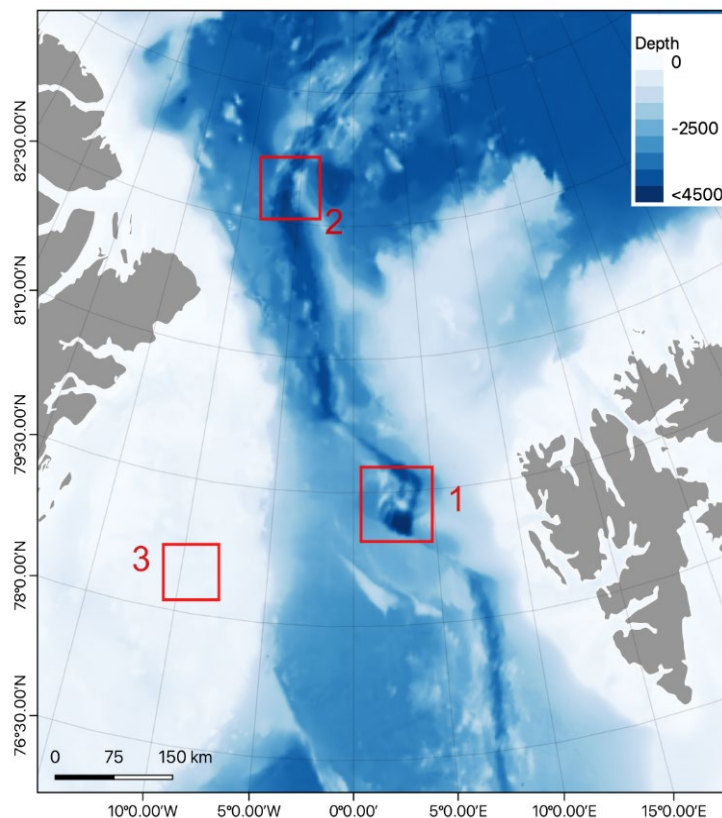


Figure 2. Map of the general area indicating the 3 study areas. 1: Molloy Deep; 2: Aurora Vent Field; 3: NE Greenland Shelf.

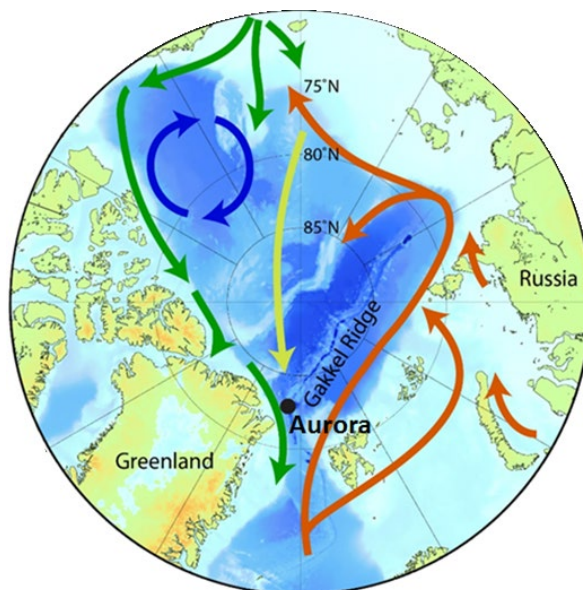
#### 3.1 Gakkel Ridge: a missing piece of the vent biogeography puzzle

Eva Ramirez-Llodra & Stefan Buenz

Forty years after the discovery of hydrothermal vents, research into these unique habitats and their ecosystems is still in the exploratory phase. These relatively recent discoveries have changed the way we understand life on Earth, have challenged knowledge of the origin of life, and are now fueling exploration for extra-terrestrial life in our solar system. Only 10% of the global ridge system has been investigated (Ramirez-Llodra et al., 2010), yielding an inventory of just over 500 confirmed active hydrothermal vent sites and estimates of 1300 ( $\pm 600$ ) existing

vents globally (Beaulieu et al., 2015). However, new estimates suggest that the number of active vents on fast- and intermediate- spreading ridges may be 3 to 6 times higher (Baker et al., 2016), forecasting a wealth of discoveries to come.

The remote Arctic Gakkel Ridge (Figure 3), though briefly investigated in regions by previous exploratory expeditions (see section 4 for details), remains largely unexplored and ecosystems in this northerly, under-ice region, largely unknown. In 2001, Edmonds and colleagues (2003) obtained first evidence of hydrothermal venting on the Gakkel Ridge (83-86°N), previously predicted to host an extremely low number of active sites, owing to the ultra-slow spreading nature of the ridge. In 2007, the AGAVE expedition provided evidence of explosive volcanism at 85°N, supporting growing evidence that ultra-slow spreading ridges host unique modes of crustal accretion and tectonic extension (Sohn et al., 2008). In 2014, the RV *Polarstern* cruise PS86 to the Aurora seamount obtained the first visual confirmation of black smokers on the Aurora Vent Field (82°53'N, 6°15'W) in the Gakkel Ridge, using the OFOS towed camera system (Boetius et al., 2014)).



*Figure 3. Map of the Arctic Ocean, showing the Gakkel Ridge, the Aurora vent field and the main hydrographic currents (allows). Map by L. Victorero.*

Although the autoecology of many of the more than 400 vent species described to date globally has been unraveled, the biogeography of vent fauna remains poorly understood, with 11 distinct biogeographic provinces thus far identified (Rogers et al., 2012). Tectonic dynamics influence biogeography across geological time scales, but a number of physical factors play key roles in determining the distribution of species, operating within the lifetime of individuals, particularly during the planktonic larval phase (Hilario et al., 2015). Initial investigation of vent fauna from Loki's Castle at the northern terminus of the Mohn's Ridge suggests that its fauna has evolved through local adaptation and by migration from Atlantic cold seeps and Pacific vents (Pedersen et al., 2010). These results lead to questions on the role of the deep Arctic Ocean in driving regional and across-basin connectivity and in shaping global biogeography.

Data from the PS86 cruise (Boetius, 2014) show that the Aurora seamount (4300-3850 m

depth) has steep vertical basalt walls, encrusted by filter feeders, intermixed with lower angle, sediment draped steps and sledges. The top of the seamount is flat and sediment covered. Identified fauna on the Aurora seamount was characterized by high abundance of sponges and anemones on the rocks and at least 2 species of shrimp. Ophiuroids, swimming polychaetes and crustaceans (potentially isopods) were also observed. The active vent sites were colonized by bacterial mats and small white organisms (potentially limpets and/or other small gastropods) and a low density of amphipods (Boetius, 2014).

In 2019, the first cruise (HACON19) of the HACON project (FRINATEK-Norwegian Research Council) took place on board RV Kronprins Haakon. The cruise was designed to conduct a multidisciplinary survey of the Aurora seamount centered around the black smokers identified in 2014. The scientific objective was to obtain visual and physical samples of the different habitats on the seamount to better understand hydrothermal vent communities on the Gakkel Ridge and abyssal Arctic communities. Although the sedimented habitat of the Aurora seamount was well sampled with a multicore, boxcore, gravity core and CTD, technological and ice coverage challenges prevented the research team from sampling the vent field itself.

The HACON21 cruise was organized to re-visit the Aurora vent field and conduct a full multidisciplinary survey with a focus on observations and sampling of the hydrothermal vent habitat and ecosystem. The specific objectives of the cruise included the following:

1. Conduct exploratory ROV dives on the Aurora Vent Field.
2. Sample vent fluids with IGTs (Isobaric Gas Tight sampler) for geochemical analyses.
3. Sample rocks from active and inactive vent chimneys for geochemistry, geology and microbiology.
4. Sample the sedimented system on the active vent field with blade cores and pushcores for geochemistry, microbiology and meiofauna analyses.
5. Sample the macro-fauna for taxonomic (morphological and molecular), phylogenetic and ecological studies.
6. Sample the hydrothermal plume with a CTD rosette and Niskin bottles using the ROV.
7. Conduct ROV video transects for faunal community analyses and habitat mapping.
8. Collect additional multicore and gravity core samples in areas of the Aurora seamount that were not sampled in 2019.
9. Raise awareness of the investigation of Arctic hydrothermal vents through a dedicated communications team.

### **3.2 NE Greenland**

The shelf off northeast Greenland is a highly interesting area to study in terms of past climate changes and glacial cycles as it covers an area of 100.000 km<sup>2</sup> of mainly unexplored seafloor between 0-500 m depth on a high-latitude shelf. The shelf region spans between 76-81°N and 5-17° W and has an almost permanent sea ice cover, oscillating with seasons. The sea ice is transported south from the Arctic sea by the East Greenland Current (EGC). It is thus impractical to acquire scientific data from the shelf for most of the year. This has resulted in extremely

sparse coverage of high-resolution data such as bathymetry (Arndt et al., 2015; Jakobsson et al., 2020).

The NE Greenland shelf was covered by grounded ice during the last glaciation; however, the detailed glacial history is poorly understood, and the extent and dynamics of the palaeo-ice sheet is not known. Our understanding of the past glacial cycles and climate changes that caused it, rely on high-resolution data to decipher and reconstruct past glacial extent and dynamics (Evans et al., 2009; Winkelmann et al., 2010; Arndt et al., 2017; Laberg et al., 2017). At present, our high-resolution data is limited to small widespread surveys and scattered single traces of high-resolution multibeam bathymetry (Evans et al., 2009; Winkelmann et al., 2010; Arndt et al., 2017; Laberg et al., 2017). In addition, 2D seismic surveys have revealed a very shallow and sometimes outcropping sedimentary strata, which are locally tilted with an erosional surface. There were also revealed the presence of salt and salt diapirism, causing folding, tilting and possibly faulting of the overlying strata it pierces. The same seismic studies have indicated the presence of fluids in the subsurface.

This part of the cruise focused on data acquisition and sediment sampling between 78-79°N and 5-16°W. Our two main objectives were:

1. To acquire high-resolution acoustic data and sediment samples to shed light on the glacial history of this highly unexplored shelf.
2. To investigate the potential migration and leakage of fluids from the seafloor to the water column, through eroded tilted surfaces and faults of sub-cropping sedimentary bedrock.

## 4 GEOLOGICAL SETTING OF THE AURORA SEAMOUNT

Christopher German

The Aurora hydrothermal field sits in the westernmost segment of the Gakkel Ridge within the Western Volcanic Zone (Michael et al., 2003) which extends for 220 km from 7°W to 3°E. The spreading rate here is 14.5-13.5mm/yr and the ridge axis floor at 4200 m depth is bounded by steep normal-fault rift valley walls and punctuated by a series of axial volcanic ridges and smaller volcanic mounds that rise up hundreds of meters above that axial floor depth (Michael et al., 2003). The Aurora field was first located associated with one such volcanic mound as part of the InterRidge two-icebreaker AMORE expedition in 2001. At 82°53'N, 6°15'W a small volcanic mound measuring ~1.5-2km in extent rises approximately 400m from the seafloor at a saddle-point where the rift- valley narrows from ~20 km to ~15 km wide. A dredge from S to N across this volcanic mound in 2001 recovered components of an extinct sulfide chimney in addition to abundant pillow basalts while *in situ* sensor data from a MAPR instrument attached to that dredge revealed clear evidence for a particle-rich lens, consistent with a nearby source of active black smoker venting, at a plume depth of 2800-3400 m (Edmonds et al., 2003).

During a return cruise to the site aboard the RV *Polarstern* in 2014 (Boetius et al., 2014a) CTD profiling coupled with water column sampling and CH<sub>4</sub>, TDMn and He-isotope anomalies revealed clear evidence for ongoing hydrothermal activity including strong evidence from CH<sub>4</sub>:TDMn ratios of ultramafic influence in the underlying vents (Boetius et al., 2014b, German et al., 2017). Buoyant plume signals intercepted with the CTD during that cruise suggested at



least one source of venting was situated toward the south/southwest of the shallowest summit of the Aurora seamount and OFOS deep-tow camera tows from North to South across that summit revealed deep rifts through the thickly sediment seafloor surrounding the base of the volcanic mound. Those rifts were observed striking approximately E-W (across axis) immediately south of the summit of the seamount on at least two OFOS tows. These paired observations (CTD, seafloor imaging) led to first imaging of an active vent at ~3900 m depth at a Posidonia position of 82°53.83'N, 006°15.32'W.

## 5 NARRATIVE OF THE CRUISE

Stefan Buenz & Eva Ramirez-Llodra

A Gantt chart showing the different activities during the cruise is included in Appendix 1.

*Note: Given times in this narrative are local times. Log sheets are in UTC.*

### Tuesday, 28<sup>th</sup> September

The scientific team arrives at RV *Kronprins Haakon* early in the morning. The ROV team had already started mobilization of the REV Ocean ROV a day earlier. Still much is left to do and the main focus for the first and second day is to finish mobilization and conduct a test of the ROV in shallow water outside of Longyearbyen.

### Wednesday, 29<sup>th</sup> September

Mobilization of the ROV continued in the morning and was completed around mid-day. Scientific crew received a safety briefing at 09:00. The remainder of equipment from UiT and UiB was mobilized and lifted onboard during the morning hours. At 12:30 the REV Ocean ROV was baptized, its name being "*Aurora Borealis*", "*Aurora*" for the ROV and "*Borealis*" for the TMS (Tether Management System) (Figure 4). We then sailed out of Adventfjorden into a water depth of about 250 m for the maiden test of the ROV. At 19:29, the ROV descended into the ocean for the first time ever. Technical readings of the ROV showed an oil leakage and most likely we saw the oil on some of the camera feeds of the ROV. All other electrical systems appeared to be in good working order. The ROV was hauled back into the hangar. The locations of the oil seepage could not be clearly identified, several plugs were tightened and oil refilled. The ROV descended again but oil leakage persisted. The ROV returned to the hangar and at about 23:00 we ceased working. The ROV was thoroughly cleaned so it would make it easier to identify the location of the oil seepage the next morning.



*Figure 4. The Aurora Borealis team during the baptism ceremony.*

#### **Thursday, 30<sup>th</sup> September**

The ROV team identified and changed a hose that was responsible for the leakage. However, problems with the ROV docking system of the ship prevented further deployment. Investigation of the docking system indicated water and oil leakage into an electrical housing. At 12:00 we realized that repair of the docking system would take much longer. We decided to leave Longyearbyen for the Molloy Ridge area to conduct a deep test of the ROV. In the afternoon and early evening, mechanical and electrical engineers completed repair of the docking system. In the meantime, ROV *Aurora* was prepared for its first deep dive and test of sampling equipment.

#### **Friday, 1<sup>st</sup> October**

At 07:30, we arrived at the test site in the northern part of the Molloy Ridge. Water depth here is about 3600 m. At 08:30, we conducted a CTD station with water sampling in order to calibrate acoustic systems onboard. At 11:12, the ROV descended for its deep test. After about 2 hours it reached the seafloor. The ROV surveyed the seafloor for several hours checking and testing a number of system components. At around 18:00, the ROV blacked out and all communication was lost. Electrical systems however, do not show any short cuts or grounding failures. At the same time, the TMS also shut down. USBL navigation data showed that the ROV was sitting on the seafloor. There was still about 210 m of umbilical cable out between the TMS and ROV. The ROV team could not reestablish communication with the ROV. Their focus was on restarting the TMS such that they can pull in the umbilical cable and ROV into the TMS. After many unsuccessful attempts, they decided to start pulling up the TMS slowly at 0,1 m/s to make an emergency recovery. However, in the meantime they continued to restart the TMS and after replacing some parts of the power supply unit, they succeeded. It allowed them to pull in the

ROV into the TMS and secure it there. Shortly after 23:00, ROV *Aurora* was safely back in the hangar. During the recovery, a small indentation was spotted along the umbilical between TMS and ROV, a likely reason for the failure. We continued our journey northwards to the ice edge, feeling confident that the failure could be repaired and that we could conduct another test before entering the ice.

### Saturday, 2<sup>nd</sup> October

A breakage of fiber-optical communication wires was confirmed early after breakfast and the ROV team started to repair the umbilical cable. We reached the ice edge at about 81,75N around 12 noon. Repairs of the ROV were finished at 14:00. The ROV launched for a final test at 15:00 slightly north of the Yermak Plateau, on the ice edge. After about an hour, ROV *Aurora* reached the seafloor at 1700 m water depth. A number of technical readings and statuses were checked. The ROV used the suction sampler to pick up a few biological samples and returned into the hangar at 17:40. We then sailed into the ice towards the Aurora hydrothermal vent field.

### Sunday, 3<sup>rd</sup> October

On Sunday morning 08:00 we had made good progress through the ice. It was 65 nm on a straight line to the Aurora vent field. By 20:00 in the evening, we had cut this distance in half. The ship navigated mostly through open or slightly frozen-over leads but sometimes also had to break ice for passage (Figure 5). The map on the left of Figure 5 shows the overall track of RV Kronprins Haakon during HACON21, from Svalbard to the Molloy Deep, then on to the Aurora Vent field, back to Molloy Deep, across to the NE Greenland shelf and finally back to Longyerabyen.

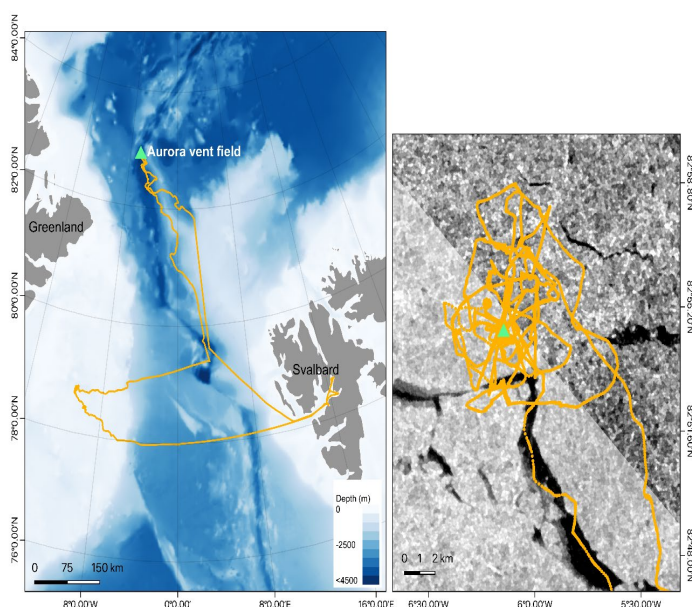


Figure 5. Shiptrack for RV Kronprins Haakon during the HACON21 cruise, and shiptrack over the Aurora Vent Field (green triangle) over an ice satellite image.

### Monday, 4<sup>th</sup> October

The ship stopped for three hours during the night due to lack of visibility required for navigating the ice. At 08:00, we still had about 20 nm to travel to the vent field. At the end of the day we had made it to the Aurora vent field. On the way, we had the encounter of two polar bears, a mum and her cub, both looking healthy (Figure 6). The vessel passed by the vent field in order to place the ship in position northeast of the site with expected ice drift in a southwest direction.



*Figure 6. A polar bear mum and her cub observed on our way to the Aurora Vent Field.*

### Tuesday, 5<sup>th</sup> October

The ship was maneuvered into position for launching the ROV up-drift from the vent location in the early hours of the day. At 06:45, the ROV was launched and descended 3900 m into the rift valley of the Gakkel Ridge (ROV 005). A SSW drift of the ice took the ship and ROV across the Aurora Seamount. Increasing ice drift and slight change of drift direction made the dive challenging. The ROV reached the bottom about 200 m northeast of the vent field at 08:30. After some time of visually surveying the seafloor, the ROV found the Hans Tore Vent, a spectacular black smoker apparently situated in a field of many inactive chimneys. Attempts to sample a rock or vent fluids failed due to too low temperature of the hydraulic oil for both thrusters and manipulators limiting its flexibility and handling. Only a small rock piece from a fallen-over chimney was sampled before the ROV had to return to the TMS. At 11:15, the ROV was back in the hangar after its first successful dive under ice in the Arctic Ocean. Issues with the temperature of the hydraulic oil did not allow ROV thrusters and manipulators to operate at optimum. The ROV launched again on dive number 6 at 16:00. However, increasing speed of the ice drift made it difficult for the ROV to keep up with the ship and in order to avoid risks, the dive was aborted. The ROV returned to the hangar at 21:00.

### Wednesday, 6<sup>th</sup> October

The ship repositioned northward against an increasing ice drift. Poor visibility at night made breaking ice and navigating to position very difficult. Early in the morning at 07:00, we conducted CTD station 509 launching northeast of the vent site and drifting close by the vent on its western flank. On the upcast, transmissometer data showed an anomaly at around 3400 m - the same depth as the previously identified Aurora hydrothermal plume (Edmonds et al., 2003). Several water samples have been taken in the depth range of the possible plume signal. We repositioned and conducted another CTD station (no. 510) northeast of the vent site at 17:10. During the day, ROV technicians made a few modifications to the hydraulic system of ROV *Aurora*. ROV007, launched at 22:15 and on arrival at the seafloor, tested modified hydraulics. The test proved successful and hence the dive proceeded on a southward drift for a visual survey and sampling. The dive continued into the early hours of the next day (Thu 07/10).

### Thursday, 7<sup>th</sup> October

A number of biota samples were taken on the transect towards the vent site. However, ice drift velocities were still high at 0,5-0,7 kn such that bottom time was very short. The ROV had to return to the hangar before reaching the vent site. ROV *Aurora* was back in the hangar at 04:30. The ship repositioned through ice into small open water areas to the northeast of the vent site. A gravity core was launched at 08:20 and finished about 2 hours later. The southward ice drift had taken the ship southeast of the vent, where we subsequently deployed the multicorer at 12:00. The multicorer returned with six full liners at 15:00. The ship repositioned to the north of the vent site and ROV *Aurora* was launched on dive ROV008 on a southbound drift at 18:40. During the dive, ROV *Aurora* took two vent fluid samples using the IGT, and a number of rock samples from the same vent that was later named Enceladus.

### Friday, 8<sup>th</sup> October

ROV *Aurora* returned to the hangar shortly after midnight as ice drift didn't allow for a longer time at the bottom. The ship was sitting in tight ice conditions with up to 1 m ice thickness. In addition, nighttime and foggy conditions resulted in poor visibility and as the ice radar didn't show any obvious leads, we had to remain on site for the night. Early in the morning as visibility improved, the ship repositioned to the northeast of the vent sites, breaking through heavy ice. ROV009 started on a southwest drift. However, changing ice drift directions forced us to abort the dive as we would have missed the vents by more than 200 m. The ship repositioned slightly to adjust for the ice drift. However afterwards, also dives no. 10 and 11 had to be aborted due to ever-changing drift directions. ROV012, our 4<sup>th</sup> attempt of the day, launched at 18:00 and finally kept a steady drift in the northeast direction. The dive was successful and obtained several biological samples from the flank of the vents and returned to the hangar at 22:45.

### Saturday, 9<sup>th</sup> October

For another night, the ship was in tight ice conditions with no obvious open water leads on the ice radar and poor visibility were such that we were not able to conduct stationary work off

the vessel. In the early morning hours, the ship was maneuvered into position for another ROV deployment. Ice drift directions had changed so we positioned the ship to the southwest of the vent site for a northeasterly drift. However, both ROV dives 13 and 14 had to be aborted due to constantly changing drift directions trending more east with time. The vessel needed to be repositioned constantly adjusting for ice drift. Ice drift velocity though had slowed down significantly to around 0,1 – 0,15 kn. ROV015 launched at 15:15 and with the decreased ice drift velocity we put the launch position closer to the vent site. The dive reached bottom at 16:30. The dive placed a memorial stone at the Hans Tore vent in memory of the late Hans Tore Rapp from UiB, a former key member of the HACON team, after whom this vent was named. The dive then proceeded with taking several sediment samples (blade and push cores) close to the vent sites. After sampling was completed, ROV *Aurora* flew eastwards to catch up with the TMS and the vessel. The transect crossed several rounded and elongated depressions, crevasses where basaltic rocks could be observed beneath a few meters of sediment. The dive then discovered a vent site, but ran out of time to stay at the bottom in order to confirm whether this site had any active vents or not. ROV *Aurora* returned to the hangar at 20:00. The Captain tried for 2,5 h to put the ship into position for a CTD or coring station. However, for yet another night, we were unsuccessful in finding open leads and we were breaking ice in poor visibility conditions. The vessel finally settled down at 23:00.

### Sunday, 10<sup>th</sup> October

In the early morning hours, the ship found a lead to the northwest of the vent site. The lead mostly was made up of thin ice, up to 10 cm thick and hence, provided good maneuverability for the vessel. As ice conditions were tough elsewhere and ice breaking would not necessarily be possible but potentially would lock us into a more difficult position, we conducted a CTD station (no. 511) northwest of the vent site while drifting closer to it. ROV016 launched at 14:10 on a southeast drift with relatively slow drift speed and ROV *Aurora* was equipped with two IGTs and bio-syringes. The dive reached bottom at 15:33. The dive stopped at another small vent, later named 'Ganymede' and acquired a few chimney pieces and two fluid samples using the IGTs. The dive proceeded to the Hans Tore vent and measured temperature at the rim of the crater structure and in areas of diffuse flow. The bio-syringe slurped in biomass and bacteria from the rim and upper flank of the crater. After that, the suction sampler and manipulator obtained several additional faunal samples off the vent sites. Beneficial ice conditions allowed the ROV to stay at the bottom for 2,5 h, returning to the hangar at 19:40. The ice conditions allowed us to easily reposition the vessel to the northwest of the vents and we conducted a CTD station (no. 513) aiming to drift as close as possible through the plume in order to take water samples of it.

### Monday, 11<sup>th</sup> October

The CTD station was completed at 01:35. Unfortunately, the CTD hit bottom during the cast due to a problem with its altimeter. That resulted in it picking up sediment that dusted off during its upcast invalidating the transmissibility readings. We stayed at the same position drifting south of the vents and conducted a gravity core station that unfortunately returned empty. The vessel then repositioned northwards again for the last dive at the Aurora vents.

ROV017 launched at 09:00 but aborted immediately after launch due to a small camera problem. ROV018 launched at 09:55 and reached bottom at 11:16. The major objective for this dive was habitat mapping on a designed pattern of 6 transects across the whole vent field. Shortly after the dive started, communications were lost. The failure was found to be related to network switches at the onboard control container. The dive resumed after a 20 min boot-up and system check. Fortunately, ice drift conditions were still very beneficial with the vessel very close to the position of ROV *Aurora* and hence the dive did not have to be aborted. After the video transects, ROV *Aurora* acquired a few more faunal samples with its suction sampler. And finally, two Niskin bottles were closed in the plume to obtain water samples. ROV *Aurora* returned to the hangar at 16:00. Subsequently, a gravity core was taken southeast of the vents and successfully recovered ~2,5 m of sediment. This completed our work at the Aurora Vent Field in 2021 and we headed out of the ice towards our working area on the NE Greenland shelf.

### Tuesday, 12<sup>th</sup> October

We sailed in a southeast direction towards the ice margin with the vessel often having to break through thick ice in order to connect the open water leads. At 14:00 in the afternoon, we stopped at an ice floe and the science team were allowed to go on the ice for an hour before we continued sailing. Team photos were acquired by the communications team (Figure 7).



Figure 7. The HACON21 team on the ice by RV Kronprins Haakon.

### Wednesday, 13<sup>th</sup> October

We left the ice at about 18:00. The deck crew had discovered a problem with the CTD winch

and it would have to be spooled off completely before it could be used again. Hence, we set course for the Molloy Deep area, which is deep enough for this operation.

#### Thursday, 14<sup>th</sup> October

We arrived at the Spitsbergen Transform at the northern end of the Molloy Deep and started CTD station no. 514 at 06:30 in 4500 m water depth. As we were in the area, we conducted another ROV dive (no. 19) after our initial test in this area (ROV003) lost communication and failed. One major goal was to sample mantle rocks from the oceanic Deep. However, we found an area that was mostly sedimented with sparsely occurring outcrops. Several samples of what looked like crusts were taken in addition to a few sediment and faunal samples. ROV Aurora returned to the hangar at 21:10. We continued towards the NE Greenland Margin.

#### Friday, 15<sup>th</sup> October

Very shortly after midnight, we surprisingly found the ice margin already about 40 nm off the shelf break, which significantly slowed down progress. Ice floes are tightly packed and several 100s of m<sup>2</sup> large, and unexpectedly they were up to 2 m thick.

Later in the afternoon, we found a good lead with thin ice that we followed. During the transit, we could observe a polar bear that seemed big and healthy (Figure 8).



*Figure 8. A polar bear observed on the transit to the NE Greenland shelf.*

#### Saturday, 16<sup>th</sup> October

Our main target area was located in the middle of the NE Greenland shelf, which, at this location, is at its widest (~150 nm). At 09:30, as we were getting closer through difficult ice conditions, we briefly halted in an ice opening to conduct CTD no. 515 in order to calibrate acoustic systems. We realized that it was impossible to run a constructive multibeam and sub-



bottom survey through ice. It was not only stressful for officers but also was impacting crew and personnel and data quality was poor. However, fortunately, the main target was located in a large lead between ice floes, and only covered with occasional thin ice (~5 cm). We also realized during the CTD station that the ice drifted southwest with a speed of 1,5 kn. This high speed and the limited space between ice floes made any stationary work almost impossible. We therefore decided to stay within the big open water lead traversing it in mostly east-west direction and followed it in a southwest direction.

### Sunday, 17th October

Multibeam mapping continued during the night, but moved to another ice opening slightly to the southeast. We took a gravity core at 11:00. Afterwards we continued mapping in the opening. However, at around 12:00 we headed in a WSW direction towards the ice margin expecting similar tight ice conditions as on the way onto the shelf. At midnight, we were still ~50 nm off the ice margin.

### Monday, 18th October

We passed the ice margin at around 10:00 in the morning. Earlier that day, the ship received a call from mainland Norway informing that the wife of one of the chief engineers on board was hospitalized with complications ahead of the birth of their baby. The captain decided to immediately return to Longyearbyen in order to drop of the engineer in time for a flight to mainland Norway at noon the following day.

### Tuesday, 19th October

We reached Longyearbyen at 09:30 in the morning. The chief engineer left the vessel. With almost a full day left before demobilization must start but any conceivable working area offshore outside the 12 nm zone in about 10-12 hours of sailing, there was no point to leave Isfjorden again. Instead, the ship made a small field trip around Sassenfjorden and members of the scientific team discussed outcrop formations and glacial retreat observed in this area.



*Geology field course in Sassenfjorden by Claudio and Karen.*

### Wednesday, 20th October

Demobilization of ROV Aurora, other scientific equipment and lab areas starts. A lot of work had already been done during transit. All labs and working spaces are cleared and cleaned.

End of cruise dinner with most crew and science party at Kroa.

### Thursday, 21<sup>st</sup> October

Demobilisation is finalized and the science and ROV teams leave the vessel. Several people from the science party fly back home today.

End of cruise.

## 6 SCIENTIFIC EQUIPMENT ONBOARD RV *KRONPRINS HAAKON*

Stefan Bünz

### 6.1 Hydroacoustic systems

The hydroacoustic systems onboard RV *Kronprins Haakon* can be operated simultaneously, where a dedicated software intelligently manages transducer pings to avoid interferences. In-ice operations only allow using acoustic systems that are mounted in the so-called Arctic tank, an ice window in the hull of the ship, where sea ice can slide along without damaging any transducers during ice breaking. However, ice operations make data acquisition more prone to noise.

Among the hydroacoustic systems, the following were used extensively during the HACON21 cruise:

1. Simrad Kongsberg EA 600 – 12kHz single beam echosounder
2. Kongsberg EM 302 multibeam echosounder and SBP 300 Sub-Bottom Profiler

#### 6.1.1 Kongsberg EA 600 –12kHz single beam ekkolodd

The EA 600 single beam echosounder operates up to four high power transceivers simultaneously. Available frequencies span from 12 to 710 kHz. A variety of highly efficient transducers is available to suit all your operational needs from extreme shallow water to a depth of 11.000 meters. Major applications of this echosounder is to identify the depth and finding high-reflective objects in the water column. During this cruise, we operated the echosounder at 12 kHz as this frequency provided best bottom detection. Higher frequencies were notably affected by sea ice under the hull and hence did not often detect bottom.

#### 6.1.2 EM 302 and SBP 300

The EM 302 multibeam echo sounder has an operating frequency of 30 kHz and is designed to perform seabed mapping with high resolution and accuracy to a maximum depth of more than 7000 m. Beam focusing is applied both during reception and transmission. EM 302 is equipped with a function to reduce the transmission power in order to avoid disturbing mammals if they are close by.

The system has up to 432 soundings per swath with pointing angles automatically adjusted

according to achievable coverage or operator defined limits. With dual swath (two swaths per ping) the transmit fan is duplicated and transmitted with a small difference in along-track tilt. The applied tilt takes into account depth, coverage and vessel speed to give a constant sounding separation along track. In dual swath mode, 2 swaths are generated per ping cycle, with up to 864 soundings. The beam spacing is equidistant or equiangular.

The transmit fan is split in several individual sectors with independent active steering. This allows stabilization, which compensates for the vessel movements: yaw, pitch and roll. Each transmit sector has individual beam focusing.

In conjunction with a separate low frequency transmit transducer, the EM 302 may optionally be able to deliver sub-bottom profiling capabilities with a very narrow beam width. This system is known as the SBP 300 sub-bottom profiler. During this cruise, the SBP was operated constantly with a chirp pulse of 50 ms and frequency bandwidth of 2.5 – 6.5 kHz.

The EM 302 (including the SBP 300) is mounted in the ice window in the bottom hull of the vessel. During ice breaking, ice sliding beneath and along the ice window significantly affects the acquisition leading to high noise levels and false measurements.

During the cruise, the multibeam bathymetry data was processed and cleaned using QPS Qimera Software. Initial grid surfaces with a resolutions of 25, 40 and 100 m were produced for the perimeter of the Aurora Seamount. However, high noise levels merit further processing to improve map quality.

## 6.2 Oceanographic systems

Physical and chemical measurements are measured in the water column from a CTD/rosette. The CTD model is a Seabird 911 plus mounted on a 12 or 24 10-liters Niskin bottles carousel and was brought close to the seafloor. The CTD is coupled with different types of equipment such as oxygen sensor, transmissiometer and fluorimeter.

## 6.3 Attributed Sensors

### 6.3.1 GPS/Navigation, Motion Reference Unit

RV *Kronprins Haakon* Uses a Kongsberg Seapath 330-5 system, an integrated global navigation satellite system (GNSS), using the GPS, GLONASS, Galileo or Beidou signals and inertial measurements to provide high quality results for applications including hydrographic surveying, dredging, oceanographic research, seismic work etc. This Seapath system includes a 5th generation MRU motion sensor package, providing up to 0.008° RMS roll and pitch accuracy. This accuracy is achieved by the use of accurate linear accelerometers and unique MEMS type angular rate gyros.

### 6.3.2 USBL HiPaP

RV *Kronprins Haakon* is equipped with a HIPAP 501 Acoustic Underwater Positioning and Navigation System. ROV NUI, OFOBS, CTD and partly also coring equipment were outfitted with a HiPaP beacon for exact positioning information on the seafloor. The HiPaP 501 system operates with the transducer mounted on the hull to allow the transducer to be lowered some

meters below the hull of the vessel. A transceiver unit containing transmitter, preamplifiers and beam forming electronics is mounted close to the hull unit. The HiPaP 501 system has a spherical transducer with several hundred elements covering the whole sphere under the vessel. The system will dynamically control the beam so it is always pointing towards the transponder. The transponder may be moving, and roll, pitch and yaw affect the vessel itself. Data from roll/pitch sensors are used to roll and pitch compensate the position.

The Super Short Base Line (SSBL) principle has the obvious advantage that it only requires installation of one hull mounted transducer and one subsea transponder to establish a three-dimensional position of the transponder. An SSBL system is measuring the horizontal and vertical angles together with the range to the transponder. An error in the angle measurement causes the position error to be a function of the range to the transponder. To obtain better position accuracy in deep water with an SSBL system it is necessary to increase the angle measurement accuracy. The frequency band of the HiPaP 501 is 21 - 31 kHz and the operating range is 1 - 5000 m. The range detection accuracy is given as 0.02 m assuming free sight between transducer and transponder, no or very little noise in the water column and no error from heading/roll/pitch sensor. We recognized interference between HiPaP and multibeam EM 302 systems due to usage of similar frequency bands. For most operations at the seafloor, EM 302 acquisition was stopped, leading to more stable positioning of the USBL transponder.

## 7 REV Ocean ROV “Aurora Borealis”

Leighton Rolley



### 7.1 Overall description

The ROV *Aurora* is a SUPPORTER 32-type ROV from Kystdesign in Akedal, Norway (Figure 9). The system is owned and operated by REV Ocean. *Aurora* is configured to operate as part of a two-bodied system that comprises a separate Tether Management System (TMS) called *Borealis*. Together the ROV and TMS form “*Aurora Borealis*”. The TMS contains an additional 1000 m of neutrally buoyant tether. The HACON 21 mission was only possible due to the two-bodied configuration, which permitted rapid descent (0.8-1m/s) of *Aurora* while the vessel was drifting with ice. HACON21 was ROV *Aurora*'s first deployment.

Figure 9. *Aurora Borealis* being recovered through the RV Kronprins Haakon moon pool.

*Aurora* has a total combined power of 115 Kw, a depth rating of 6000 m and is maneuvered by 7 Sub-Atlantic thrusters. Its dimensions are (LxBxH) 2,75 m x 1,70 m x 1,65 m and it weighs 3600 kg in air. *Aurora* is fitted with both a Schilling TITAN 4 and an Atlas manipulator for sampling and tooling operations.

For videography during HACON 2021 the vehicle was fitted with 2 forward facing Orca HD (IP) cameras and a separate SubC Rayfin 4k camera/strobe. These cameras were mounted on pan and tilt assemblies. Additional cameras for operator situational awareness, piloting and sampling operations are also fitted to the vehicle. The forward-facing lighting capacity of the vehicle includes sixteen LED lights with a total output of 120,000 lumens.

The SUPPORTER 32 can accommodate up to 24 additional hydraulic tooling functions, up to 21 additional survey sensors and 8 camera connectors. During HACON21, hydraulic connections were used by IGT's and bio-syringes.

The ROV control system offers a variety of auto-functions such as AutoPOS and AutoTRACK capabilities. Due to the complexity of HACON21, *Aurora* was always flown manually by the pilot.

*Aurora* is fitted with multiple, interchangeable "skids". During HACON21 the ROV was fitted with the standard science skid (basket/DVL/Suction sampler). *Aurora* is equipped with a large drawer to store sample material during dives. Up to three Bio-Boxes are mounted on the drawer for storing any type of biota as well as rocks. Aside from the manipulator arms providing the opportunity to take direct bio or rock samples, the ROV provides a number of sampling tools including push cores and blade corers (see below). A large capacity suction sampler is fitted to the vehicle with 8 separate sample chambers.

For Subsea tracking the ROV is fitted with two HiPAP (USBL) beacons. One beacon is configured in Responder mode and the backup beacon is configured as a transponder. The TMS (*Borealis*) is fitted with a HiPAP beacon configured as a responder.

## 7.2 Sampling equipment used by ROV Aurora

**IGT:** two Isobaric Gas-Tight samplers from UiB were deployed on the ROV to sample vent fluids. The samplers are of the WHOI design (Seewald et al. 2002) and also were used for temperature measurements of active vents. IGTs, by design, allow for collection of vent-fluid samples suitable for dissolved gas, inorganic and organic geochemical analyses.

**Suction sampler:** suction tube connected to 8 chambers positioned on the back of the ROV.

**Biosyringe:** hydraulic sampling cylinder with ca 1 cm wide tube was used.

**Scoop:** a scoop named Frankenstein was used to collect rubble and rocks.

**Blade corer:** the UiB and REV Ocean blade corers were used. Frame 320 x 100 x 250 mm.

**Pushcores:** two pushcores of 80 mm inner diameter were used.

**Niskin Bottles:** two Niskin bottles operated with Aurora's articulated arm were used.

## 8 HULL-MOUNTED HYDROACOUSTIC SURVEYS

Stefan Bünz & Kate Waghorn

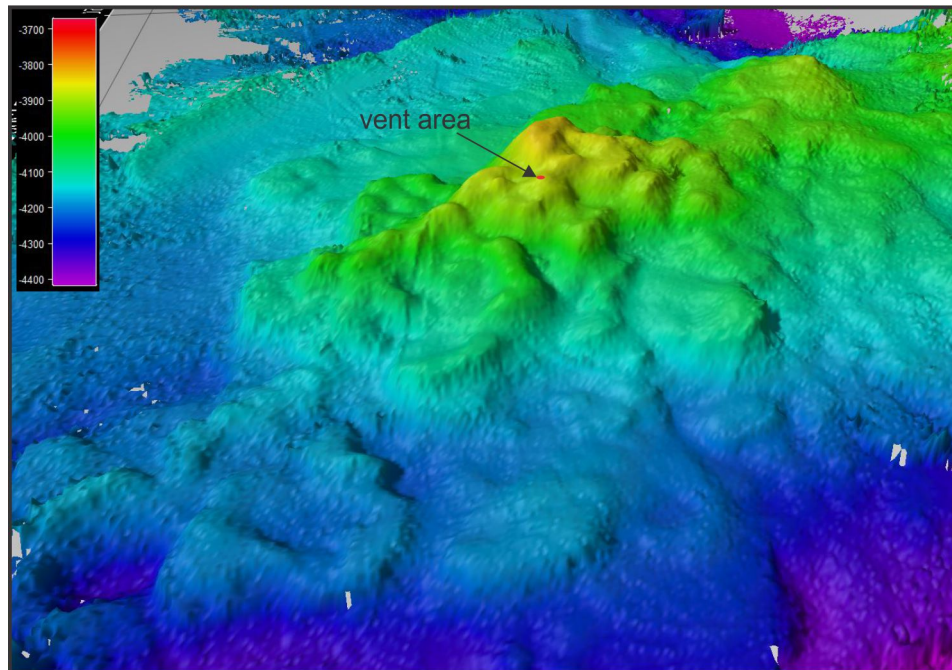
### 8.1 Introduction and objectives

We acquired bathymetric data throughout the expedition with the EM302 multibeam system. There were periods where acquisition was difficult/data was unideal due to ice floats interfering with hydroacoustic systems under the ship. Nonetheless, we acquired a sufficient number of data points across the Aurora hydrothermal vent field. This data was preliminarily processed to grid resolutions of 25, 40 and 100 m. Alongside the bathymetry acquired during the HACON19 expedition, we anticipate a bathymetric map that can resolve seafloor morphology to 15 m. A high-resolution bathymetric dataset is crucial for linking large scale geologic processes (i.e. tectonics) to smaller scale processes like venting and finally to even smaller scale processes such as the distribution of fauna over the vent field.

Data sets from 2019 and 2021 will be merged once ashore, however in the meantime the 2021 dataset is available for initial analyses.

## 8.2 Multibeam Echosounder EM302

The 2021 multibeam data shows the Aurora Seamount in similar detail than the data acquired during the HACON19 expedition. Figure 10 shows a three-dimensional perspective view of the seamount showing a gridded surface with 25 m resolution. The seamount stands about 200-300 m high above the seafloor of the Gakkel Ridge valley. It has a soft conical structure and it is elongated predominantly in SW- NE direction, following roughly the direction of the ridge valley. The summit of the seamount lies at slightly below 3800 m water depth. The vent area is located to the southwest of the summit along one of the volcanic ridges that extend away from the summit.



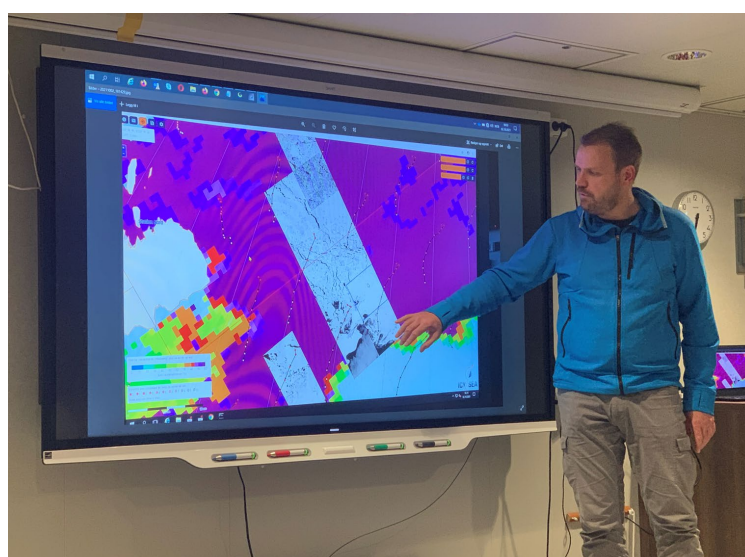
**Figure 10.** Three-dimensional view (facing approximately north) of the seafloor bathymetry and structure of the Aurora seamount obtained from multibeam surveying during the HACON21 cruise.

## 9 ROV AURORA VISUAL SURVEYS AND SAMPLING

Eva Ramirez-Llodra, Ana Hilario, Ida Steen, Pedro Ribeiro, Lissette Victorero, Sofia Ramalho, Maria Baker, Emily Denny, Carolina Costa, Eoghan Reeves, John Jamieson and Stefan Buenz

## 9.1 ROV operations under ice

A total of 19 dives were made, including 4 test dives off ice, 2 science dives at the Molloy Deep and 13 science dives under ice, on or close to the Aurora Vent Field (AVF). Of these vent dives, 6 dives were successfully conducted on the AVF, and 1 dive was conducted off vent. The metadata for all dives, including sampling, is available in Appendix 2. Each dive was carefully planned, with a detailed dive plan that included the objectives and responsible people for each sampling regime, along with a thorough assessment of the ice drift direction and speed, including predictions of regional ice drift from Drift Noise (covering an area of 360 km<sup>2</sup> around the Aurora volcano) (Figure 11), and the vessel ice radar which has a maximum range of 6 nm. The vessel would be positioned ahead of the vent, at a distance that varied depending on the sea ice drift speed. Drift speeds up to 0.3 knt are deemed to be good providing enough bottom time for the ROV to sample. Between 0.3 and 0.6 knt operations are feasible but challenging. But above 0.6 knt operations become difficult. Ice drift was assessed by positioning the vessel in the ice floe and letting it drift for a few minutes in order to get a good reading of direction and speed. The ROV would then be launched at a distance from the vent that was far enough to allow for the ROV to descend to the seafloor (which took around 1.5 hours at 0.8 m/s descent speed) and fly ahead of the vessel towards the target. If the ROV was launched too far away, particularly with slow drift, there was a higher probability of the drift changing direction during the descent, taking the vessel away from the target. The seafloor time of the 7 successful under-ice dives ranged from 25 min to just over 2.5h on the vent field.



*Figure 11. Stefan Buenz during the daily science meeting explaining the ice drift predictions for the following day.*

## 9.2 Introduction and objectives for ROV dives

The HACON21 cruise has achieved, for the first time, successful ROV dives on deep hydrothermal vents under permanent Arctic ice cover. Black smokers of the Aurora Vent Field (AVF) were first observed in 2014, during the RV *Polarstern* PS86 cruise led by A. Boetius from AWI (Boetius, 2014). Transects of the AWI towed Ocean Floor Observation System (OFOS) provided images of the seafloor from the Aurora seamount, and a few frames of the only black smoker observed at the time. The AVF was revisited with the upgraded towed Ocean Floor Observation and Bathymetry System OFOBS (AWI) in 2019 (Buenz & Ramirez-Llodra, 2019). In 2021, we have re-visited the AVF on board RV *Kronprins Haakon* with the REV Ocean ROV *Aurora* in order to conduct a full multidisciplinary survey and sampling of the vent field, including the following samples and data:

- Video transects for a detailed understanding of the distribution of black smokers (active and inactive) in the AVF and habitat mapping.
- Hydrothermal fluids for comprehensive geochemical analyses.
- Chimney pieces from active and inactive vents for geochemistry, geology, radioisotope geochronology, microbiology, and macrobiology.
- Sediment samples collected with blade corers and pushcorers, for geochemistry, microbiology and meiofauna.
- Faunal samples collected with the suction sampler and on rocks collected from the manipulator, for morphological and molecular taxonomy, phylogeny, population genetics and early-life history analyses.

## 9.3 General description of the Aurora Vent Field

The Aurora vent field is located on the flank of the Aurora seamount. The seamount consists of pillow basalts variably covered by up to ~3 m of sediment. The vent field occurs over an area of ~140 m x 100 m, marked by the visible extent of abundant hydrothermal chimney and crust debris, which are variably covered by sediment. Active hydrothermal venting occurs near the center of the vent field, and consists primarily of isolated vigorously venting black smoker chimneys that occur in a ~10 m diameter cluster. Abundant inactive chimneys, chimney debris, and yellow/orange iron-oxide rich accumulations associated with lower-temperature diffuse venting occur near the active vents. Three active black smoker chimneys are described below.

### 9.3.1. Hans Tore Vent

The Hans Tore Vent (Figure 12) is located on the flank of a large hydrothermal sulfide mound. The vent consists of a tall (at least 2 m), narrow chimney emitting black smoke fluid from its summit. A second, ~1 m tall chimney, also emitting black smoke fluid, occurs next to the main chimney. Both chimneys sit in the middle of a ~2 m diameter, ~1m deep circular crater, with black smoke fluid emitting from the bottom of the crater through two small chimneys. Diffuse, lower-temperature venting occurs along the rim of the crater and small iron-oxide chimneys are evident on the rim of the crater.

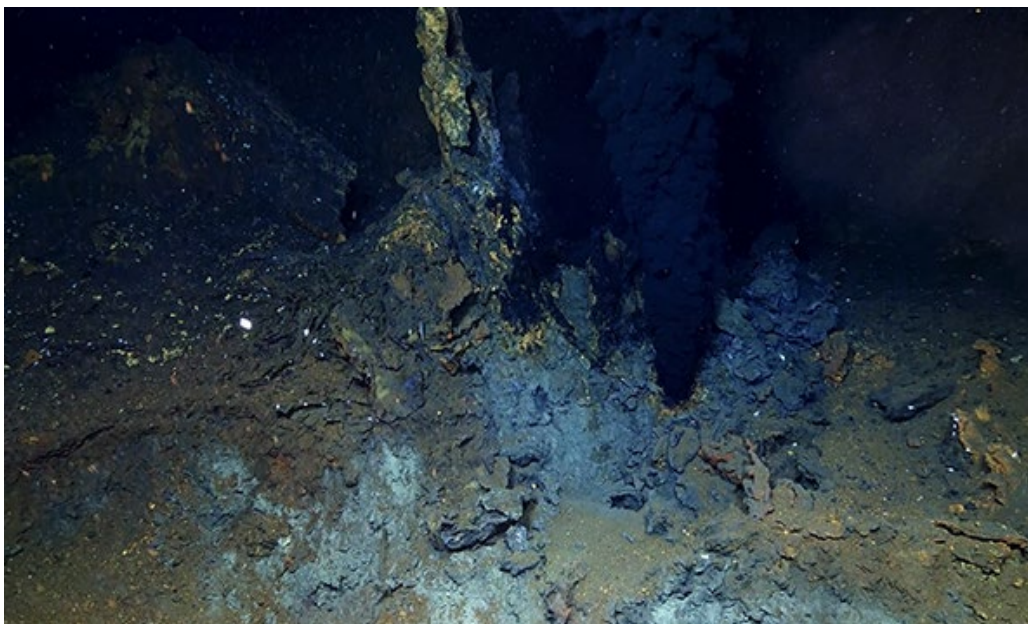




*Figure 12. Hans Tore vent, Aurora Vent Field. © ROV Aurora/REV Ocean.*

### **9.3.2. Enceladus Vent**

The Enceladus vent (Figure 13) is located in a forest of inactive chimneys ~10 m southwest of the Hans Tore vent. The vent consists of a single ~1.5 m tall chimney structure with black smoke emanating from the walls along the entire length of the chimney and from the top of the chimney. During sampling of the chimney, the entire structure toppled over, due to the fragile nature of the highly porous walls.



*Figure 13. Enceladus vent, Aurora Vent Field. © ROV Aurora/REV Ocean*

### 9.3.3. Ganymede Vent

The Ganymede vent (Figure 14) is situated ~5 m northeast of Enceladus, slightly south of a line between Enceladus and Hans Tore vent. The vent occurs on relatively flat seafloor, and consists of black smoke venting from ~5 individual exit orifices at the base or sides of a partially collapsed chimney structure. The vent is surrounded by a rampart of collapsed chimney debris.

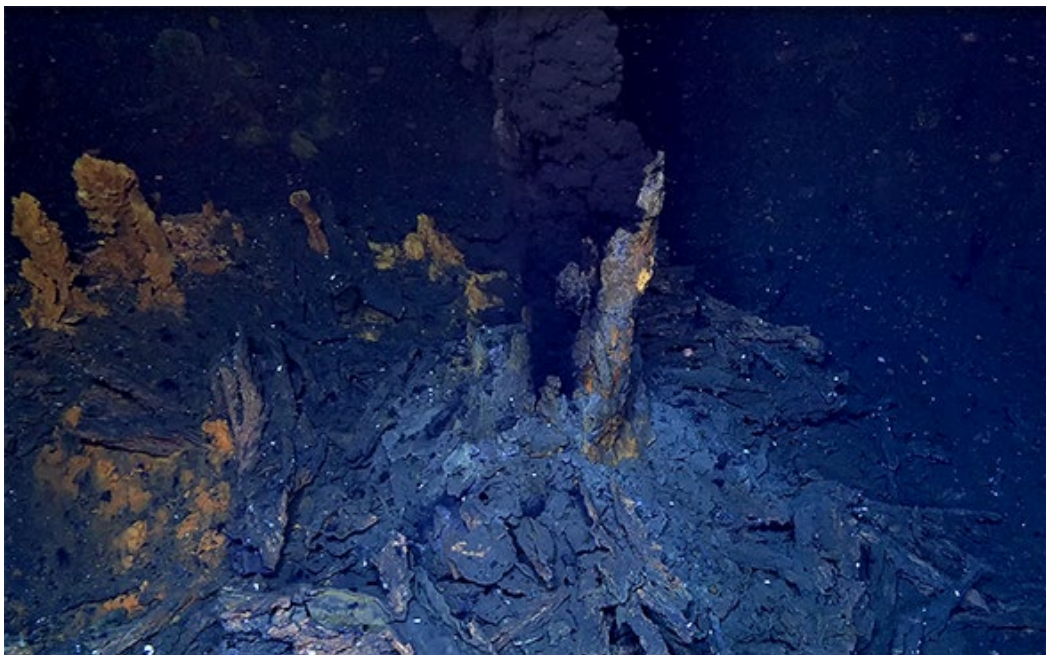


Figure 14. Ganymede vent, Aurora Vent Field. © ROV Aurora/REV Ocean

## 9.4 Naming of the Aurora Vent Field smokers

The largest smoker that was already observed with OFOBS during HACON19 was named Hans Tore Vent, in memory of Prof Hans Tore Rapp, colleague from UiB and good friend, who passed away in 2020. Hans Tore was key in developing the HACON project. The two other smokers have been named after ‘Ocean World’ moons in the Solar System, some of which may harbor hydrothermal activity, and therefore, possibly associated life. Enceladus was chosen as it is an ice-covered moon of Saturn, with a suspected ocean many 10s of km deep, one that has been predicted to host hydrothermal activity (Waite et al. 2017). Ganymede - an ice-covered satellite of Jupiter, is not only the largest moon in the Solar System, but may have its largest saline ocean (one which is implicated in altering its polar aurora (Saur et al. 2015)), and provides a fitting connection to this locale. Though the ocean world Europa was also considered as a potential name, it was not chosen simply to avoid confusion with a previously inferred hydrothermal source at the Mid-Cayman Rise (German et al. 2010).

## 9.5 Vent Positions

Kate Waghorn and John Jamieson

The three active vents within the Aurora vent field are all close together, at ca. 4000 m water depth. During the HACON21 expedition, we relied on USBL positioning for the ROV and, thus, for all our samples and observations. With this in mind, we can locate the vent field, but the

individual vents within the field are difficult to assign an accurate position. Deciding on a ‘best position’ for the vents is in part an attempt to illustrate various sample positions – for example a blade core acquired on the flank of Hans Tore vent appears to be on the flank of Hans Tore vent in illustrations and maps. However, the positioning error has meant that both samples and vent observations have a ~10 m margin of error at 4000 m water depth. Therefore, we have to give all the vents a best position that reflects our video observations and sampling locations. At times when we know that the ROV was stationary on the seafloor for 2 minutes during sampling procedures, within those 2 minutes the position drifted up to 8 m. Assigning positions to the vents has attempted to keep all the sampling locations as close to the visually observed location as possible (i.e. eastern flank of Hans Tore vent), while also using observations (heading, altitude, depth and time stamped location from USBL) from the ROV video. The relative positioning of vents and samples are plotted to be spatially relative based on ROV video and heading information and that these positions may differ from reported coordinates by ~10 m. An average location of all the vent observations and sample locations across all dives yielded a coordinate per vent.

It should be noted that the sample locations also have this margin of error and may not be correct in and of themselves. A more thorough approach to locating the vents (and samples where necessary) will be part of the work to integrate videos and create a 3D model of the vent field.

- **Hans Tore:** 82.8971789 -6.2554189, 3883 m
- **Enceladus:** 82.8971308 -6.2560058, 3887 m
- **Ganymede:** 82.897111 -6.2560139, 3884 m

The relative positions of the three active vents (Figure 15) are based on estimated distances between vents from ROV video footage and ROV headings recorded during transits between the active vents during ROV Dive 16.

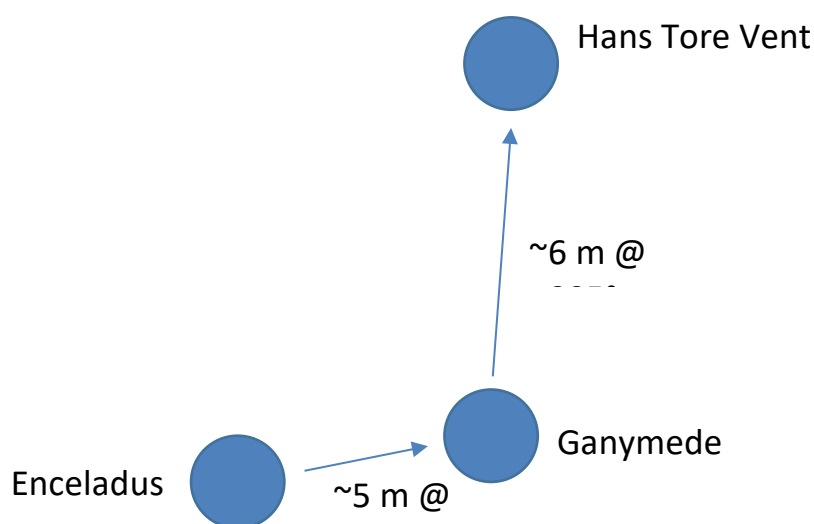
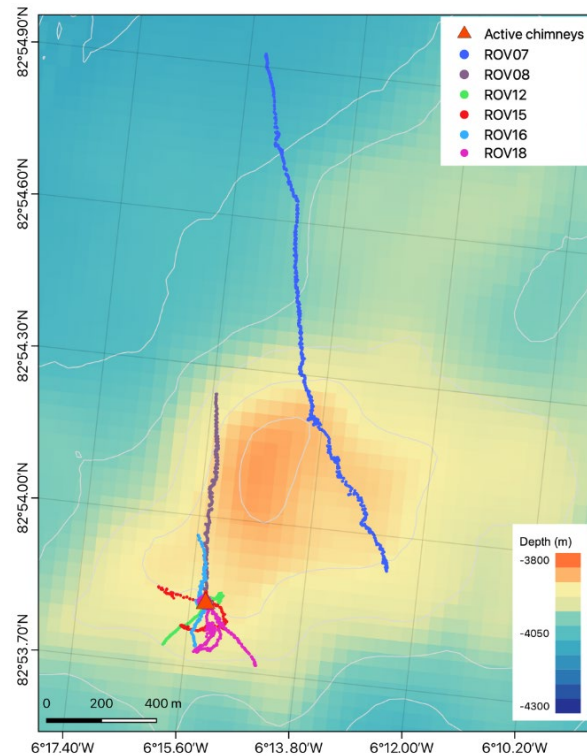


Figure 15. Relative position of the 3 active black smokers on the Aurora Vent Field.

## 9.6 ROV dives description

Nineteen dives were conducted, of which 6 were successful dives on the active vent field, and 1 was off vent (Figure 16).



**Figure 16.** Map showing all successful ROV Aurora dives on the Aurora Vent Field (red triangle) and Aurora seamount during HACON21.

### ROV001 – 29/09/2021 – Adventfjorden

ROV001 was the first time *Aurora Borealis* was in the ocean. The aim of this dive was to conduct a shallow-water (<200 m) test in Adventfjorden. Aurora was launched at 17:29. Technical readings of the ROV showed an oil leakage and we seemed to see this on the camera feeds. All other electrical systems appeared to be working fine. *Aurora* is recovered to troubleshoot the problem. The origin of the oil leakage could not be clearly identified, but several plugs were tightened and oil refilled.

### ROV002 – 29/09/2021 – Adventfjorden

ROV *Aurora* is launched again for a second shallow-water test at 19:00. The ROV goes down to approx. 250 m, with the aim to calibrate the doppler and check all systems are working. The 4k camera is not working and there is still an oil leakage problem. *Aurora* is back in the hangar at around 20:00 and thoroughly cleaned to help identify the location of the oil seepage the next morning.

### ROV003 – 01/10/2021 – Molloy Deep

ROV *Aurora* is launched at 09:25 for its first deep-water test, on the Molloy Deep. The oil leak

has been sorted. The 4k camera was an issue with the camera using too much power, so the fuse was changed and the camera is now working well. However, there is a problem with the winch that lowers the TMS docking stage, and although the engineers have been looking at it, for this dive it needs to be operated manually, which is a difficult operation. Aurora dove at  $0.5 \text{ m.s}^{-1}$ , going to 1440 m. We reached the seafloor at 3714 m depth. It is a sedimented area with lebenspuren, polychaete tubes or stalked crinoids, sponges, anemones and some shrimp. We saw our first Dumbo Octopus. The suction sampler and chambers were working fine. We then needed to pay out all the tether from the TMS, to pay it in again ensuring there are no crossed or loose turns.

15:40 – When we have about 200 m of tether out, we suddenly lose communication with Aurora, and shortly after the TMS shuts down. The USBL on the ROV shows that *Aurora* sits on the seafloor. The ROV team starts troubleshooting, focusing on re-starting the TMS. At about 19:00, after many unsuccessful attempts, they decided to start recovering the TMS slowly at  $0.1 \text{ m.s}^{-1}$  to make an emergency recovery. However, in the meantime they continued to restart the TMS and after replacing some parts of the power supply unit, they succeeded. *Aurora* is brought back to the TMS and then recovered on board. The operation through the moon pool is difficult, as the ROV is slightly on its side on the TMS, and the recovery is still done manually.

21:00 – *Aurora* is back on board. The oil from the junction box is being drained to work on the tether the following day. During recovery of the TMS, a small indentation was observed on the tether between TMS and ROV, which is a likely reason for the failure.

This has been a nerve-wracking start, which could have resulted in the end of the cruise. But the ROV team is confident that the failure can be repaired and a new deep test dive can be conducted on the ice edge.

#### **ROV004 – 02/10/2021 – Yermak Plateau**

A breakage of 2 fibers in the fiber-optical communication wires was confirmed. The tether was cut and re-terminated, and Aurora was ready to dive again (Figure 17).



*Figure 17. Repair of the ROV's umbilical tether.*

13:00 – ROV *Aurora* was launched by the ice edge (81 47.09'N, 2 26.42'EN) for a final deep-water test north of the Yermak Plateau. The seafloor was reached after approx. 1h, at 1700 m depth. *Aurora* lands on sedimented seafloor with many small holes. The suction sampler is tested, and we sample a stalked crinoid, an asteroid and a few amphipods from dead sponge spicules. This has been a successful test dive, with no major issues and we are now ready to go in the ice. At 15:30 *Aurora* is back on board.

#### **ROV005 – 05/10/2021 – Aurora Vent Field**

04:47 – First launch of ROV *Aurora* on the Aurora Hydrothermal Vent. This is considered as potentially the only dive on the vents, so the dive is planned to maximise the possibility of having samples for all teams. The main goals of the dive are to take good footage with the 4k, without lasers or equipment in view, sample the hydrothermal fluids with 2 IGTs and chimney pieces for geochemistry and microbiology, and suction sample fauna. If time is available, it is also planned to take 2 blade cores and collect rubble/rocks. The vessel is positioned well into an ice floe by breaking through ice, NE from the vent, taking into account the ice drift speed and direction, and the time needed to get to the seafloor. The ROV is still being launched manually. The ice drift is SSW and 0.3 knt. *Aurora* dives at  $0.8 \text{ m}\cdot\text{s}^{-1}$ . The drift increased speed and slightly changed direction as the ROV was diving, which made the dive challenging, with the only adjustments possible being the maneuverability of the ROV once off the TMS. *Aurora* reaches the seafloor at 06:27, about 200 m NE of the vent field, on sediment. From there, *Aurora* flies towards the position of the Hans Tore Vent obtained from OFOBS in 2019. We find the lower part of the mound and navigate up to the top and arrive on the spectacular Hans Tore Vent, with its crater and now tall chimney rising from inside. This chimney did not seem to be present when we visited the Aurora vent field OFOBS in 2019, suggesting that the chimneys grow relatively quickly, and the fall and new chimneys grow. This is supported by the high number of fallen chimneys within the crater of the HTV, as well as around Encedalus and Ganymede. The attempt to collect vent fluid fails, as it is a difficult setting where the ROV cannot position itself on the seafloor to stabilize, and *Aurora* is experiencing issues with hydraulic oil pressure in the thrusters and manipulators, which limits its flexibility and power. In addition, the stronger ice drift is moving the vessel fast away, so we move away from the Hans Tore Vent. We see another smoker, and then fly over an area with many fallen inactive chimneys. A piece of dead chimney is collected, with difficulty as they break in the manipulator. Then the vessel has drifted too far from the vent, so *Aurora* needs to go back to the TMS and is recovered on board at 09:15. The total bottom time was 43 min, with under 20 min on the vent field. This has been a spectacular dive on the Aurora Vent Field. **This is the first ROV dive under Arctic ice on a hydrothermal vent.** The whole team is incredibly happy.

#### **ROV006 – 05/10/2021 – Aurora Vent Field**

13:56 – The vessel has been repositioned on the ice floe and *Aurora* is launched again, descending at  $0.6 \text{ m}\cdot\text{s}^{-1}$ . The main goals of the dive were the same as for ROV005. However, the ice drift increases considerably, and we reach 0.7 knt and the direction slightly changes, which pushes the vessel slightly off the trajectory to the vent. *Aurora* leaves the TMS well ahead of the AVF, and we navigate slightly above the seafloor, which we see a few times. The seafloor

off vent is sediment with sponges on rocks. When the vessel drifts west of the vent site, Aurora is still 500 m behind and 150 m off the vent site. We try to fly to the vent, but there is not enough power in thrusters (oil pressure issue), and we miss the vent. In order to avoid risks, the dive is aborted and Aurora is back on board at 19:00.

#### ROV007 – 06/10/2021 – Aurora Vent Field

20:21 – The vessel is positioned 2 nm N of the Aurora Vent Field. Ice drift is S at 0.4 knt, which is relatively strong. The filter for the oil hydraulics in the ROV (250  $\mu$ m) has been removed as the cold water makes the oil denser, significantly reducing the oil flow through the small filter mesh (250  $\mu$ m), thus affecting the thrusters and manipulators. The modified hydraulics are tested successfully and the dive proceeds. The main goals of the dive were the same as for ROV005. During the descent, the drift changes to the SE and we know we will miss the AVF by over 650 m. We made the decision to continue the dive off vent, to explore the surroundings on top of the mound. This is a sedimented habitat. We fly over a large basalt rockslide, with many sponges and anemones. We collect two rocks, an anemone and two sponges, but these are unstable formations, and we move away. We continue flying over sediment with sponges. Most of the dive takes place between 3700 and 3850 m depth, but at 21:58 we crossed the 4000 m depth mark (Figure 18)! Total bottom time is 2 hours and 40 minutes. Aurora Borealis is back on board at 01:00.



Figure 18. ROV Aurora passing the 4000 m depth mark for the first time.

#### ROV008 – 07/10/2021 – Aurora Vent Field

The vessel is re-positioned N of the AVF. The ice drift is S, 0.3 knt. The main goals of the dive were the same as for ROV005. This dive is started closer to the AVF, to try to minimize the possibility of the drift changing and the vessel moving away from the planned trajectory. Aurora descends at  $0.8 \text{ m}\cdot\text{s}^{-1}$ , and the drift increases to 0.4 knt, slightly moving westwards from the original drift. Aurora arrives on the seafloor just before the mound. Aurora then speeds up ahead of the vessel towards the AVF. We fly over sediment with sponges on rocks, and pass the rockslide. The dive then climbs the mound and on top, we arrive on a different smoker, which was subsequently named Encedalus. This is a thin smoker surrounded by other smaller chimneys on complex topography. The ROV is stabilised on the seafloor. This creates a large sediment plume, as the sediment is very soft. When this has settled, the sampling can start. The first samples are chimney pieces collected with the manipulator. This also helps make the opening of the smoker larger, which facilitates the IGT sampling (Figure 19). The chimney will grow back within weeks. Then 2 IGTs are taken, successfully. Subsequently, rock/rubble material with fauna (gastropods) is collected with the scoop (named Frankenstein) and placed in the BioBox. When the vessel had passed the AVF and was drifting away, Aurora was recovered to the TMS and then on board at around 21:00.

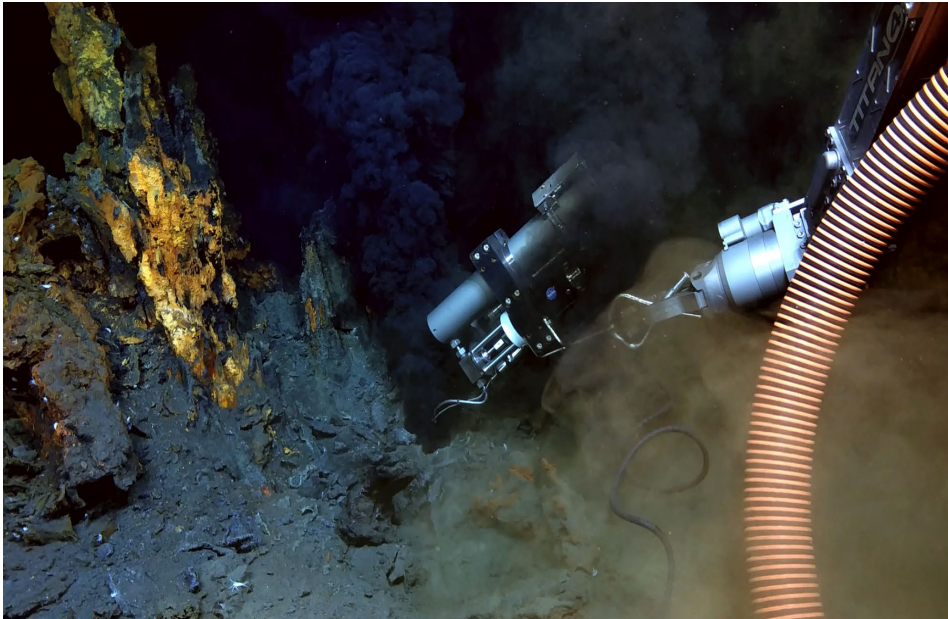


Figure 19. Sampling the Enceladus hydrothermal fluid with the IGT.

The samples are shared with the different groups:

- The 4k film is downloaded and copied.
- The IGTs go to the geochemistry lab.
- Chimney samples go first to the microbiology lab, then to the geo-lab.
- Rocks and rubble collected with the scoop go first into the bio lab, where the samples are sieved and fauna preserved for different studies. These samples then go to the geo-lab.

#### **ROV009 – 08/10/2021 – Aurora Vent Field**

08:30 – ROV *Aurora* is launched north of the AVF. Ice drift is S, very slow (0.2 knt). The main goals of the dive were to conduct a filming video transect (4k) without lasers or equipment in the field of view, followed by biological sampling (suction sampling) and collecting rocks on active and dead chimneys where animals are seen. However, during the descent, the drift changes more SE, and when the ROV is at 3400 m depth, the dive is aborted as we were going to miss the vent by 750 m. *Aurora* is on board at 11:11 for the vessel to re-position.

#### **ROV010 – 08/10/2021 – Aurora Vent Field**

11:59 – ROV *Aurora* is launched again (same dive objectives as for ROV 009), but after a few hundred meters descent, an oil leak is detected and the ROV is brought back on board. The problem is quickly solved and as we do not reposition the vessel, we deploy *Aurora* again, counting this as the same dive (ROV 010). *Aurora* starts descending again, with a very slow drift (0.2 knt), but during the descent the drift has now changed from SE to NE, and when the ROV is at 1000 m it is clear that we will miss the AVF. The dive is aborted.

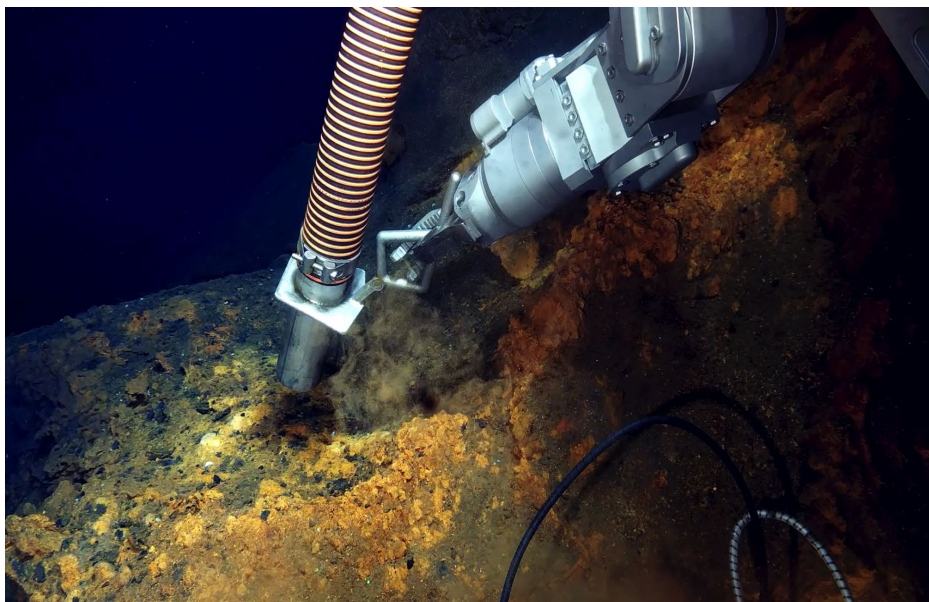
#### **ROV011 – 08/10/2021 – Aurora Vent Field**



13:50 – After repositioning the vessel, ROV *Aurora* is launched again (same dive objectives as for ROV009). However, while we dive, the drift is still slow, but continues to change northwards, and at 14:36, when the ROV is at 2200 m, we abort the dive. We may have been able to reach it by navigating out of the TMS, but we would not have time to sample properly. *Aurora* is back on board at 15:14.

#### **ROV012 – 08/10/2021 – Aurora Vent Field**

16:21 – ROV *Aurora* is launched again, SW of the AVF, with very slow drift (<0.2 knt). The dive objectives are the same as for ROV009. We start the dive relatively close to the AVF. We arrive on sedimented seafloor at 17:41 and quickly arrive at the bottom of the mound, approaching from the SW and fly over an interesting area of inactive chimneys, alternating with sedimented areas with sponges on basalt rock. We fly over chimneys that seem to have been recently active (still very yellow and standing up), before arriving on the active vent field. We take good video footage of the active vent field and then start sampling. At 17:57 we fly over a new small smoker, which is probably one of the ones we saw in 2019 with OFOBS. It stands on its own on a relatively flat area, surrounded by dead fallen chimneys. This vent is named Ganymede. We then arrive on Enceladus and Hans Tore Vent (HTV). The first suction sampling is conducted on the rim of the HTV crater (Figure 20), targeting amphipods. Subsequently, rocks are collected with the scoop, targeting the gastropods. We then reposition to Enceladus and collect additional amphipods with the suction sampler, followed by rock collection. The drift has been slow all through the dive, so this has been a long and successful dive. The dive ends at 18:55, with a total bottom time of 1h14 min.



*Figure 20. Sampling amphipods with the suction sampler.*

#### **ROV013 – 09/10/2021 – Aurora Vent Field**

08:55 – ROV *Aurora* is launched in a good area of thin ice. The drift is slow (0.2 knt). The main objectives of this dive are to sample sediments with blade cores and pushcores, collect rocks

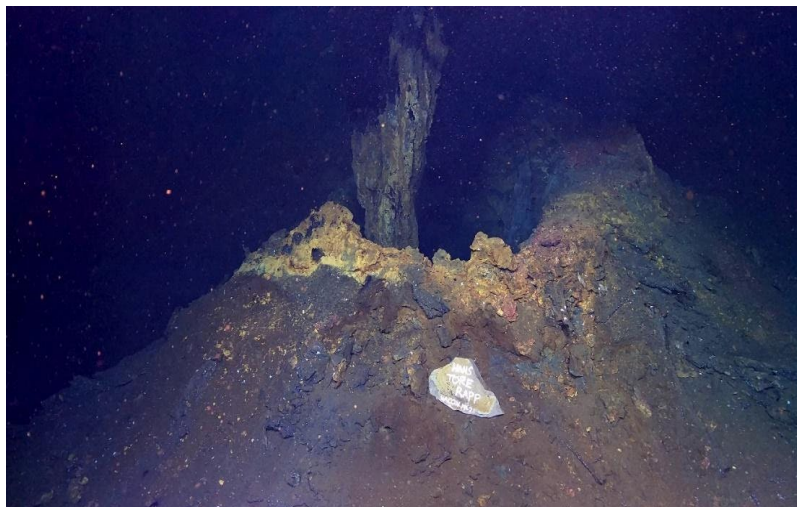
with animals and, if time allows, collect fauna with the suction sampler. Unfortunately, it changes during the descent and the dive is aborted as we would have missed the AVF. *Aurora* is on deck at 10:40.

#### **ROV014 – 09/10/2021 – Aurora Vent Field**

11:51 – The vessel has been repositioned against the ice in the area of thin ice and *Aurora* is launched again. However, when the ROV is at 1100 m depth, the dive is aborted as the drift has continued to change and is taking us past the AVF.

#### **ROV015 – 09/10/2021 – Aurora Vent Field**

17:16 – The vessel has been re-positioned, now very close to the AVF to minimise the risk of missing the vent field again due to drift change and very slow drift speed (<0.2 knt). We are on the seafloor at 18:25, flying over sediment and basalt rocks. The first thing conducted during this dive was to place a memorial stone for Hans Tore Rapp on the side of the Hans Tore Vent crater (Figure 21).



*Figure 21. Hans Tore Rapp memorial on the Hans Tore Vent, Aurora Vent Field, Gakkel Ridge*

*Aurora* moves to Enceladus and is positioned on the seafloor. 3 Blade Cores and 2 pushcores are taken (Figure 22). After the successful sediment sampling, an exploratory transect is conducted around the active vent field. Finally, rock sampling is conducted. During this exploration we fly over a large fissure where the different sediment layers can be seen, and colonised by sponges on its axis. The vessel has already passed the AVF and continues to drift away, but the drift is so slow that *Aurora* can fly quickly to Fix 1 (furthest dead chimneys observed so far) to collect chimney pieces, including some large yellow pieces and black pieces covered with gastropods.



Figure 22. Sampling sediment with the blade corer and a pushcore.

### ROV016 – 10/10/2021 – Aurora Vent Field

12:15 – ROV *Aurora* is launched in calm conditions. The ice drift is extremely slow (0.1 knt) and to the S. The main objectives of this dive were to sample fluid with 2 IGTs and accompanying chimney pieces and collect biofilm with 2 biosyringes, followed by faunal collection if time was available. *Aurora* reaches the seafloor at 13:35, on sediment and moves towards the AVF ahead of the vessel. We fly over the dead chimney field and arrive at Enceladus and then move to Ganymede. Two rock samples are taken, followed by two IGTs and then a piece of chimney from the active smoker. The ROV goes back to HTV and temperature measurements are taken with the IGT probe around the rim of the crater, most of which seems to be shimmering. Two biosyringes are taken at HTV (Figure 23). The ROV then returns to Ganymede to collect amphipods with the suction sampler and rocks with gastropods with the manipulator. At 15:35, when the vessel has already drifted over the vents and is ahead of us, we move to the outcrop with carnivorous sponges, which is just a few meters from the active chimneys (within the hydrothermal influence zone). Several specimens are collected with the suction sampler. From the sponge wall we start flying towards the vessel and fly over a sinkhole. At 15:59 it is the end of the dive.



Figure 23. Sampling microbial mats with the biosyringe.

### ROV017 – 11/10/2021 – Aurora Vent Field

07:15 – ROV *Aurora* is launched. The aim for this dive was to collect video transects across the vent field, imagery for photomosaics, sample rocks and biological specimens and to collect fluids from the plume into two Niskin bottles. The aim of the dive is to conduct 6 video transects over the vent field, od 360° video around the smokers; collect dead chimney; collect amphipods; collect chimney piece from Enceladus for microbiology; and collect 2 Niskin bottles from the plume. After a few meters, *Aurora* is recovered because the cameras have grease on the lens. There has been an issue with grease from the TMS docking station winch, because the winch has not been used at this depth for a long time. We re-position the vessel again.

### ROV018 – 11/10/2021 – Aurora Vent Field

07:57 – ROV *Aurora* is launched, with the same dive plan as for ROV017. The drift is very slow (0.1 knt), but during the descent it changes slightly SW, so the vessel will drift about 70 m south of the AVF. But because the drift is slow, we continue with the dive. We arrive on the seafloor at 09:16 and fly towards the AVF on a NW course. We fly over the fissure on the sediment, with sponges on the axis. At 09:35, a rock is collected off the vent. At 10:00, there are communication issues with the ROV and subsequently lose navigation. The issue is sorted while the ROV is in midwater and the dive can continue. At 10:35 *Aurora* is heading to the start of the first transect line. Six video transects were achieved (Figure 24), each approximately 30 m long, flying at variable height ranging from 1.2 to 3 m at ~0.2 – 0.3 knots. The small size of the fauna required us to maintain a low altitude over the irregular topography resulting in the ROV producing occasional sediment plumes and limiting the visibility of the transect data. During the dive, three smokers were visited and Ganymede and Hans Tore Vent were filmed with the aim of reconstructing a 3D surface for visualisation. During this video, we see two small chimneys inside the crater of HTV which we had not seen before.

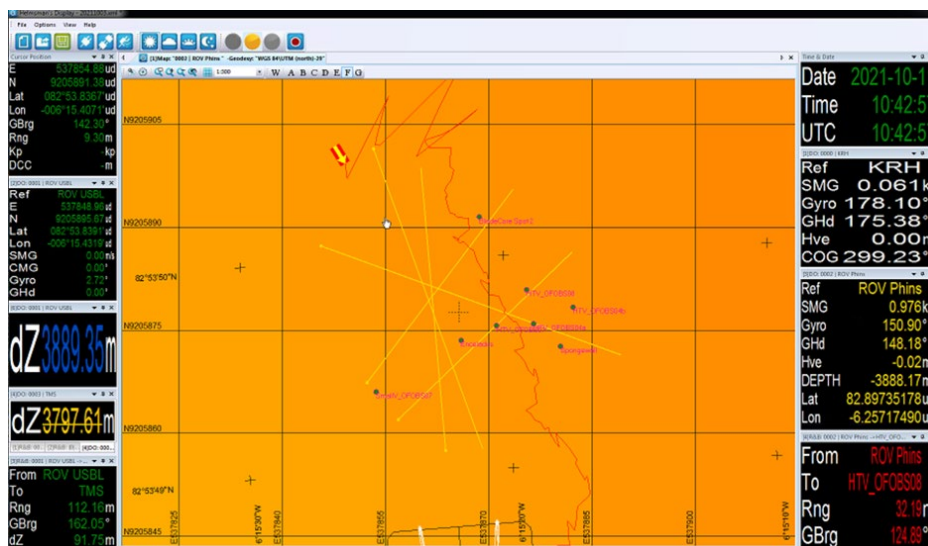
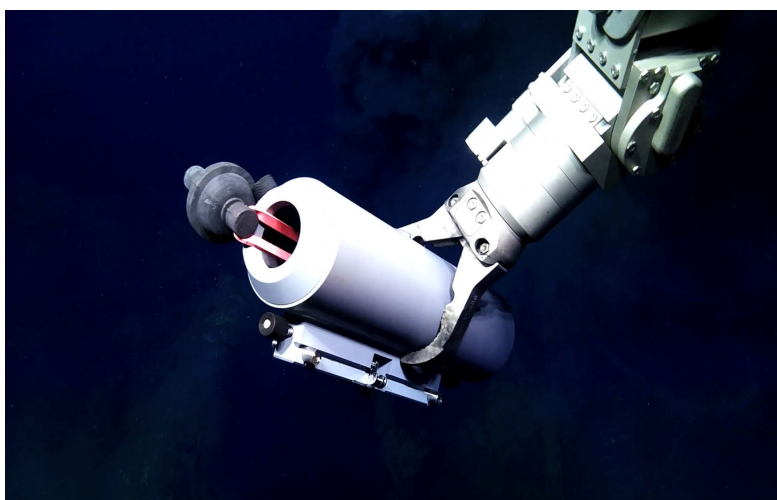


Figure 24. The 6 transects planned over the Aurora Vent Field (yellow lines) and the positioning of ROV

*Aurora (red line) to start the first transect.*

As the drift is very slow, we have enough time on the seafloor, so we proceed to sample amphipods between Ganymede and Enceladus, and chimney pieces at Enceladus. Finally, we proceed to collect plume fluid at HTV for biogeochemical analyses. The two Niskins were collected at 7 m and 10 m height inside the rising plume. This was not an easy task, as the ROV is flying in mid-water. After several attempts, the first Niskin was collected and placed in the basket. During the collection of the second Niskin, the bottle handle breaks, and the bottle falls to the seafloor, luckily not inside the crater. The Niskin is recovered, and a sample taken (Figure 25). The dive ends at 12:21, with a total seafloor time of just over 3h. This was the last dive on the AVF for this cruise and as Aurora ascends back to the vessel, there is a great sense of relief and achievement on board.



*Figure 25. ROV Aurora with the Niskin bottle that had a broken handle moving towards the rising plume of the Hans Tore Vent.*

#### **ROV019 – 14/10/2021 – Molloy Deep**

14:43 – ROV *Aurora* is launched to survey the Molloy detachment and then fly to a very steep wall to collect rocks. The dive takes place between 3763 and 3623 m depth, over sedimented seafloor. There are many large rocks completely covered with stalked crinoids, and sponges are also present on the smaller rocks. Towards the end of the dive, the ROV flew over an area covered with many tubes, but we could not identify what they were, so a few of them were collected with the suction sampler and the 4k zoomed in for future analyses. Sponges are collected with the suction sampler, and rocks with the manipulator. 2 blade cores and 1 pushcore were also taken. We also observed seafloor areas covered by hardened sediment slabs of unclear origin and displaying plane-parallel stratification.

During the dive, we encountered several Dumbo octopuses on the seafloor (Figure 26), and we took good video footage of the first one. There were some issues with losing camera connection during the dive, but it was sorted in situ. Unfortunately, we could not reach the wall, as the transect was very long and we had to end the dive at 17:28, when we were still 700 m away from the wall.



Figure 26. One of the Dumbo Octopus (*Grimpoteuthis* sp) observed on the Molloy Deep Deep.

## 10 VENT FLUID GEOCHEMISTRY

Eoghan Reeves, Samuel Pereira

### 10.1 Introduction and Objectives

Sampling of fluids (together with ‘paired’ chimney material, see 11 below) was a major priority of the HACON project proposal. The earliest ROV dives at the site and ice conditions allowed for rapid direct sampling of the hydrothermal fluids – for the first time in history – previously only observed to be venting during the PS86 and HACON2019 expeditions. Within the framework of Task 1.3 (Geology and Geochemistry of the Aurora Vent Site), the major goal was sampling of high temperature ( $\pm$  diffuse flow/low temperature) fluids using UiB’s isobaric gas-tight (IGT) samplers (Seewald et al., 2002), deployed from the ROV manipulator arms. Comprehensive ship-/shore-based analyses of all biogeochemically-relevant species from the IGTs, e.g. abundances of key microbial/symbiont substrates ( $H_2S$ ,  $CH_4$ ), as well as fundamental biogeochemical parameters (pH,  $H_2$ , major/minor elements, metals), and organic species, were planned to decipher (i) the types of chemical compositions venting at Aurora and how they can support biota at the site, (ii) the styles of venting, as well as (iii) interactions of fluids with the underlying crustal substrate. These data will also allow for direct comparison of the biogeochemical “landscape” of Aurora with other vent sites along the global mid-ocean ridge system, supporting the other project aims.

### 10.2 Sampling Strategy and Sample Collection

The IGT samplers were successfully deployed, with real time temperature measurements during fluid collection, in duplicate pairs within each of 2 vigorously active black smoker chimney orifices on two dives (ROV08 and ROV16) to the area of the main venting surrounding the Hans Tore Vent (Figure 27). Due to the configuration of the ROV Aurora basket, the IGTs were not stored in holsters as is typical, but simply laid within the front tool skid of the ROV basket, with the ICL communications cables tidied and managed alongside the rock boxes. Dive time considerations due to ice drift meant that it was not practical to consider carrying a typical deployment of 2 pairs of IGTs at once, and if

needed, the aim was to sample one IGT at a time in an active vent orifice until a complete pair was collected over one or more dives.

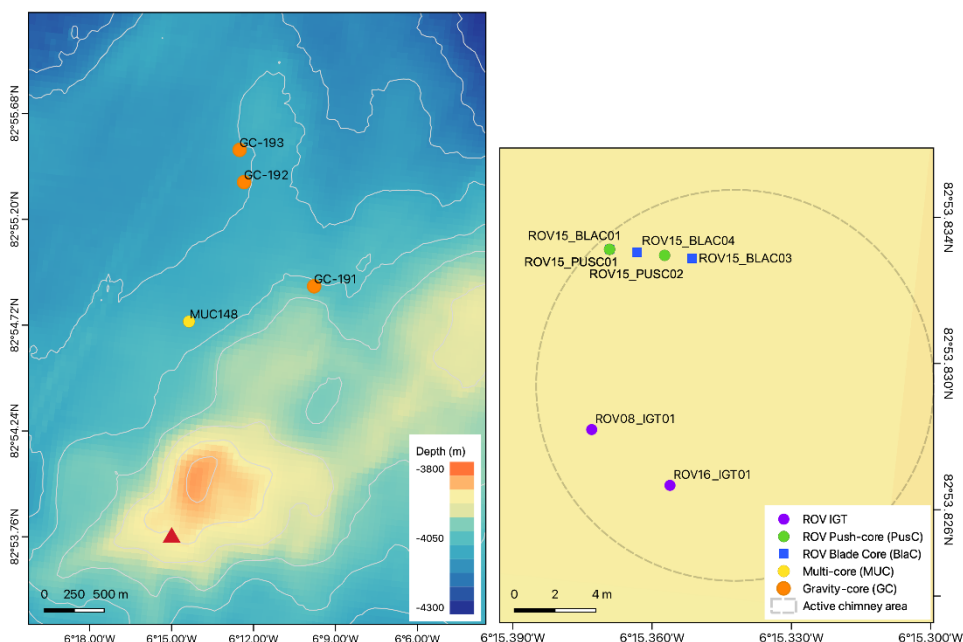


Figure 27. Sample locations for vent fluids (IGT) and sediments (puschores, blade cores, multicores and gravity cores).

During Dive ROV08, samples CAGE-KH-HACON21-02-ROV08-IGT1 and CAGE-KH-HACON21-02-ROV08-IGT2 were successfully fired within the Enceladus high temperature vent orifice in quick succession, after first excavating the orifice for sampling chimney wall material, and to allow for easier access for the IGT snorkel inlet and temperature probe. Much of the excavated chimney rubble fell into the orifice but a stable maximum temperature (within a few °C) was achieved for IGT1 during the fill period of the sampler deployment, indicating the snorkel was correctly positioned in the pure fluid flow. Due to an unknown malfunction (likely a cable issue), temperature data was not collected with IGT2 on the seafloor, but the orifice was re-excavated before its deployment, and was nicely visible positioned well into the wide and open orifice, with much better visibility than for IGT1. In both cases, the IGT sampler inlet valve was observed to open and close as expected, confirming successful filling was occurring.

During Dive ROV16, samples CAGE-KH-HACON21-02-ROV16-IGT1 and CAGE-KH-HACON21-02-ROV16-IGT2 were successfully fired within the Ganymede high temperature vent orifice in quick succession, after first excavating the orifice for sampling chimney wall material samples, and to allow for easier access for the IGT snorkel inlet and temperature probe. Stable maximum temperatures (agreeing within <0.2°C) were achieved for both IGT1 and IGT2 during their respective fill periods, indicating the snorkels were correctly positioned in the pure fluid flow.

Due to the difficult-to-access nature of the main Hans Tore Vent active smoker orifices, located on a tall structure protruding from a large (several m wide) crater, with steep sedimented sides, it was decided to prioritize the fluid sampling at the nearby Enceladus and Ganymede vents, which had similarly vigorous fluid flow. These vents proved to be far more accessible and provided stable positions for the ROV during the sensitive sampling. Despite this, hydrothermal venting at Hans Tore

Vent was probed indirectly. During ROV16, after successful deployment at Ganymede, IGT1 was used to temperature probe survey the diffusely venting rim of the crater, and recorded temperatures at several spots. Sampling of these diffuse fluids themselves using IGTs was also decided against, due to the poorly focused flow (poor chance of recovery), porous sandy nature of the sediment the diffuse fluids were emanating from (risk of clogging the IGT snorkel), and the close (1-2m) proximity to the main Hans Tore Vent. However, 2 successful Niskin bottle samples of the nascent buoyant plume above Hans Tore Vent (~8-10m altitude above the vent – see CTD section) were taken during Dive ROV18. Shipboard gas measurements indicated reasonable suspected dilution levels ( $\sim 10^2$  to  $10^3$ ) of pure hydrothermal endmember for this approximate height (German and Seyfried, 2014), and these Niskin data can be compared then to Enceladus and Ganymede endmember compositions.

### 10.3 Shipboard Methods

All 4 IGT samples came up with full expected volumes of high-quality vent fluid, under near-bottom pressures, with no indications of any serious leakages that would compromise the sample quality. Fluids were successfully processed for diverse shipboard analyses (pH(25°C), H<sub>2</sub>S, CH<sub>4</sub>, H<sub>2</sub>, CO) using the standard set of methodologies employed and referred to in Reeves et al.(2011), with the addition that Total Alkalinity was analyzed using a simple Gran Titration method using 0.01N HCl. All other shipboard processing of the fluid volumes was to ensure adequate preservation of various aliquots for the larger set of shore-based chemical analyses.

### 10.4 Post-cruise analyses

As per Reeves et al. (2011), shorebased analyses will consist of major and minor element (cation/anion) concentration measurements (using either ion chromatography or inductively coupled plasma optical emission spectroscopy), more complete gas analyses using gas chromatography (TCO<sub>2</sub>, C<sub>2+</sub> hydrocarbons etc.), as well as reconstitution of concentrations of the particulate-forming metals (Fe, Cu, Zn etc.) after careful re-digestion and ICP-MS analyses. Metal particulates were successfully collected from the IGT sample chambers on all 4 samples, and there appeared to be minimal evidence of any contamination by entrained chimney particles, suggesting the reconstruction of accurate endmember metal concentrations is likely to be successful for both Enceladus and Ganymede vents. Several novel organic species (methanol, carboxylic acids), as well as ammonium (NH<sub>4</sub><sup>+</sup>), will also be analyzed for in the fluid samples onshore, and aliquots were frozen for shipping for these sensitive species. Stable carbon ( $\delta^{13}\text{C}$ ) isotope compositions of the major carbon species (TCO<sub>2</sub>, CH<sub>4</sub>, C<sub>2+</sub> hydrocarbons) will also be conducted.

## 11 ROCK SAMPLING

John Jamieson

### 11.1 Introduction and Objectives

The first ROV dives at the Aurora vent field provided the first opportunity for direct sampling of the hydrothermal deposits that have accumulated at this site. Fifteen rock samples were collected from seven ROV dives. These samples will be used to: 1) characterize the mineralogy and bulk composition of the hydrothermal deposits at the seafloor; and 2) apply U-series geochronology techniques to determine the age of the deposits.



## 11.2 Methods

Samples were collected either directly with the ROV manipulator arm, or with a metal scoop held by the manipulator arm. In most cases, samples collected from active chimneys and chimney debris proved to be very fragile, and thus the scoop was the more effective sampling tool. As a result, most samples consist of many rock fragments instead of a single coherent rock. Samples were stored on the ROV in either a closed biobox or open plastic container. Once the ROV was back on board, the samples were carefully moved to sterilized trays for removal of surface material for microbiological analyses (see section 13.3 Microbiology), followed by removal of any animals attached to the samples (see section 13.4 Benthic biology). Samples were then rinsed in fresh water and set out to dry in ambient air for at least 3 days. Preliminary onboard descriptions of the samples, based on features identified visually and with a stereo microscope, include the major minerals present, their relative abundances, and macro-textural features (e.g. porosity estimates, identification of fluid channels, surface oxidation).

## 11.3 Samples

Fifteen rock samples were collected from seven ROV dives (Figure 28; Table 1). Four massive sulfide samples were collected from active, high-temperature vents. Four massive sulfide samples were collected from chimney debris at or near the base of the active vents (Figure 29A). Four massive sulfide samples were collected from old, hydrothermally inactive areas at up to ~120 m away from the active vents. Two samples of bright yellow-orange-brown Fe-oxide-rich crust/chimneys were collected from near the active vents (Figure 29B). A single basalt sample was recovered from near the summit of the seamount, ~700 m northeast of the active field.

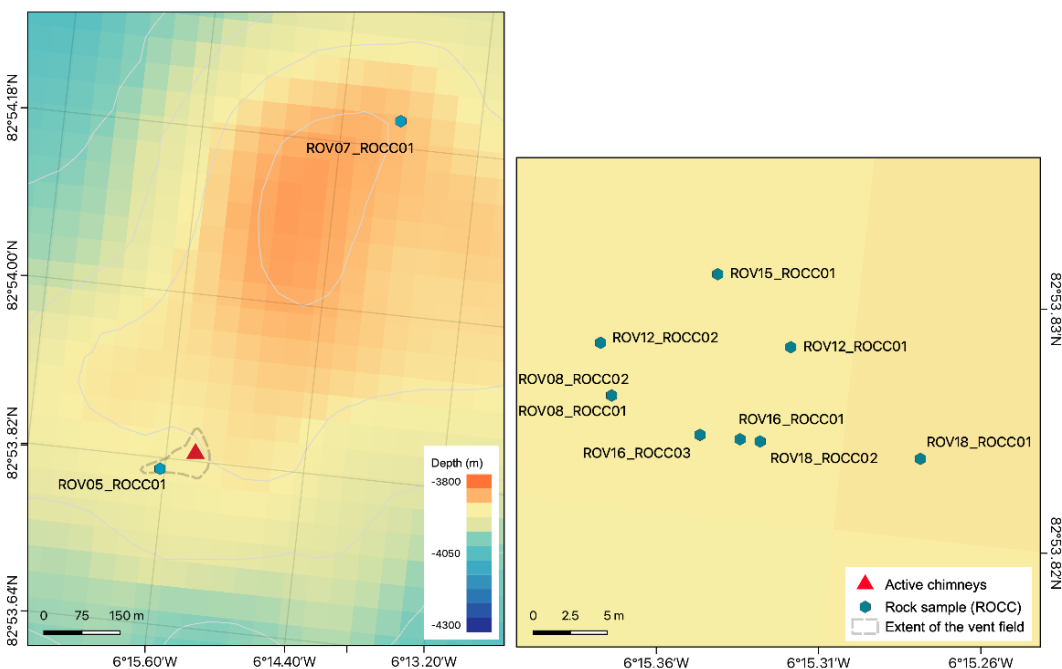


Figure 28. Sample location for rock samples. Plotted sample locations are based on ROV USBL navigation and are therefore only accurate to within 10 m.

Table 1: Rock samples collected by ROV.

| Name                           | Latitude | Longitude | Depth (m) | Type     | Description  |
|--------------------------------|----------|-----------|-----------|----------|--|
| CAGE-KH-HACON21-02-ROV05-ROC01 | 82.8964  | -6.2526   | 3905      | Inactive | Toppled chimney in inactive area                   |
| CAGE-KH-HACON21-02-ROV07-ROC01 | 82.9028  | -6.2334   | 3850      | Basalt   | Basalt from top of Aurora seamount                 |
| CAGE-KH-HACON21-02-ROV08-ROC01 | 82.8971  | -6.2562   | 3885      | Active   | Active Enceladus vent                              |
| CAGE-KH-HACON21-02-ROV08-ROC02 | 82.8971  | -6.2562   | 3885      | Inactive | Sulfide talus next to Enceladus vent               |
| CAGE-KH-HACON21-02-ROV12-ROC01 | 82.8972  | -6.2553   | 3882      | Inactive | Sulfide talus near Hans Tore vent                  |
| CAGE-KH-HACON21-02-ROV12-ROC02 | 82.8972  | -6.2563   | 3885      | Inactive | Sulfide talus next to Enceladus vent               |
| CAGE-KH-HACON21-02-ROV12-ROC03 | 82.8972  | -6.2554   | 3882      | Oxide    | Fe-oxide sample near Hans Tore                     |
| CAGE-KH-HACON21-02-ROV15-ROC01 | 82.8963  | -6.2610   | 3908      | Oxide    | Yellow oxide talus from inactive area              |
| CAGE-KH-HACON21-02-ROV15-ROC02 | 82.8963  | -6.2614   | 3900      | Inactive | Massive sulfide from old chimney                   |
| CAGE-KH-HACON21-02-ROV16-ROC01 | 82.8971  | -6.2557   | 3886      | Active   | Sulfide collected from active Ganymede             |
| CAGE-KH-HACON21-02-ROV16-ROC02 | 82.8971  | -6.2558   | 3888      | Active   | Toppled chimney from base of Ganymede              |
| CAGE-KH-HACON21-02-ROV16-ROC03 | 82.8971  | -6.2558   | 3885      | Inactive | Inactive chimney near Ganymede                     |
| CAGE-KH-HACON21-02-ROV16-ROC04 | 82.8971  | -6.2549   | 3880      | Inactive | Sulfide material attached to sponge                |
| CAGE-KH-HACON21-02-ROV18-ROC01 | 82.8971  | -6.2546   | 3890      | Inactive | Dead sulfide rubble from SE of active vent cluster |
| CAGE-KH-HACON21-02-ROV18-ROC02 | 82.8971  | -6.2560   | 3906      | Active   | Piece of active Ganymede                           |

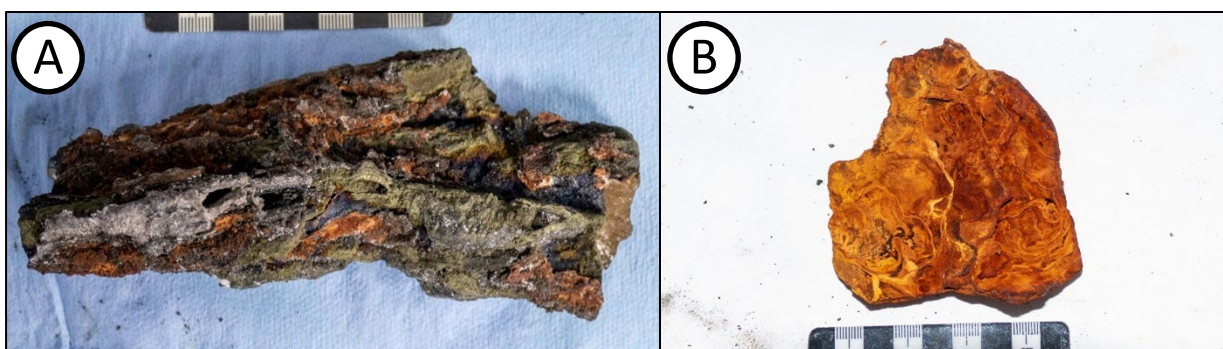


Figure 29: Examples of hydrothermal samples collected at the Aurora vent field. A) Sample CAGE-KH-HACON21-02-ROV16-ROC02, collected at the base of Ganymede. B) Sample CAGE-KH-HACON21-02-ROV12-ROC03, collected from a diffuse venting area at the crater rim near Hans Tore vent.

#### 11.4 Post-cruise work

Rock samples will be taken to Memorial University of Newfoundland (Canada) for further analysis. Thin sections will be made for mineralogical and textural characterization of the samples using reflected and transmitted light petrography. The bulk composition of the samples will be determined using a combination of two methods: 1) sodium peroxide fusion followed by measurement using inductively coupled plasma mass spectrometry (ICP-MS) or optical emission spectroscopy (ICP-OES); and 2) instrumental neutron activation analysis. Samples will be dated using two uranium series disequilibrium methods:  $^{226}\text{Ra}/\text{Ba}$  of hydrothermal barite by gamma spectrometry; and  $^{230}\text{Th}/\text{U}$  of pyrite using multi-collector ICP-MS.

## 12 MARINE GEOLOGY

Claudio Argentino, Sofia Ramalho, Ida Steen

### 12.1 Introduction and objectives

Marine sediments are an invaluable source of information for many disciplines in Earth Sciences, i.e. Sedimentology, geochemistry, micropaleontology, (micro)biology, geophysics, oceanography. By studying the physical and chemical composition of the sediment we obtain insights into depositional processes (e.g. bottom currents, mass-waste deposits), biogeochemical reactions (in the sediment and at the seafloor), fauna-sediment interactions as well as water-column processes (e.g. productivity). The sedimentary record enables us to obtain accurate paleo-environmental reconstructions using geochemical and micropaleontological proxies. Moreover, the pore fluids extracted from the sediment provide information on processes taking place at great depth within the sediment (origin of gas, fluid-rock interactions) and about shallow redox conditions and biogeochemistry.

The main objectives of this team were to collect sediment samples from microbial mats around the active venting areas using the ROV (1) and to complete a grid of gravity cores and multi-cores around the seamount (2). Sediment samples collected with the ROV will be used to study the (micro)biology and biogeochemical processes occurring in microbial mat habitats at diffusive venting sites. The same for multicores. Gravity cores will be used to reconstruct the history of hydrothermal activity in this area.

## 12.2 Sediment sampling

### 12.2.1. Blade cores and push cores

Sediment sampling of microbial mats was carried out using blade corers and push corers operated by the ROV (objective 1). Blade corers have a rectangular section (25 cm x 10 cm), they are 32 cm in height and have an automatic closing mechanism at the bottom to avoid sample loss. Push corers have a round section with inner diameter of 8 cm and length of 56 cm. Push corer and blade corer liners were pre-drilled for pore water sampling with a resolution of 1-2 cm. Push corers were also pre-drilled onboard for gas sampling every 5 cm. We collected 5 blade cores and 3 push cores (2 were empty) from microbial mats and reference background areas (Figure 27). The sub-sampling of blade cores and push cores was well coordinated and involved different research groups (Figure 30). Sub-sampling followed the order: bottom water, pore water, gas in the sediment, surface sediment (foraminifera TEM and CTG, food web analysis), microbiology, meiofauna + sediment geochemistry/micropaleontology.

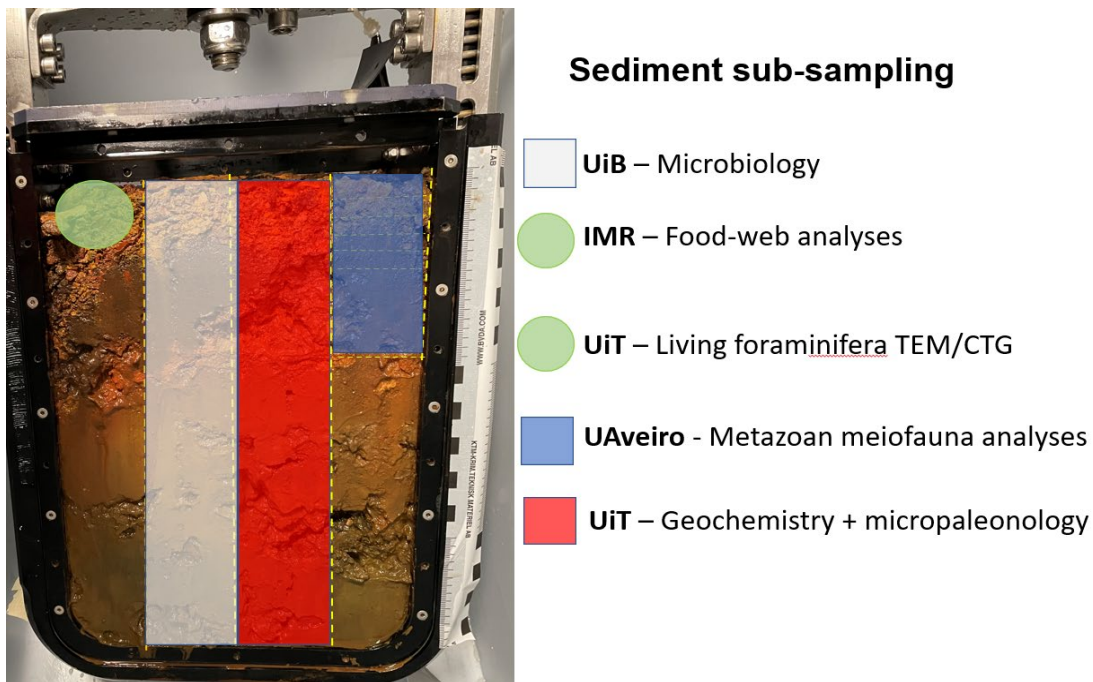


Figure 30: Sub-sampling of blade core CAGE-KH-HACON21-02-ROV15-Blac-01.

### 12.2.2. Multicore

The multicore (MUC) sampling system is a KC Denmark DK8000 mounted with six parallel 70 cm long transparent tubes (liners) with an inner diameter of 10 cm (Figure 31). The core tubes are loaded with open upper and lower ends. The MUC is deployed at 1 m/s, until 100 m above bottom, then lowered to the seafloor at 0.5 m/s, left on the seafloor for about 1 min and recovered at 1 m/s. When the multicorer lands on the seafloor, the tubes are pushed into the soft sediment by lead weights and, upon recovery, are closed on both ends. Up to 60 cm of sediment and the immediate overlying water can be sampled. This allows the analysis of undisturbed faunal samples within their undisturbed environment. The liners are carefully taken out of the sampling device, the ends were sealed with

yellow caps, and the cores moved, in an upright position, in a cool room (4 °C). We collected 1 multicore with more than 40 cm of sediment recovery in each of the 6 liners (Figure 31). The multicore was sub-sampled for pore water, microbiology, micropaleontology and meiofauna.



*Figure 31. Multicorer on deck with six sediment cores.*

### **12.2.3. Gravity core**

The gravity corer consists of a 6 m long steel barrel with weights attached on top of it, with a total weight of 1.3 t (Figure 32). Before coring, we insert a plastic liner with an inner diameter of 10 cm into the steel barrel and attach a core catcher and core cutter to the lower end of the gravity corer. The core catcher keeps the sediments from falling out of the core, whereas the core cutter helps the penetration of the core into the sediments. The gravity corer is lifted vertically and lowered to the seafloor at 1 m/s until ca. 50 m above the seafloor, and then dropped. When the gravity corer is back on deck, we collect the sediment from the core catcher and core cutter (if any). Then, the plastic liner is pulled out of the barrel and cut into 1-meter sections. Headspace gas samples are collected at the bottom of each section, prior to capping and taping. Sections are finally taken to the cool room (4 °C) for pore water sampling. We collected a total of 3 GC (1 was empty).



*Figure 32. Gravity corer pulled on deck after sampling*

### 12.3 Sediment geochemistry and Micropaleontology

Samples for sediment geochemistry and investigation of fossil foraminifera (benthic and planktonic) were collected from all blade cores, push cores and multicore CAGE-KH-HACON21-02-MC-148 #5. Cores were sliced onboard every 1 cm, put in zip lock bags and stored in a cool room (4°C). Gravity cores will be split and sub-sampled on shore at UiT following X-Ray Fluorescence analyses and X-ray radiography of whole cores. Quantitative sediment geochemical analysis will include organic matter characterization (Total Organic Carbon, Total Organic Nitrogen,  $\delta^{13}\text{C}_{\text{TOC}}$ ,  $\delta^{15}\text{N}_{\text{TON}}$ ). Foraminifera will be classified and analyzed for  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$ .

### 12.4 Pore water

Pore water was extracted immediately after core recovery using 5-cm-long Rhizons. Rhizons were pre-wetted in MilliQ water at least 30' before use. During sampling, we inserted the Rhizons into pre-drilled holes, we attached 10 mL syringes and used spacers to create a vacuum inside the syringes and to keep them open (Figure 33). We discarded the first ~100  $\mu\text{L}$  of water. Around 125 pore water samples were collected and then split into different aliquots (Table 2). For Blade core samples, pH (at 25°C, 1 atm) was measured potentiometrically onboard using a Ag/AgCl combination reference electrode and alkalinity was determined performing a Gran-style titration using 0.01N HCl.



Figure 33. Pore-water sampling of gravity core CAGE-KH-HACON21-02-GC-193

**Table 2.** Aliquots of pore water samples collected during the cruise.

| Analysis                                | Volume (mL) | Treatment   | Storage |
|---|-------------|---|---------|
| DIC, $\delta^{13}\text{C}_{\text{DIC}}$ | $\geq 1$    | Addition of 10 $\mu\text{l}$ $\text{HgCl}_2$                    | 4°C     |
| Anions                                  | $\geq 1$    | untreated and frozen  | -20°C   |
| Sr-Nd isotopes                          | $\geq 1$    | Addition of 10 $\mu\text{L}$ Suprapur© grade 65% $\text{HNO}_3$ | 4°C     |
| Organics                                | >1          | Untreated and frozen  | -20°C   |

### 12.5 Gas in the sediment

Gas in the sediment was collected from 2 blade cores, 1 push core and 3 gravity cores. Bulk sediment samples were collected from the bottom of gravity core sections using 5 mL syringes without the luer tip. 5 mL of sediment was transferred into a 20 mL serum vial containing 5 mL of 1M NaOH. The vial was immediately closed with a rubber septum, sealed with an aluminum crimp cap and shaken to facilitate equilibration. A sediment sample from each gravity core was collected and put into gas-tight IsoJar® containers (Isotech Laboratories Inc., Champaign, IL, USA) for headspace gas isotope analysis. Sediment was collected using a spatula from the base of the second section from the bottom of the core. The sediment sample filled one-third of the jar while another third was filled with MilliQ water, leaving the top third filled with air (headspace). We added a few drops of diluted benzalkonium chloride bactericide, we screwed the lid on as tight as possible, taped it with duct tape in the same direction (clockwise) and shook it. Both the small vials and the jars were stored upside-down at 4°C (Figure 34). We collected a total of 12 sediment samples for headspace gas analysis.



Figure 34. Headspace gas samples in gas-tight jars (left) and glass vials (right).

The complete list of sediment sampling activities carried out during this cruise and types of sub-samples are reported in Table 3.

**Table 3.** Summary of sediment samples and sub-samples collected during the cruise. PW = pore water; HS = headspace gas; MF = meiofauna; MB = microbiology; SG: sediment geochemistry.

| Sediment core                    | Latitude [DD] | Longitude [DD] | Depth (m) | Recovery (cm) | PW | HS | TEM/CTG | MF | MB | SG + microfossils |
|----------------------------------|---------------|----------------|-----------|---------------|----|----|---------|----|----|-------------------|
| CAGE-KH-HACON21-02-GC-191        | 82.9173       | -6.1855        | 3949      | 218           | x  | x  |         |    |    |                   |
| CAGE-KH-HACON21-02-MC-148        | 82.9136       | -6.2597        | 4125      |               | x  | x  | x       | x  | x  | x                 |
| CAGE-KH-HACON21-02-ROV15-BlaC-01 | 82.8972       | -6.2563        | 3886      | 28            | x  | x  | x       | x  | x  | x                 |
| CAGE-KH-HACON21-02-ROV15-BlaC-03 | 82.8972       | -6.2563        | 3886      | 17            | x  |    | x       | x  | x  | x                 |
| CAGE-KH-HACON21-02-ROV15-BlaC-04 | 82.8972       | -6.2562        | 3886      | 20            |    |    |         | x  |    |                   |
| CAGE-KH-HACON21-02-ROV15-PusC-02 | 82.8972       | -6.2563        | 3886      | empty         |    |    |         |    |    |                   |
| CAGE-KH-HACON21-02-ROV15-PusC-01 | 82.8972       | -6.2561        | 3886      | empty         |    |    |         |    |    |                   |
| CAGE-KH-HACON21-02-GC-192        | 82.9246       | -6.2353        | 3868      | empty         |    |    |         |    |    |                   |
| CAGE-KH-HACON21-02-GC-193        | 82.9270       | -6.2402        | 3909      | 250           | x  | x  |         |    |    |                   |
| CAGE-KH-HACON21-01-ROV19-BlaC-01 | 79.3933       | 3.5954         | 3686      | 17            |    |    |         | x  |    | x                 |
| CAGE-KH-HACON21-01-ROV19-BlaC-03 | 79.3933       | 3.5954         | 3686      | 21            |    |    |         | x  |    | x                 |
| CAGE-KH-HACON21-01-              | 79.3933       | 3.5954         | 3686      | 39            | x  | x  |         | x  |    | x                 |



## 13 MARINE BIOLOGY

Ana Hilario, Eva Ramirez-Llodra, Ida Helene Steen, Claudio Argentino, Maria Baker, Carolina Costa, Emily Denny, Sofia Ramalho, Pedro Ribeiro, Lissette Victorero

### 13.1 Introduction and objectives

A comprehensive baseline study of the Aurora seamount is essential to understand the system's biodiversity and functioning, and to provide the necessary data against which to monitor natural or anthropogenic changes. Prior to this cruise, our knowledge on the biological communities from this remote region was based on limited seafloor imagery and sediment coring from the periphery of the vent field collected during the PS86 and HACON19 cruises (Boetius et al., 2014a,b, Bünz and Ramirez-Llodra, 2019). Although these data are still being analysed, preliminary results indicate the presence of vent-endemic fauna in the immediate vicinity of black smokers and sponge aggregations in the enrichment zone around the vent field.

The main objective for the biology team during this cruise was to collect samples to 1) describe the microbial and faunal communities from the Aurora vent field and how they relate to the local geochemical settings; 2) test the hypothesis that the Gakkel Ridge provides a connecting pathway for gene flow of vent species between the Pacific and Atlantic oceans; and 3) to understand the role of the Gakkel Ridge in the global biogeography of hydrothermal vent communities.

In addition to the Aurora vent field and its vicinity, two exploratory dives were carried out in the Molloy Deep.

### 13.2 Methods - general

Samples were collected with the ROV Aurora (section 9). Rocks hosting visible fauna were collected with the manipulator arm and placed inside a Biobox. Fauna were also directly collected with the suction sampler. Microbial mats and meiofauna were targeted using a ROV-operated blade corer. For microbial studies, Biosyringe samples were taken on areas of diffuse venting covered by microbial mats.

Although the collection was focused on the vent field, sponge aggregations and associated communities from the periphery were also sampled (Figure 35). Video imagery was collected throughout all dives and selected video transects were performed during the last dive on the vent field (HACON21-02-ROV18, Figure 35).

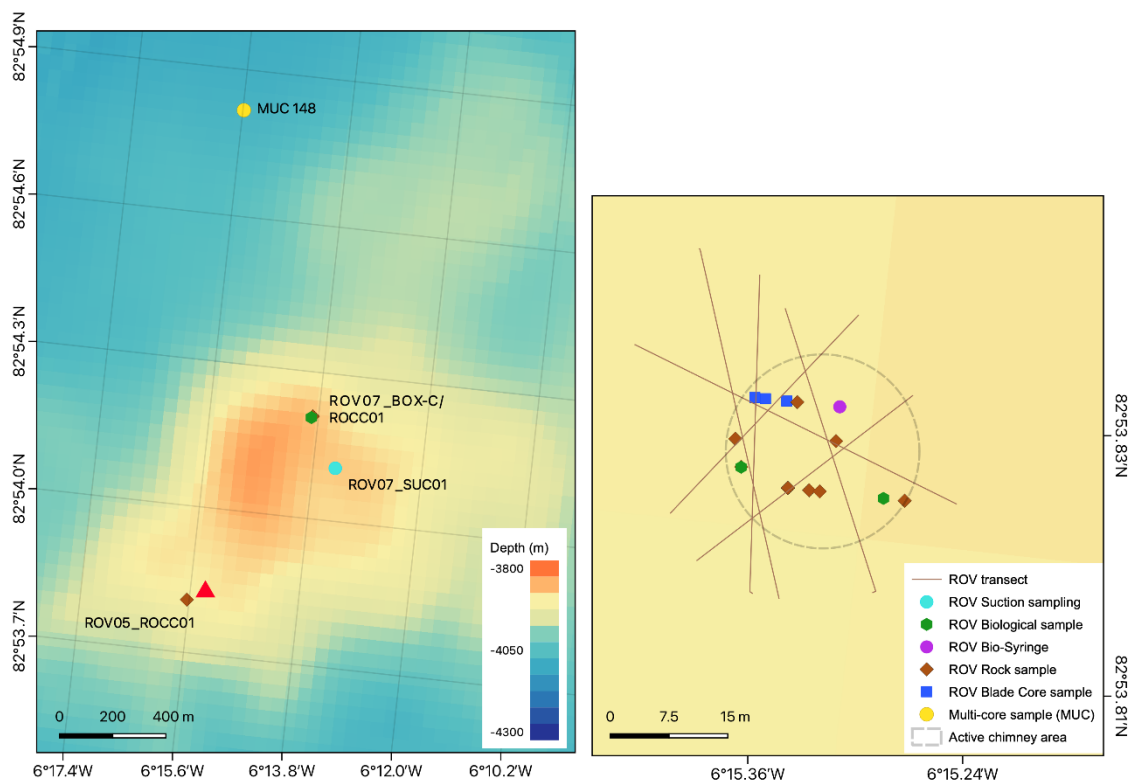


Figure 35. Biological sampling on the Aurora Vent Field and the Aurora seamount.

### 13.3 Microbiology

Biological communities in hydrothermal systems are typically largely driven by chemotrophic microorganisms acquiring energy from the oxidation of reduced compounds in hydrothermal fluids (e.g. sulfide, methane, hydrogen) and oxidized compounds in seawater (e.g. sulfate, nitrate, oxygen). However, due to the geological setting and the various geochemical and biological processes occurring within a vent field, the chemical composition of hydrothermal fluids in hydrothermal chimneys, surrounding sediments, and mounds may vary considerably. In order to decipher the geobiological interactions occurring in a hydrothermal system, and to determine the overall effect hydrothermal fluid flow has on the biological communities associated with the vent field, detailed analyses of the composition of fluids alongside analyses of microbial community structure and functioning is necessary. One of our objectives was therefore to characterize chemical and microbiology community profiles in the chimney walls of active black smokers and in sediments within and in the surrounding of the Aurora vent field. Second, was to provide microbiology data for the assessment of functional groups associated with key invertebrate taxa. Metagenomic-based community analyses (post-cruise work) will shed further light on the microbial community structure and function. Successful sampling (Table 4) was performed for active high-temperature venting chimneys, inactive chimneys, low-temperature diffuse flow venting sites and background sediments.

**Table 4.** Microbiology samples processed for DNA and SEM analyses.

| Name                           | DNA | SEM | Subsamples |
|--------------------------------|-----|-----|------------|
| CAGE-KH-HACON21-ROV05-02-Rocc1 | X   |     |            |
| CAGE-KH-HACON21-ROV08-02-Rocc1 | X   |     | X          |
| CAGE-KH-HACON21-ROV12-02-Rocc1 | X   | x   | X          |
| CAGE-KH-HACON21-ROV12-02-Rocc3 | X   |     | X          |
| CAGE-KH-HACON21-ROV16-02-Rocc1 | X   |     |            |
| CAGE-KH-HACON21-ROV16-02-Rocc3 | X   |     | X          |
| CAGE-KH-HACON21-ROV18-02-Rocc2 | X   |     | X          |
| CAGE-KH-HACON21-02-BlaC1       | X   | x   | X          |
| CAGE-KH-HACON21-02-BlaC3       | X   | x   | X          |
| CAGE-KH-HACON21-02-BioS        | X   | x   | X          |
| CAGE-KH-HACON21-02-SucS-Ch1    | X   | x   | X          |
| CAGE-KH-HACON21-02-SucS-Ch3    | X   | x   | X          |
| CAGE-KH-HACON21-02-MC-148#4    | X   |     | X          |

**13.3.1 Microbiology – black smokers**

Altogether, 5 chimney pieces of active Enceladus vent were sub-sampled (outside-inside) for DNA extraction, respectively. Moreover, from a large chimney piece of the Ganymede active vent, gradients (outside-inside, top-bottom) were sub-sampled. There was no visible sign of biofilms on the chimney pieces. Chimney from active vents were also successfully sampled with IGTs, allowing future direct comparisons between geochemistry and microbial community structure and function. Two inactive chimney pieces, one beside Enceladus and at the Hans Tore chimney crater were also collected. From each chimney piece, material was transferred to sterile cryotubes and stored at -80°C. Additionally, bulk samples were stored at -80°C in sterile plastic bags.

**13.3.2 Microbiology – sediments**

Sediment samples from diffuse venting sites within the active vent field were collected using blade

cores and the Biosyringe. The blade cores were taken close to the active Enceladus vent (Figure 35). The sediment surface was covered with yellowish/brownish iron oxyhydroxide deposits indicative of venting of Fe-rich fluids. These mineral deposits may be abiogenic and/or formed as a result of the metabolic activity of Fe-oxidizing bacteria. Two of the cores, with a depth of 28 and 17 cm, respectively, were sampled for microbiology. Using a sterile spatula, every 1 cm was subsampled and stored in sterile plastic bags at -80°C. Two replicates were sampled from each sediment horizon. A selection of subsamples was processed for scanning electron microscopy (Table 4). As described in section 12, the same cores were sampled for sediment geochemistry and meiofauna, respectively.

A Biosyringe sample was taken at the rim of the Hans Tore vent. Temperature was measured with the IGT temperature probe. The highest observed temperature was approximately 80°C. Sampling was performed by centrifugation (5.5 min, 6000 g, 5°C) of sediments in cryotubes. The supernatants were removed, and the pellets stored at -80°C. A similar protocol was used for sampling of sediments in the suction sample chambers 1 and 3, respectively. Subsamples were processed for scanning electron microscopy.

Control sediment, collected away from the vent-site by MUC, was subsampled every 1 cm using a sterile spatula and stored in sterile plastic bags at -80°C.

## 13.4 Benthic fauna

### 13.4.1 Macro- and megafauna

#### *Visual observations*

Three active smokers have been identified during the cruise (section 9.3). On the Hans Tore vent, consisting of a black smoker growing from the bottom of a circular crater with thick microbial mats and fluids shimmering from its rim, amphipods and gastropods can be seen on the rim and slopes of the crater. On the other two black smokers (Enceladus and Ganymede), amphipods can be seen on the chimney walls, whereas gastropods are mostly seen on chimney-debris on the base of the smokers (Figure 36A). In contrast to vents on the AMOR (Pedersen et al., 2010), no sedimented areas with diffuse venting were found, explaining the restricted spatial distribution of vent-adapted fauna to the close vicinity of the smokers. Basalt outcrops within the vent field host dense aggregations of carnivorous sponges (Family Cladorhizidae) that seem to take advantage of the food-enriched environment promoted by the hydrothermal activity.

As previously reported (Bünz and Ramirez-Llodra, 2019), rocks, pillow lavas and basaltic crests and outcrops in the proximity of the vent field were covered by dense aggregations of the hexactinellid sponges *Caulophacus arcticus* and *Asconema megaltrialia*. The sponges may act as facilitators for other fauna elements, since bythocarid shrimps, anemones, crinoids and several species of isopods and amphipods seem to be more abundant in areas covered by sponges.

Video transects performed during dive HACON21-02-ROV18 will be used to construct 3D models of the vent field and to calculate species distribution, abundance and density in relation to the local geochemical conditions.

#### *Specimens' collection and preservation*

Rocks collected with the manipulator arm were screened under a stereomicroscope. Specimens were

removed and identified to the lowest possible taxonomic level (Table 5). The Gastropoda families cf. Skeneidae, represented by two different species, and cf. Cocculinidae were the most abundant taxa found on the collected rocks (Figure 36C and D). Samples collected with the suction sampler targeted amphipods from the chimneys and chimney-debris, as well as sponges from the vent periphery and background. Larger sponge specimens were picked with the manipulator arm. Preliminary morphological identification places these within the family Melitidae (Figure 36B), known from hydrothermal vents in the AMOR (Tandberg et al., 2012). Suction sampling on Hans Tore and Ganymede vents also retrieved tubes of polychaetes resembling those of the family Maldanidae.

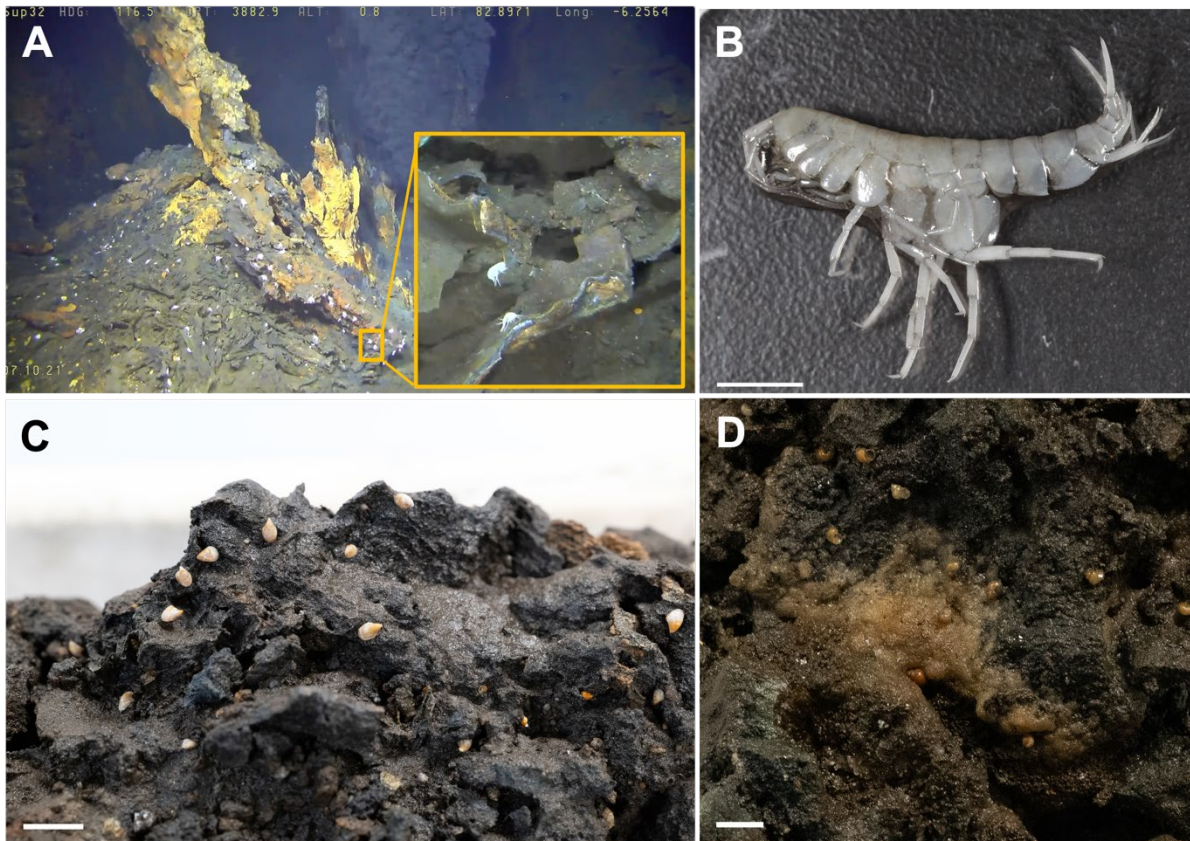


Figure 36. Examples of macro- and megafauna collected from the Aurora vent field. A: Vicinity of the Enceladus smoker. Inset shows *Melitidae* amphipods in situ; B: *Melitidae* amphipod. Scale bar: 5 mm; C: Rock hosting cf. *Cocculinidae* and cf. *Skeneidae* gastropods. Scale bar: 10 mm; D: Detail of rock shown in C showing the high abundance of and cf. *Skeneidae* gastropods. Scale bar: 5 mm.

The water and sediment/rock material deposited in all the Bioboxes where samples have been placed and in the chambers of the suction sampler were sieved through a 250  $\mu\text{m}$  sieve. All visible organisms were sorted and the remaining material, as well as all rocks were fixed as bulk in formalin and transferred to 70% ethanol for preservation after 48h. All specimens were fixed and preserved following specific protocols for subsequent analyses (Table 5): 100% ethanol for DNA barcoding and population genetics, 4% formaldehyde for taxonomy and reproductive ecology studies and frozen at  $-80^{\circ}\text{C}$  for food web analyses. The same procedure was followed for samples collected outside the vent field.

### 13.4.2 Metazoan meiofauna

Sediment samples were collected in the vicinity of the Enceladus black smoker, as well as North of the Aurora seamount, using the Blade Corer and the multicore sampler ( $\varnothing$  10cm; Table 3), respectively. This sampling aimed at describing the meiofaunal density, community composition and diversity of the Aurora seamount, with particular focus on free-living nematodes. Moreover, samples were also collected for subsequent molecular analyses, for barcoding and population connectivity studies.

In each of the locations, three replicates were collected for both meiofaunal analyses and for environmental characterization of the sediments, namely for TOC, TN, pore-water geochemistry, grain size (for more details see section 12). Cores were sliced into 3 sediment depth layers (0-1 cm, 1-2 cm, 2-3 cm, 3-4 cm, 4-5 cm and 5-10 cm) and fixed in a formaldehyde (4%)/seawater solution for quantitative community analyses based on morphology the sediments. Additional surface sediments from the Blade corers were preserved in 70% Ethanol solution for future molecular studies.

### 13.4.3 Living benthic foraminiferal communities

Foraminifera are eukaryotic unicellular microorganisms inhabiting all marine environments. These organisms are useful environmental indicators as they respond quickly to small environmental changes. They are widely distributed in marine environments, and we found them in sediment around the Aurora seamount. During this expedition we collected samples from the surface of all cores (except for gravity cores), for future analysis of living benthic foraminifera from hydrothermal vent environments in order to evaluate the effect of hydrothermal activity on foraminifera communities. Samples from the top 0-1 cm of multicore CAGE-KH-HACON21-02-MC-148 #5 and blade cores CAGE-KH-HACON21-02-ROV15-BlaC-03 and CAGE-KH-HACON21-02-ROV15-BlaC-01 were treated for TEM and CTG labelling (Table 3).

#### *TEM staining*

We prepared a solution composed of 100 mL of filtered seawater, 6 mL of glutaraldehyde and 4 mL of paraformaldehyde. During sampling, we collected 20 mL of sediment and put it into a HDPE container, added 20 mL of fixative and 20 mL of filtered seawater, we sealed the container, gently shook it and stored it at 4°C.

#### *Cell Tracker Green - CTG labelling*

CTG labelling was used to accurately distinguish living foraminifera and is based on enzymatic reactions. Before sampling, we prepared a solution of 50 mL of dimethylsulfoxide (DMSO) and 50 mL of Cell-Tracker™ Green (CTG 5 CMFDA: 5-chloromethylfluorescein diacetate). During sampling we collected 10 mL of sediment and put it into a HDPE container, added 20 mL of filtered seawater and 18 mL of CTG-DMSO solution and gently shook the container to make sure that all sediments are resuspended in solution. Samples were incubated for 12 h at room temperature. During this time, CTG passes through the cellular membrane of living organisms, and reaches the cytoplasm where hydrolysis with nonspecific esterases creates fluorogenic elements. After the death of the cell, esterases are decomposed in a few hours to some days at maximum, depending on environmental conditions, making the CTG method highly accurate to discriminate between living and dead organisms. After incubation, the samples were fixed in 96% ethanol and stored at -20 °C.

**Table 5.** Summary of macro- and megafauna collection, fixation method and future uses.

| Collection site             | Taxa  | Fixation |          |               |                       | Purpose  |                 |                      | Recipient      |
|-----------------------------|---|----------|----------|---------------|-----------------------|----------|-----------------|----------------------|----------------|
|                             |   | Ethanol  | Formalin | Frozen (-80C) | Barcoding / Pop. Gen. | Taxonomy | Trophic ecology | Reproductive ecology |                |
| Aurora seamount             | Hexactinellida, <i>Asconema megatralia</i>  | x        |          |               | x                     | x        |                 |                      | UiB            |
|                             | Hexactinellida, <i>Caulophacus arcticus</i> | x        |          |               | x                     | x        |                 |                      | UiB            |
|                             | Demospongiae, <i>Cladorhiza cf gelida</i>   | x        |          |               | x                     | x        |                 |                      | UiB            |
|                             | Polychaeta                                  | x        |          |               | x                     | x        |                 |                      | UiB            |
|                             | Isopoda                                     | x        |          |               | x                     | x        |                 |                      | UiB            |
| Aurora Vent field periphery | Gastropoda, cf. Lepetodrilidae              | x        |          | x             | x                     | x        | x               |                      | UiB, IMAR      |
| Hans Tore vent              | Gastropoda, cf. Skeneidae 1                 | x        | x        | x             | x                     | x        | x               | x                    | UiB, UAVR, IMR |
|                             | Gastropoda, cf. Skeneidae 2                 | x        | x        |               | x                     | x        |                 | x                    | UiB, UAVR      |
|                             | Gastropoda, cf. Lepetodrilidae              | x        | x        | x             | x                     | x        | x               | x                    | UiB, UAVR, IMR |
|                             | Polychaeta, cf. Maldanidae                  | x        |          |               | x                     | x        |                 |                      | UiB            |
|                             | Amphipoda, Melitidae                        | x        | x        | x             | x                     | x        | x               | x                    | UiB, UAVR      |
|                             | Bulk  |          | x        |               |                       |          | x               |                      | x              |
| Enceladus vent              | Polychaeta, cf. Maldanidae                  | x        |          |               | x                     | x        |                 |                      | UiB            |
|                             | Amphipoda, Melitidae                        | x        | x        |               | x                     | x        |                 | x                    | UiB, UAVR      |

|                         |  |   |   |   |   |   |   |   |                   |
|-------------------------|--|---|---|---|---|---|---|---|-------------------|
|                         | Bulk   |   | x |   |   |   |   |   | UAVR              |
| Ganymede vent           | Gastropoda, cf. Skeneidae 1                  | x | x |   | x | x |   | x |                   |
|                         | Gastropoda, cf. Skeneidae 2                  | x | x |   | x | x |   | x |                   |
|                         | Gastropoda, cf. Lepetodrilidae               | x | x |   | x | x |   | x |                   |
|                         | Polychaeta, cf. Maldanidae                   | x |   |   | x | x |   |   | UiB               |
|                         | Amphipoda, Melitidae                         | x | x |   | x | x |   | x | UiB, UAVR         |
|                         | Bulk   |   | x |   |   |   |   |   | UAVR              |
| Ganymede vent periphery | <i>Cladorhiza cf gelida</i>                  | x |   | x | x | x | x |   | UiB, IMR          |
|                         | Hexactinellida, <i>Asconema megaatrialia</i> | x |   |   | x | x |   |   | UiB               |
|                         | Hydrozoa                                     | x |   |   | x | x |   |   | UiB               |
| Molloy Deep             | Hexactinellida, <i>Caulophacus arcticus</i>  | X |   | x | X | X |   |   | UiB and REV Ocean |
|                         | Anthozoa, Actiniaria                         | x |   |   | X | X |   |   | UiB               |
|                         | Polychaeta, cf. Siboglinidae                 | x |   |   | x | x |   |   | UAVR              |
|                         | Shrimp                                       | X |   |   | X | X |   |   | UiB               |
|                         | Amphipoda                                    | X | X |   | X | X |   |   | UiB               |

## 14 WATER COLUMN

Marie Stetzler, Eoghan Reeves, Samuel Pereira

### 14.1 Introduction and objectives



Mixing and spreading of a hydrothermal plume can be identified from the water mass properties inside and outside the Aurora hydrothermal plume, provided by the CTD on-board the R/V Kronprins Haakon. Water samples were taken during CTD casts (Figure 37) for geochemical properties of the water column, analyzed directly after sampling or later on in different partners' labs. Current velocity and direction in the water column and close to the seafloor were obtained from the ADCPs mounted on the ship, which have a sounding depth down to 800m. Due to technical challenges, neither the LADCP of the CTD rosette nor the ADCP of the ROV Aurora could be used.

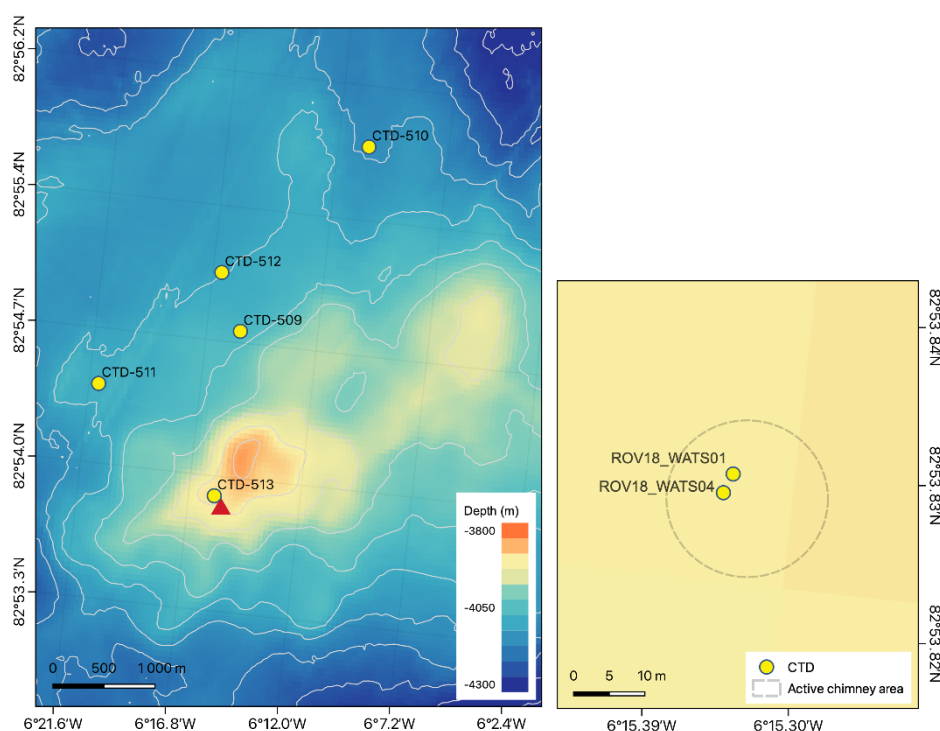


Figure 37. Aurora seamount showing CTD stations indicated by yellow dots, and the Aurora vent field represented by the red triangle (left map); Zoomed in graph showing the ROV's position when sampling the rising plume of the Hans Tore Vent with two Niskin bottles.

## 14.2 Geochemistry

Composition of the dissolved organic matter (DOM) in the abyssal ocean is known to be refractory and considered primarily unavailable for organisms. Yet, hydrothermal vents and surrounding environments are rich in terms of biodiversity and provide a source for many different chemosynthetic organisms and hydrothermal fauna. For such organisms, reduced carbon (such as methane) and DOM (which includes DOC) would be the main carbon source and they might have an adaptation to utilize refractory DOM and modify the composition in the deep-sea environments. Additional to the microbial modification, DOM composition around the hydrothermal vents is expected to be thermally and/or chemically altered. The extent of these modifications is unknown in many deep-sea hydrothermal vents and our objective is to reveal compositional changes of DOM and other nutrients in the water column under the influence of hydrothermal input at the Aurora Vent Field in the Gakkel Ridge. During the last expedition (HACON19), DOM, nutrients and further geochemical data throughout the water column were gathered through CTD casts around the Aurora

vent field. Some casts measured background values, while others sampled plume material that was strongly diluted. Characterizing the rising plume composition by sampling in the immediate vicinity to the Aurora vents was hence a goal of this HACON21 cruise. Dissolved methane (CH<sub>4</sub>), dissolved organic carbon (DOC), stable oxygen isotope ( $\delta^{18}\text{O}$  of water), total and dissolved inorganic nutrients (nitrate, phosphate, silicate, ammonia), dissolved inorganic carbon (DIC) and  $\delta^{13}\text{C}$ -DIC were sampled for the characterization of the water column around the Aurora vents including from Niskin bottles mounted on the ROV Aurora. This collected data will also be compared to cold, methane seeping areas around the Svalbard archipelago.

### 14.3 Physical Oceanography

The Arctic Ocean is characterized by three distinct water layers, i.e. Arctic surface water, Atlantic Water and Deep Water. Each of these layers presents different water masses and properties. The different water masses around the Aurora seamount are represented in Figures 38 and 39 and described here. The Arctic surface water contains mainly Polar Mixed Water (down to 200 m water depth), characterized by low temperature because of the ice cover, with seasonal and geographical salinity variation freezing or melting of sea ice as well as input from shelf water from river runoff. A strong halocline precedes the Arctic Atlantic Layer down to ~900 m water depth, highlighted by a temperature maximum in all profiles (up to 1.4°C).

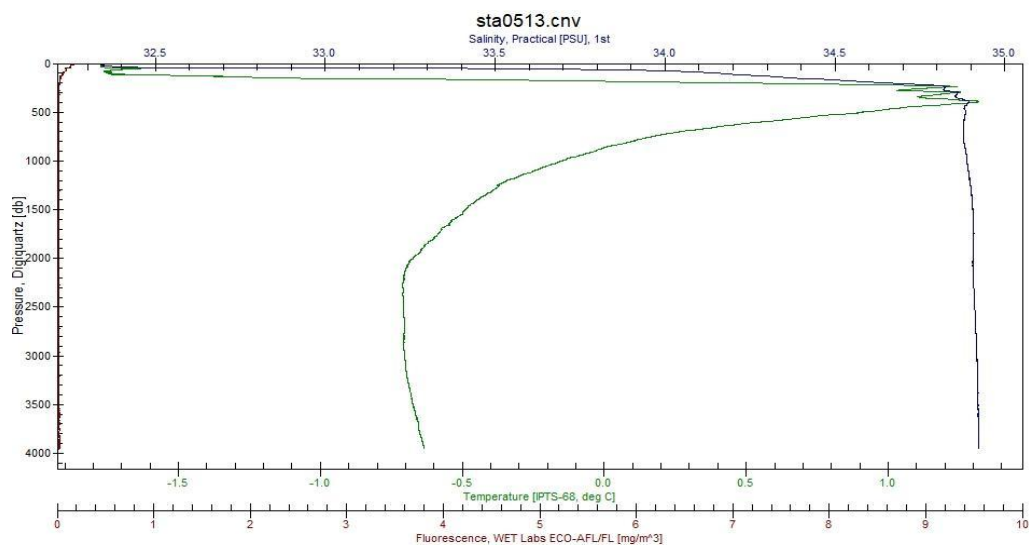


Figure 38. Temperature, Salinity, and Fluorescence profiles of the water column at CTD station 513, in immediate vicinity to the Aurora Vent Field.



samples were filled in 60 ml plastic vials and kept in a -20°C freezer until analysis date back onshore.

#### **14.1.2 Water sampling with the ROV**

The ice drift conditions made our attempts to collect plume water via CTD casts challenging and only moderately successful. We opted for the straightforward method of mounting two Niskin bottles, labeled Bottle 1 and 4 respectively, onto the ROV. Both were fired less than ten meters above the Hans Tore vent. Bottle 1 was fired within the plume and bottle 4 on the plume's edge. Both bottles were sampled for the same geochemical compositions as for a regular CTD cast (dissolved CH<sub>4</sub>, DOC, nutrients, DIC+C<sup>13</sup>, del<sup>18</sup>O) with one replicate sample. Water samples for dissolved CH<sub>4</sub> were filled in 100 ml glass vials, but some water was filled in 120 ml syringes for measuring the methane concentration right after sampling, using a gas chromatograph. Samples for DIC+C<sup>13</sup> were taken directly from the Niskin bottles into pre-evacuated 20 ml rubber-stoppered serum vials (previously poisoned with HgCl<sub>2</sub>) for onshore analyses. The CH<sub>4</sub>, del<sup>18</sup>O and DIC+C<sup>13</sup> samples were then stored in a 3 °C cooling room for further analysis in the lab back onshore. DOC, nutrients and a replicate sample were filled in 60 ml plastic vials and stored right away in a -20°C freezer until analysis date back onshore.

#### **14.5 Microplastic and plankton sampling**

The rosette of CTD 514 on the Molloy Deep was equipped with 3 Bottle Nets from Susana Agusti (KAUST). These are modified Niskin bottles functioning as a plankton net ( 20 µm net) to collect both microplastics and plankton of the water column into a sample bucket. The bottles remain closed on the downcast and are opened only over a defined depth range on the upcast. Bottle net number 1 was opened from 4457 to 1000 m depth (bathypelagic), bottle net number 2 was opened from 1000 to 100 m depth (mesopelagic), and bottle net 3 was opened from 100 m to the sea surface (surface layer, starting below the fluorescence maximum). Bottle number 3 did not close on the upcast but since it sampled the uppermost water layer this had no effect on the sample quality. After recovery, the lower area of the net / sample bucket was rinsed with filtered seawater to concentrate the sample. 30 ml of each sample was poured into 60 ml plastic vials, and complemented with 30 ml of 4% formalin solution for fixation, hence giving a concentration of 2% formalin in the sample. Three blanks with filtered seawater and a final formalin concentration of 2% were also prepared. The sample recovery was delayed due to minor technical issues. The samples were stored at +3°C until their analysis back in KAUST.

## **15 NE GREENLAND SHELF MAPPING**

Frank Jakobsen

### **15.1. Bathymetry**

Bathymetry and water column data were acquired using a hull mounted multibeam echosounder (MBE) EM302 system. Extensive sea ice conditions, icebergs and relatively fast ice-drift made data acquisition on the shelf of NE Greenland difficult. RV *Kronprins Haakon* is an ice going vessel, however going in ice causes noise in the acquired datasets (Figure 40A). To ensure data of reasonably good quality within areas of interest, we acquired data within leads (open areas between sea ice), hence our data acquisition was at times limited to these. Approximately 350 km<sup>2</sup> of high-resolution bathymetry of varying quality were acquired on the NE Greenland shelf and slope. The bathymetry

was processed and partly cleaned using QPS Qimera.

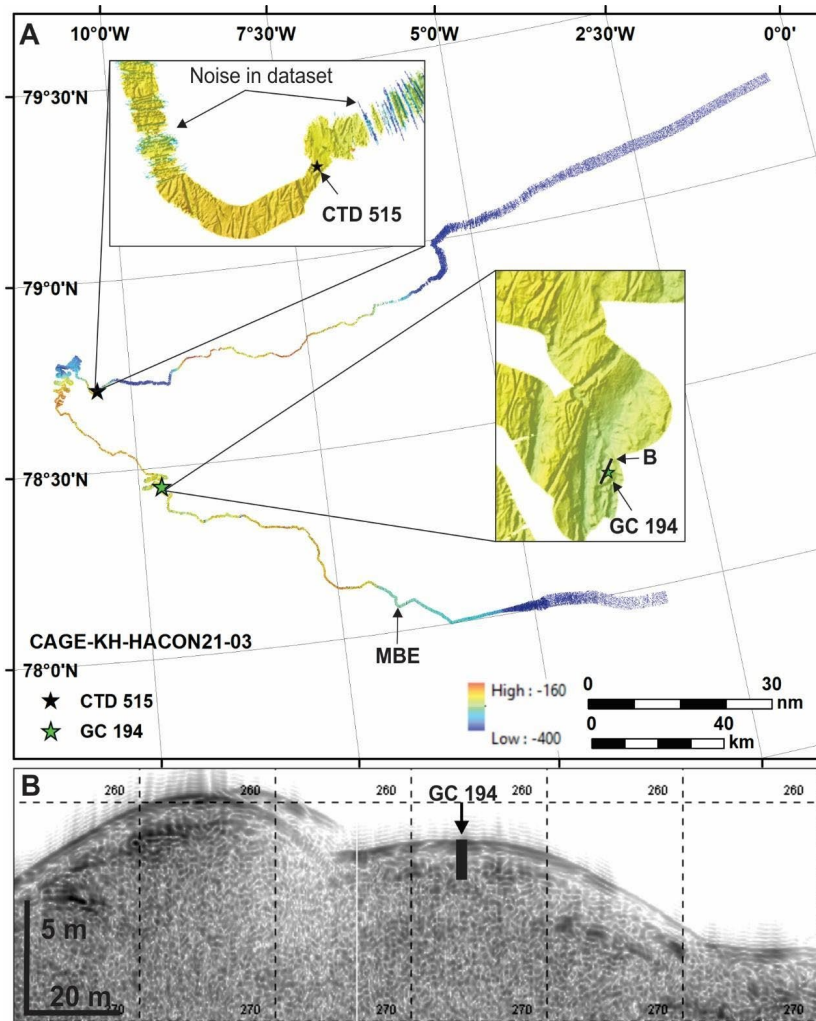


Figure 40. Data acquisition on the NE Greenland shelf. A) overview of the coverage of multibeam bathymetry (MBE), location of CTD and a gravity core (GC) on the NE Greenland shelf and slope. B) Sub-bottom profile where GC 194 were taken. Approximate location and depth of GC 194 are indicated.

## 15.2. Sub-bottom profiler

Sub-bottom profiler (SBP) data were acquired simultaneously with multibeam bathymetry using SBP300 (2,5-7 kHz) (Figure 40B). The quality of the SBP is varying in accordance with the limiting factors of acquisition of acoustic data mentioned above. An approximate 550 km of high-resolution SBP were acquired on the NE Greenland shelf and slope.

## 15.3 Sample

One gravity core (GC 194) was taken at a suitable time of open ice and low drift in an area with some draped sediments over what is believed to be glacial material (Figure 40B). The core retrieved 197 cm of sediments. The core was cut in two sections of 1 m, while the core cutter, core catcher and a rest sample from the very top of the core were sampled in separate bags. Shell fragments from the core cutter were put in a fourth separate bag. Samples for head space gas were taken at the base of

each section, while one large sample from the base of the upper section (#1). Pore-water samples to measure SO<sub>2</sub> were taken at every 10 cm interval, starting at 10 cm below surface. The rest of the core was sealed and stored cool.

#### 15.4 CTD

CTD 515 was taken to measure the sound velocity profile (SVP) on the shelf. The CTD were taken at relatively shallow depth (235 m) so the SVP may not apply for the deepest part of the trough as inflow of Atlantic water masses occurs at the bottom of the shelf. CTD 509 from the Aurora seamount is the best match we have to this area deeper than 235 m. No water samples were taken.

## 16 DATA MANAGEMENT

Kate Alyse Waghorn

We have used a data management template designed to log, identify and keep track of all samples and corresponding subsamples. All samples collected have a position in the database to identify as closely as possible the actual sample location as well as a unique identifier to keep track of the sample and related subsample. Samples are grouped based on location – during this expedition samples from Molloy Deep are grouped as superstation 01, Aurora seamount is superstation 02 and NE Greenland is superstation 03. Samples collected with the ROV are given an additional number corresponding to the dive number. A full list of samples and identifiers is given in Appendix 3. Subsamples are further listed in additional appendices. All metadata pertaining to the samples will be uploaded to an open database for posterity. Physical samples will be available for reproduction of results where possible (upon request) and they will be stored at the responsible institution (listed in subsample appendices).

## 17 DISSEMINATION AND COMMUNICATION

Lawrence Hislop, Cera McTavish, Eva Ramirez-Llodra

Hydrothermal vents under permanent ice cover are a last frontier for exploration and research, that easily raise the curiosity of children and adults alike. The cruise provided a unique opportunity to engage society's interest and increase awareness in marine and Arctic research of a region on Earth that is not accessible for most. Increasing awareness based on robust science is essential, not only to advance knowledge and educate the next generation, but also to inform the development of management and conservation measures.

### 17.1 Photography and filming

During the cruise, daily photos and videos were taken to use for documentation, educational, outreach and media purposes. The images are fully 'rights free' allowing all participants onboard to use during and after the cruise. An equal distribution and coverage were attempted so that all participants had good coverage of the work they were doing.

The contents primarily showcase 'teams at work', science methods and processes, sampling, and laboratory activity. In addition, entire team photos at embarkation, mid cruise, and post cruise were

made. The images were copied onto the shared network drive daily in order for teams onboard to easily access and copy to their computers.

The video material requires significant editing time and was not completed during the cruise. However, post-cruise processing for an additional week was done and the material distributed on-line to each institution.

#### **Recommendations:**

- For future cruises, a pre-cruise shot list for photos and videos with identified needs from each institution (group/individual photos) would be helpful for efficiency and ensuring all groups have their needs covered throughout the cruise.
- Coordination between the photographer and group participants in advance will help facilitate efficient filming on-board (shot times/days).
- Any particular storylines or pre-existing imagery from institutions that can be built upon to create a long-term story would be beneficial. Similarly, any post cruise media opportunities to continue adding to the photo/video archive would be beneficial.

#### **17.2 HACON web blog**

A cruise blog was written during the cruise (Figure 41), with 25 stories posted on the REV Ocean website during the cruise ([www.revocean.org/HACON21](http://www.revocean.org/HACON21)). We leveraged mapbox ([www.mapbox.com](http://www.mapbox.com)) to create the blog, created an iframe to host it on REV Ocean's website. The communications team onboard wrote the first 12 stories about the journey to Aurora. Once the HACON Team began collecting samples the communications team collaborated with the scientists for daily contributions to the blog to explain the work they were doing onboard. One scientist per day was asked to compose 100-200 words with flexibility to write more if necessary. Blog submissions ranged from 300 to 600 words. Mapbox was great, with a few limitations such as one photo per story unless hyperlinked to content elsewhere (ie photo platform, youtube, etc). The blog map orientation only allowed for a narrow text box and with high interest in contributing to the blog, we plan to create cruise archives highlighting the experience from different scientists to leverage the longer submissions and parts we had to cut. As we dropped from a 4G connection to Iridium satellite email as we crossed 80°N latitude, we had to send daily emails onshore to upload posts and were limited to low resolution images (typically smaller than 1MB). Since we had no access to view the blog, we saved the text file on the shared drive for cruise participants to read. The scientists helped to download GIS data to make a shapefile to upload to mapbox and plot our shiptrack.

In addition to the blog, a photo-book has been created, to highlight the main achievements of the HACON21 cruise, and in particular the first dives to deep hydrothermal vents under permanent ice cover in the Arctic.

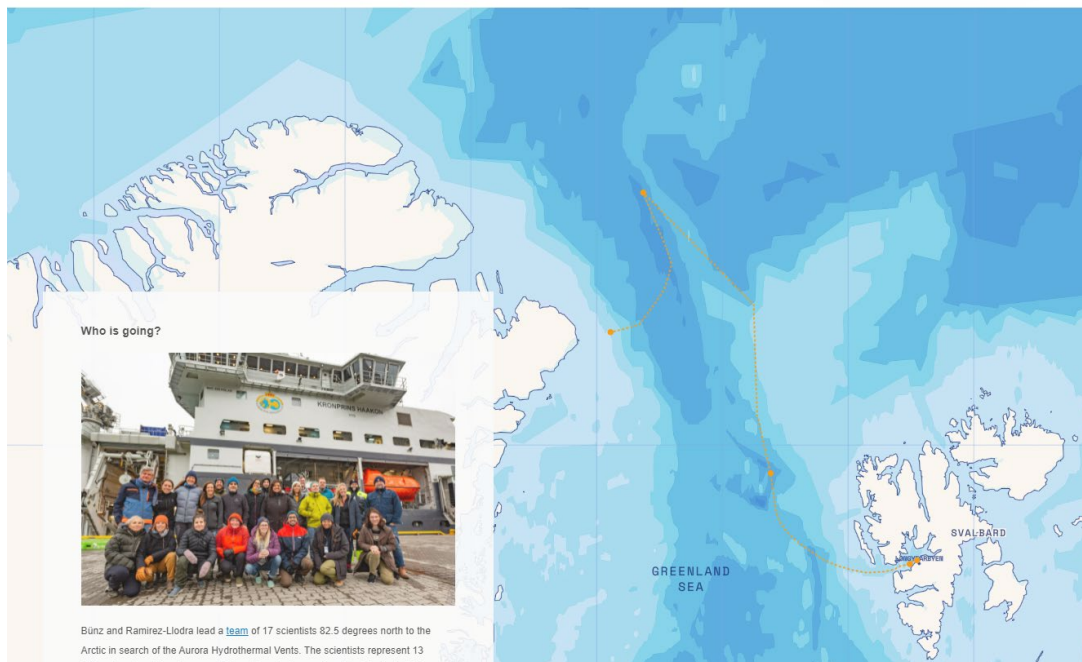


Figure 41. The HACON21 blog: <https://www.revocean.org/HACON2021>

### Recommendations for future cruises:

- Prepare blog link one month prior to cruise to start sharing stories about preparations, build excitement before departure, and promote link for people to join us on our journey.
- Blog briefing document for scientists that includes what has already been mentioned in the blog before (ie depth and novelty of our location was repeated in most submissions but in a variety of nice interpretations which help clarify and visualize communication afterwards), max word count of 200, choose a topic instead of making it open, small tips on successful blog posts.
- Onshore support to update blog, monitor performance, and find relevant content to link from blog stories to more detailed articles.
- Bring communications satellite phone to enable sending larger quality images.
- Ensure that more than one image can be used in each daily blog entry.

### 17.3 School activities

Activities with a Norwegian primary school have been organized for before and after the cruise. Before the cruise, the children of 5<sup>th</sup> and 6<sup>th</sup> grade in Billingstad School wrote their names on polystyrene cups which we took down to 4000 m on the CTD. This was then used to explain the effects of pressure at great depths. A follow up seminar in both schools was conducted. During the seminar, photos and videos of the cruise were shown, to describe the work of marine scientists and provide basic knowledge about the Arctic, the deep sea and hydrothermal vents and the technology used to



explore and investigate these remote regions. The children could also look and touch a rock collected from the rim of the Hans Tore Vent, and look for different pieces of rock from chimney rubble.

A class of the 7th grade of one school in Aveiro (Portugal) followed the web blog of the cruise and invited scientists from the University of Aveiro to give a seminar on hydrothermal vents upon arrival.

## 18 MEDICAL DOCTOR ON BOARD

I am Dr Pascal Habault, GP in Rouen, France. In June, Eva asked me if I would be interested in joining a cruise to the Arctic Ocean - I immediately said yes! The HACON21 cruise worked in the Aurora Vent field on the Gakkel Ridge and NE Greenland shelf, both covered with sea ice, thus making a fast return to port in case of an emergency, unpredictable. These regions are also out of helicopter reach. My role was to contribute with logistics in relation to the pre-cruise covid situation, and then to deal with medical issues that may arise on board during the cruise. After having organised my work and family commitments, I started the pre-cruise preparations.

Before arriving in Longyearbyen, there were 2 important issues to address:

1. How to protect the cruise participants from Covid 19, to minimise as much as possible a positive case in Longyearbyen or early in the cruise.
  - The IMR guidelines on covid were shared amongst all participants and carefully followed. All participants had to be fully vaccinated.
  - Neither a negative test nor quarantine were required by the authorities before flying to Longyearbyen, so we decided together with the cruise co-leads, to request a negative PCR test from all participants one or two days before flying to Longyearbyen. By this, we hoped to minimise the risk of contamination in the hotels and restaurants before the cruise, if anyone would have the virus but was asymptomatic.
  - In Longyearbyen, all participants conducted a covid auto-test (antigen), as required by IMR, under my supervision (Figure 42). Luckily everyone was negative.



Figure 42. Dr Habault supervising the covid auto-tests prior to embarkation in Longyearbyen.

2. During the weeks prior to departure, I checked all the material and medication available on board, through a list provided by the Captain of RV *Kronprins Haakon*. I thought that 2 or 3 important medications were missing, so I brought the following medicines with me:

- Injectable antibiotics for strong infections.
- Antibiotic for female urine infections (mono-doses)
- Subcutaneous injection to prevent thrombosis in a person that needs to be immobilized.

Luckily, during this cruise there have only been a few small issues to attend to. So, for myself, I was kindly welcomed by all scientists and engineers on board. I was interested by the exploration and sampling of the Aurora vents, and I spent a lot of hours watching the ROV dives with great emotion. I was, as well, in the laboratories, and now I am a specialist CTD, and sponge biologist.

## 19 ACKNOWLEDGEMENTS

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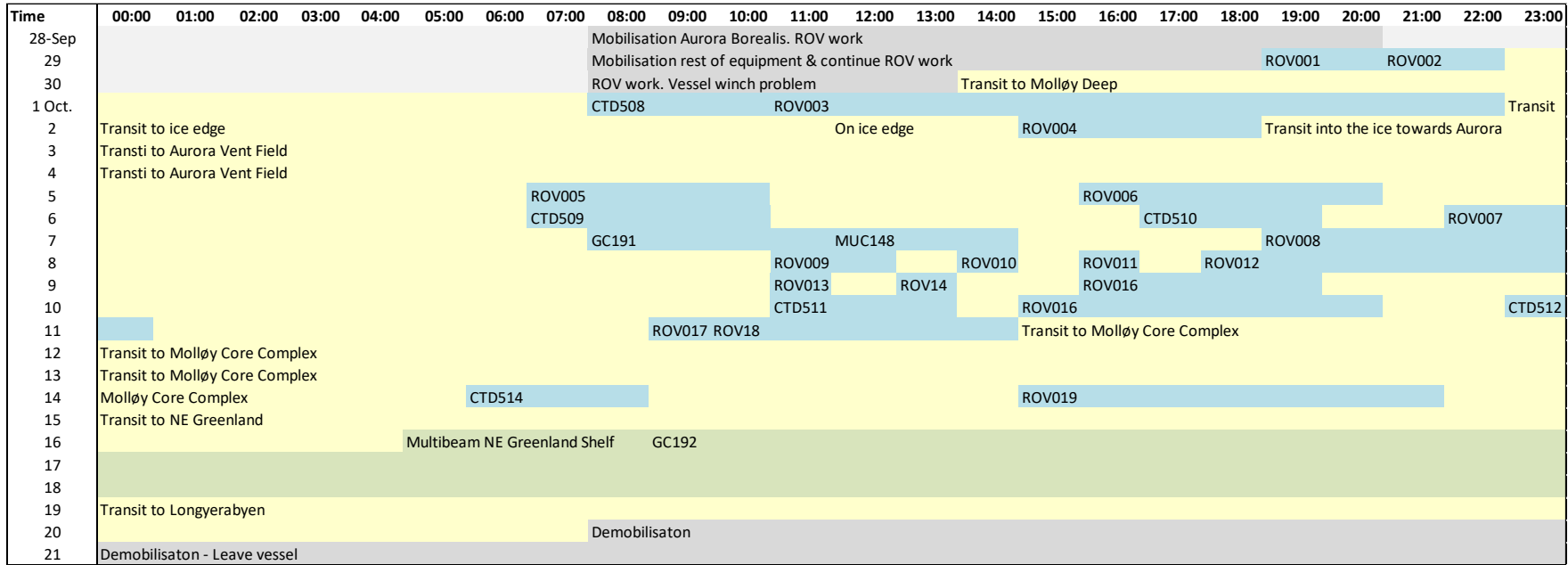
The scientific and technical party of the HACON21 cruise

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## Appendix 1 – Gantt chart of HACON21 cruise



## Appendix 2. Metadata of all ROV Aurora dives during the HACON21 cruise

| Event type: SUC (Suction Sampler), ARM (Manipulator Arm), PC (push core), BLC (blade corer), IGT, SCOP (scoop), SYR (BioSyringe), NISK (Niskin Bottle); VID (Video transect), 4k (4k Video Transect) |            |         |                   |              |            |                      |          |                            |                             |           |  |                  |
|--|------------|---------|-------------------|--------------|------------|----------------------|----------|----------------------------|-----------------------------|-----------|--|------------------|
| Unique ID  | Date       | Cruise  | Location          | ROV REV DIVE | Event type | Event Number (Start) | UTC      | Latitude (decimal degrees) | Longitude (decimal degrees) | Depth (m) | Short sample description (e.g. biology, geology, scoop of rubble, etc) | Logger           |
| HACON21_001_1  | 29/09/2021 | HACON21 | Isfjorden         | 001          | Test       | 1                    | 17:00:00 |                            |                             | 100       | First shallow water test   |                  |
| HACON21_002_1  | 29/09/2021 | HACON21 | Isfjorden         | 002          | Test       | 1                    | 19:00:00 |                            |                             | 250       | Second shallow water test  |                  |
| HACON21_003_1  | 01/10/2021 | HACON21 | Molløy Deep       | 003          | Test       | 1                    | 09:25:00 |                            |                             | 3714      | First deep-water test  |                  |
| HACON21_004_1  | 02/10/2021 | HACON21 | Ice edge          | 004          | Test       | 1                    | 13:00:00 |                            |                             | 1700      | Second deep-water test   | E Ramirez-Llodra |
| HACON21_005_1  | 05/10/2021 | HACON21 | Aurora Vent Field | 005          | ARM        | 1                    | 07:10:00 |                            |                             | 3906      | Rock from dead chimney on  | E Ramirez-Llodra |
| HACON21_006_1  | 05/10/2021 | HACON21 | Aurora Vent Field | 006          |            | 1                    | 13:56:00 |                            |                             | 3850      |  | E Ramirez-Llodra |
| HACON21_007_1  | 06/10/2021 | HACON21 | Aurora Vent Field | 007          | ARM        | 1                    | 23:51:58 | 82 54.2090                 | -6 13.8969                  | 3851      | Rock with anemone  | A Hilario        |
| HACON21_007_2  | 06/10/2021 | HACON21 | Aurora Vent Field | 007          | ARM        | 2                    | 23:56:00 | 82 54.2064                 | -6 13.9170                  | 3843      | Caulophacus sponge with de   | A Hilario        |
| HACON21_007_3  | 07/10/2021 | HACON21 | Aurora Vent Field | 007          | ARM        | 3                    | 00:16:00 | 82 54.1085                 | -6 13.434                   | 3712      | Anconema anemone   | A Hilario        |
| HACON21_007_4  | 07/10/2021 | HACON21 | Aurora Vent Field | 007          | ARM        | 4                    | 00:17:00 | 82 54.1085                 | -6 13.434                   | 3712      | Caulophacus sponge   | A Hilario        |
| HACON21_008_1  | 07/10/2021 | HACON21 | Aurora Vent Field | 008          | IGT        | 1                    | 19:25:00 |                            |                             | 3885      | IGT1 sample  | A Hilario        |
| HACON21_008_2  | 07/10/2021 | HACON21 | Aurora Vent Field | 008          | SCOP       | 2                    | 19:30:00 |                            |                             | 3886      | Piece of smoker  | A Hilario        |
| HACON21_008_3  | 07/10/2021 | HACON21 | Aurora Vent Field | 008          | IGT        | 3                    | 19:36:00 |                            |                             | 3886      | IGT2 sample  | A Hilario        |
| HACON21_008_4  | 07/10/2021 | HACON21 | Aurora Vent Field | 008          | SCOP       | 4                    | 19:42:00 |                            |                             | 3886      | Rubble/chimney pieces with   | A Hilario        |
| HACON21_008_5  | 07/10/2021 | HACON21 | Aurora Vent Field | 008          | SCOP       | 5                    | 19:42:00 |                            |                             | 3886      | Animals fom rubble   | A Hilario        |
| HACON21_009_1  | 08/10/2021 | HACON21 | Aurora Vent Field | 009          |            | 1                    | 08:30:00 | 82 9052                    | -7 7338                     |           |  | E Ramirez-Llodra |
| HACON21_010_1  | 08/10/2021 | HACON21 | Aurora Vent Field | 010          |            | 1                    | 11:59:00 |                            |                             |           |  | E Ramirez-Llodra |
| HACON21_011_1  | 08/10/2021 | HACON21 | Aurora Vent Field | 011          |            | 1                    | 13:49:00 |                            |                             |           |  | E Ramirez-Llodra |
| HACON21_012_1  | 08/10/2021 | HACON21 | Aurora Vent Field | 012          | SUC        | 1                    | 18:15:00 | 82 8971                    | -6 2554                     | 3886      | Fauna sampling on rim of H   | P Ribeiro        |
| HACON21_012_2  | 08/10/2021 | HACON21 | Aurora Vent Field | 012          | SUC        | 2                    | 18:19:00 | 82 85972                   | -6 25352                    | 3881      | Amphipods from HTV   | P Ribeiro        |
| HACON21_012_3  | 08/10/2021 | HACON21 | Aurora Vent Field | 012          | SCOP       | 3                    | 18:23:00 | 828,971                    | -6 2555                     | 3883      | Rocks/rubble   | P Ribeiro        |
| HACON21_012_4  | 08/10/2021 | HACON21 | Aurora Vent Field | 012          | SUC        | 4                    | 18:35:00 | 82 89715                   | -6 2564                     | 3884      | Amphipods from Enceladus   | P Ribeiro        |
| HACON21_012_5  | 08/10/2021 | HACON21 | Aurora Vent Field | 012          | SCOP       | 5                    | 18:40:00 | 82 89715                   | -6 2564                     | 3884      | Rocks from Enceladus   | P Ribeiro        |
| HACON21_013_1  | 09/10/2021 | HACON21 | Aurora Vent Field | 013          |            | 1                    | 08:55:00 | 82 8988                    | -6 3109                     |           |  | I Steen          |
| HACON21_014_1  | 09/10/2021 | HACON21 | Aurora Vent Field | 014          |            | 1                    |          |                            |                             |           |  | I Steen          |
| HACON21_015_1  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | ARM        | 1                    | 14:32:00 | 82.8972                    | -6.2549                     | 3883      | Rock from HTV  | I Steen          |
| HACON21_015_2  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | SUC        | 2                    | 14:52:00 | 82.8972                    | -6.2563                     | 3886      | Blade core 1   | I Steen          |
| HACON21_015_3  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | BLC        | 3                    | 15:00:00 | 82.8972                    | -6.2560                     | 3886      | Blade core 3   | I Steen          |
| HACON21_015_4  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | BLC        | 4                    | 15:04:00 | 82.8972                    | -6.2560                     | 3886      | Blade core 4   | I Steen          |
| HACON21_015_5  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | PC         | 5                    | 15:11:00 | 82.8972                    | -6.2560                     | 3881      | Pushcore 1   | I Steen          |
| HACON21_015_6  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | PC         | 6                    | 15:16:00 | 82.8972                    | -6.2561                     | 3884      | Pushcore 2   | I Steen          |
| HACON21_015_7  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | ARM        | 7                    | 15:42:00 | 82.8963                    | -6.2610                     | 3907      | Rock   | I Steen          |
| HACON21_015_8  | 09/10/2021 | HACON21 | Aurora Vent Field | 015          | ARM        | 8                    | 15:45:00 | 82.8963                    | -6.2614                     | 3886      | Rock   | I Steen          |
| HACON21_016_1  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | ARM        | 1                    | 13:52:00 | 82 8970                    | -6 255                      | 3887      | 2 rock samples from active c   | L Victorero      |
| HACON21_016_2  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | IGT        | 2                    | 14:01:00 | 82 8970                    | -6 255                      | 3887      | IGT1 sample  | L Victorero      |
| HACON21_016_3  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | IGT        | 3                    | 14:08:00 | 82 8970                    | -6 255                      | 3887      | IGT2 sample  | L Victorero      |
| HACON21_016_4  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | ARM        | 4                    | 14:20:00 | 82 8970                    | -6 255                      | 3887      | Rock sample close to active  | L Victorero      |
| HACON21_016_5  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | SYR        | 5                    | 14:43:00 | 82 8970                    | -6 255                      | 3880      | Biosyringe in mats at high te  | L Victorero      |
| HACON21_016_6  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | SUC        | 6                    | 15:08:00 | 82 8970                    | -6 255                      | 3880      | Amphipods  | L Victorero      |
| HACON21_016_7  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | SUC        | 7                    | 15:20:00 | 82 8970                    | -6 255                      | 3886      | Amphipods  | L Victorero      |
| HACON21_016_8  | 10/10/2021 | HACON21 | Aurora Vent Field | 016          | ARM        | 8                    |          | 82 8970                    | -6 255                      | 3884      | Rock for gastropods and lim  | L Victorero      |
| HACON21_016_9  | 20/10/2021 | HACON21 | Aurora Vent Field | 016          | ARM        | 9                    |          | 82 8970                    | -6 255                      | 3889      | Carnivorous sponges  | L Victorero      |
| HACON21_016_10   | 21/10/2021 | HACON21 | Aurora Vent Field | 016          | SUC        | 10                   |          | 82 8970                    | -6 255                      | 3889      | Carnivorous sponges  | L Victorero      |
| HACON21_016_11   | 22/10/2021 | HACON21 | Aurora Vent Field | 016          | SUC        | 11                   |          | 82 8970                    | -6 255                      | 3889      | Carnivorous sponges  | L Victorero      |
| HACON21_017_1  | 23/10/2021 | HACON21 | Aurora Vent Field | 017          |            | 1                    | 07:15:00 |                            |                             |           |  | L Victorero      |
| HACON21_018_1  | 24/10/2021 | HACON21 | Aurora Vent Field | 018          | ARM        | 1                    | 09:34:00 | 82.897                     | -6.254                      | 3889      | Dead chimney   | L Victorero      |
| HACON21_018_2  | 25/10/2021 | HACON21 | Aurora Vent Field | 018          | VID        | 2                    | 09:48:00 | NA                         | NA                          | 3889      | 6 video transects (30 m each   | L Victorero      |
| HACON21_018_3  | 26/10/2021 | HACON21 | Aurora Vent Field | 018          | SUC        | 3                    | 11:33:00 | 82.897                     | -6.255                      | 3859      | Sampling amphipods   | L Victorero      |
| HACON21_018_4  | 27/10/2021 | HACON21 | Aurora Vent Field | 018          | SUC        | 4                    | 11:38:00 | 82.897                     | -6.256                      | 3865      | Sampling amphipods   | L Victorero      |
| HACON21_018_5  | 28/10/2021 | HACON21 | Aurora Vent Field | 018          | ARM        | 5                    | 11:54:00 | 82.897                     | -6.256                      | 3933      | Chimney from Enceladus   | L Victorero      |
| HACON21_018_6  | 29/10/2021 | HACON21 | Aurora Vent Field | 018          | NISK       | 6                    | 12:16:00 | 82.897                     | -6.255                      | 3876      | Niskin bottle on HTV plume   | L Victorero      |
| HACON21_018_7  | 30/10/2021 | HACON21 | Aurora Vent Field | 018          | NISK       | 7                    | 12:20:00 | 82.897                     | -6.256                      | 3877      | Niskin bottle on HTV plume   | L Victorero      |

### Appendix 3 – HACON21 complete station log

| <i>Location</i>    | <i>Station Id</i>                       | <i>Date</i>       | <i>Time (UTC)</i> | <i>Lat. [N]<br/>Long. [E]</i>      | <i>Water Depth [m]</i> |
|--------------------|---|-------------------|-------------------|------------------------------------|------------------------|
| <i>Molloy Deep</i> | <i>CAGE-KH-HACON21-508-CTD</i>          | <i>01.10.2021</i> | <i>07:31</i>      | <i>79.61325 N<br/>3.66222 E</i>    | <i>3500</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV05</i>         | <i>5.10.2021</i>  | <i>04:47</i>      | <i>82.89963 N<br/>6.24944 W</i>    | <i>3906</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV05-RocC-01</i> | <i>5.10.2021</i>  | <i>07:10</i>      | <i>82.8968 N<br/>6.26065 W</i>     | <i>3906</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV06</i>         | <i>5.10.2021</i>  | <i>13:56</i>      | <i>82.91912 N<br/>6.237875 W</i>   |                        |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-509-CTD</i>          | <i>6.10.2021</i>  | <i>06:30</i>      | <i>82.91302 N<br/>6.25575 W</i>    | <i>3960</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-510-CTD</i>          | <i>6.10.2021</i>  | <i>16:30</i>      | <i>82.93057 N<br/>6.177857 W</i>   | <i>4000</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV07</i>         | <i>6.10.2021</i>  | <i>20:19</i>      | <i>82.92473 N<br/>6.26653 W</i>    | <i>4038</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV07-RocC-01</i> | <i>6.10.2021</i>  | <i>23:51</i>      | <i>82.903483 N<br/>6.231615 W</i>  | <i>3851</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV07-Biol-C</i>  | <i>6.10.2021</i>  | <i>23:56</i>      | <i>82.90344 N<br/>6.23195 W</i>    | <i>3843</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV07-SucS-01</i> | <i>7.10.2021</i>  | <i>00:16</i>      | <i>82.901808 N<br/>6.223878 W</i>  | <i>3711</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV07-SucS-02</i> | <i>7.10.2021</i>  | <i>11:17</i>      | <i>82.901808 N<br/>6.223878 W</i>  | <i>3711</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-GC-191</i>        | <i>7.10.2021</i>  | <i>07:56</i>      | <i>82.91731667 N<br/>6.18546 W</i> | <i>3949</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-MC-148</i>        | <i>7.10.2021</i>  | <i>10:35</i>      | <i>82.91362 N<br/>6.25973 W</i>    | <i>4125</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV08</i>         | <i>7.10.2021</i>  | <i>18:10</i>      | <i>82.90366 N<br/>6.20847 W</i>    | <i>3930</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV08-RocC-01</i> | <i>7.10.2021</i>  | <i>19:25</i>      | <i>82.89711 N<br/>6.25635 W</i>    | <i>3886</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV08-IGT-01</i>  | <i>7.10.2021</i>  | <i>19:25</i>      | <i>82.897118 N<br/>6.2563567 W</i> | <i>3885</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV08-IGT-02</i>  | <i>7.10.2021</i>  | <i>19:36</i>      | <i>82.897118 N<br/>6.2563567 W</i> | <i>3885</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV08-Biol-A</i>  | <i>7.10.2021</i>  | <i>19:42</i>      | <i>82.897118 N<br/>6.256357 W</i>  | <i>3886</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV08-RocC-02</i> | <i>7.10.2021</i>  | <i>19:42</i>      | <i>82.897118 N<br/>6.25635 W</i>   | <i>3886</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV09</i>         | <i>8.10.2021</i>  | <i>08:30</i>      | <i>82.9052 N<br/>7.7338 W</i>      | <i>3900</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV10</i>         | <i>8.10.2021</i>  | <i>11:59</i>      | <i>82.9052 N<br/>7.7338 W</i>      | <i>3900</i>            |
| <i>Aurora</i>      | <i>CAGE-KH-HACON21-02-ROV11</i>         | <i>8.10.2021</i>  | <i>13:49</i>      | <i>82.9052 N<br/>7.7338 W</i>      | <i>3900</i>            |

|        |                                 |            |       |                          |      |
|--------|---------------------------------|------------|-------|--------------------------|------|
| Aurora | CAGE-KH-HACON21-02-ROV12        | 8.10.2021  | 16:21 | 82.89867 N<br>6.224015 W | 3930 |
| Aurora | CAGE-KH-HACON21-02ROV12-SucS-01 | 8.10.2021  | 18:12 | 82.89713 N<br>6.25546 W  | 3881 |
| Aurora | CAGE-KH-HACON21-02ROV12-SucS-02 | 8.10.2021  | 18:19 | 82.89723 N<br>6.25522 W  | 3881 |
| Aurora | CAGE-KH-HACON21-02ROV12-SucS-03 | 8.10.2021  | 18:19 | 82.89723 N<br>6.25522 W  | 3889 |
| Aurora | CAGE-KH-HACON21-02ROV12-RocC-01 | 8.10.2021  | 18:23 | 82.89716 N<br>6.2555 W   | 3883 |
| Aurora | CAGE-KH-HACON21-02ROV12-SucS-04 | 8.10.2021  | 18:35 | 82.89715 N<br>6.25644 W  | 3884 |
| Aurora | CAGE-KH-HACON21-02ROV12-RocC-02 | 8.10.2021  | 18:40 | 82.89715 N<br>6.25644 W  | 3884 |
| Aurora | CAGE-KH-HACON21-02-ROV13        | 9.10.2021  | 08:55 | 82.89887 N<br>6.31026 W  | 3990 |
| Aurora | CAGE-KH-HACON21-02-ROV14        | 9.10.2021  | 10:00 | 82.89887 N<br>6.31026 W  | 3990 |
| Aurora | CAGE-KH-HACON21-02-ROV15        | 9.10.2021  | 13:18 | 82.7824 N<br>5.9428 W    | 3860 |
| Aurora | CAGE-KH-HACON21-02ROV15-Blac-01 | 9.10.2021  | 14:49 | 82.8972 N<br>6.2563 W    | 3886 |
| Aurora | CAGE-KH-HACON21-02ROV15-Blac-03 | 9.10.2021  | 15:00 | 82.8972 N<br>6.256 W     | 3886 |
| Aurora | CAGE-KH-HACON21-02ROV15-Blac-04 | 9.10.2021  | 15:04 | 82.8972 N<br>6.2562 W    | 3886 |
| Aurora | CAGE-KH-HACON21-02ROV15-Pusc-02 | 9.10.2021  | 15:11 | 82.8972 N<br>6.2563 W    | 3886 |
| Aurora | CAGE-KH-HACON21-02ROV15-Pusc-01 | 9.10.2021  | 15:16 | 82.8972 N<br>6.2561 W    | 3886 |
| Aurora | CAGE-KH-HACON21-02ROV15-RocC-01 | 9.10.2021  | 15:43 | 82.8972 N<br>6.2559 W    | 3907 |
| Aurora | CAGE-KH-HACON21-511-CTD         | 10.10.2021 | 10:33 | 82.90703 N<br>6.35323 W  | 4092 |
| Aurora | CAGE-KH-HACON21-02-ROV16        | 10.10.2021 | 12:18 | 82.9014 N<br>6.2651 W    | 3900 |
| Aurora | CAGE-KH-HACON21-02ROV16-RocC-01 | 10.10.2021 | 13:52 | 82.8971 N<br>6.2557 W    | 3880 |
| Aurora | CAGE-KH-HACON21-02ROV16-IGT-01  | 10.10.2021 | 14:01 | 82.897 N<br>6.255 W      | 3887 |
| Aurora | CAGE-KH-HACON21-02ROV16-IGT-02  | 10.10.2021 | 14:08 | 82.897 N<br>6.255 W      | 3887 |
| Aurora | CAGE-KH-HACON21-02ROV16-RocC-02 | 10.10.2021 | 14:20 | 82.8971 N<br>6.2559 W    | 3880 |
| Aurora | CAGE-KH-HACON21-02ROV16-BioS-01 | 10.10.2021 | 14:43 | 82.8972 N<br>6.2555 W    | 3880 |
| Aurora | CAGE-KH-HACON21-02ROV16-SucS-01 | 10.10.2021 | 15:08 | 82.8972 N<br>6.2555 W    | 3880 |



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| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV16-SucS-02 | 10.10.2021 | 15:14 | 82.8971 N<br>6.2559 W     | 3880 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV16-RocC-03 | 10.10.2021 | 15:30 | 82.8971 N<br>6.2559 W     | 3880 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV16-Biol-C  | 10.10.2021 | 15:38 | 82.8971 N<br>6.255 W      | 3880 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV16-SucS-03 | 10.10.2021 | 15:40 | 82.8971 N<br>6.255 W      | 3880 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV16-SucS-04 | 10.10.2021 | 15:47 | 82.8971 N<br>6.255 W      | 3880 |
| <i>Aurora</i>      | CAGE-KH-HACON21-512-CTD         | 10.10.2021 | 18:42 | 82.91805 N<br>6.27369 W   | 3836 |
| <i>Aurora</i>      | CAGE-KH-HACON21-513-CTD         | 10.10.2021 | 22:00 | 82.89823 N<br>6.26157 W   | 3831 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02-GC-192       | 11.10.2021 | 01:22 | 82.92461 N<br>6.23531 W   | 3868 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02-ROV17        | 11.10.2021 | 07:09 | 82.8947 N<br>6.2311 W     | 3942 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02-ROV18        | 11.10.2021 | 08:08 | 82.895 N<br>6.242 W       | 3942 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV18-RocC-01 | 11.10.2021 | 09:34 | 82.8971 N<br>6.2548 W     | 3889 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV18-SucS-01 | 11.10.2021 | 11:33 | 82.8971 N<br>6.255 W      | 3880 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV18-SucS-02 | 11.10.2021 | 11:33 | 82.8971 N<br>6.255 W      | 3880 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV18-RocC-02 | 11.10.2021 | 11:53 | 82.8971 N<br>6.2556 W     | 3889 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV18-WatS-01 | 11.10.2021 | 12:16 | 82.8971 N<br>6.2558 W     | 3876 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02ROV18-WatS-04 | 11.10.2021 | 12:16 | 82.8971 N<br>6.2557 W     | 3876 |
| <i>Aurora</i>      | CAGE-KH-HACON21-02-GC-193       | 11.10.2021 | 15:42 | 82.92701 N<br>6.240233 W  | 3909 |
| <i>Molloy Deep</i> | CAGE-KH-HACON21-514-CTD         | 14.10.2021 | 05:10 | 79.75112 N<br>2.9483067 E | 4457 |
| <i>Molloy Deep</i> | CAGE-KH-HACON21-01-ROV19        | 14.10.2021 | 10:43 | 79.3917 N<br>3.6118 E     | 3763 |
| <i>Molloy Deep</i> | CAGE-KH-HACON21-01ROV19-SucS-01 | 14.10.2021 | 12:15 | 79.392 N<br>3.6113 E      | 3763 |
| <i>Molloy Deep</i> | CAGE-KH-HACON21-01ROV19-Biol-B  | 14.10.2021 | 12:29 | 79.392 N<br>3.6113 E      | 3763 |
| <i>Molloy Deep</i> | CAGE-KH-HACON21-01ROV19-RocC-01 | 14.10.2021 | 12:50 | 79.3923 N<br>3.6104 E     | 3756 |
| <i>Molloy Deep</i> | CAGE-KH-HACON21-01ROV19-SucS-02 | 14.10.2021 | 13:11 | 79.3929 N<br>3.6037 E     | 3739 |
| <i>Molloy Deep</i> | CAGE-KH-HACON21-01ROV19-RocC-02 | 14.10.2021 | 13:35 | 79.3935 N<br>3.5991 E     | 3708 |

|                     |  |                   |              |                                  |             |
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| <i>Molloy Deep</i>  | <i>CAGE-KH-HACON21-01ROV19-BlαC-01</i> | <i>14.10.2021</i> | <i>13:59</i> | <i>79.3933 N<br/>3.5954 E</i>    | <i>3686</i> |
| <i>Molloy Deep</i>  | <i>CAGE-KH-HACON21-01ROV19-BlαC-02</i> | <i>14.10.2021</i> | <i>14:04</i> | <i>79.3933 N<br/>3.5954 E</i>    | <i>3686</i> |
| <i>Molloy Deep</i>  | <i>CAGE-KH-HACON21-01ROV19-PusC-01</i> | <i>14.10.2021</i> | <i>14:08</i> | <i>79.3933 N<br/>3.5954 E</i>    | <i>3686</i> |
| <i>Molloy Deep</i>  | <i>CAGE-KH-HACON21-01ROV19-RocC-03</i> | <i>14.10.2021</i> | <i>15:05</i> | <i>79.3949 N<br/>3.5788 E</i>    | <i>3623</i> |
| <i>NE Greenland</i> | <i>CAGE-KH-HACON21-515-CTD</i>         | <i>16.10.2021</i> | <i>07:41</i> | <i>78.71571 N<br/>10.45936 W</i> | <i>235</i>  |
| <i>NE Greenland</i> | <i>CAGE-KH-HACON21-01-GC-194</i>       | <i>17.10.2021</i> | <i>07:04</i> | <i>78.4513 N<br/>9.6899 W</i>    | <i>268</i>  |