CAGE - Centre for Arctic Gas Hydrate Environment and Climate Report Series, Volume 5 (2017)

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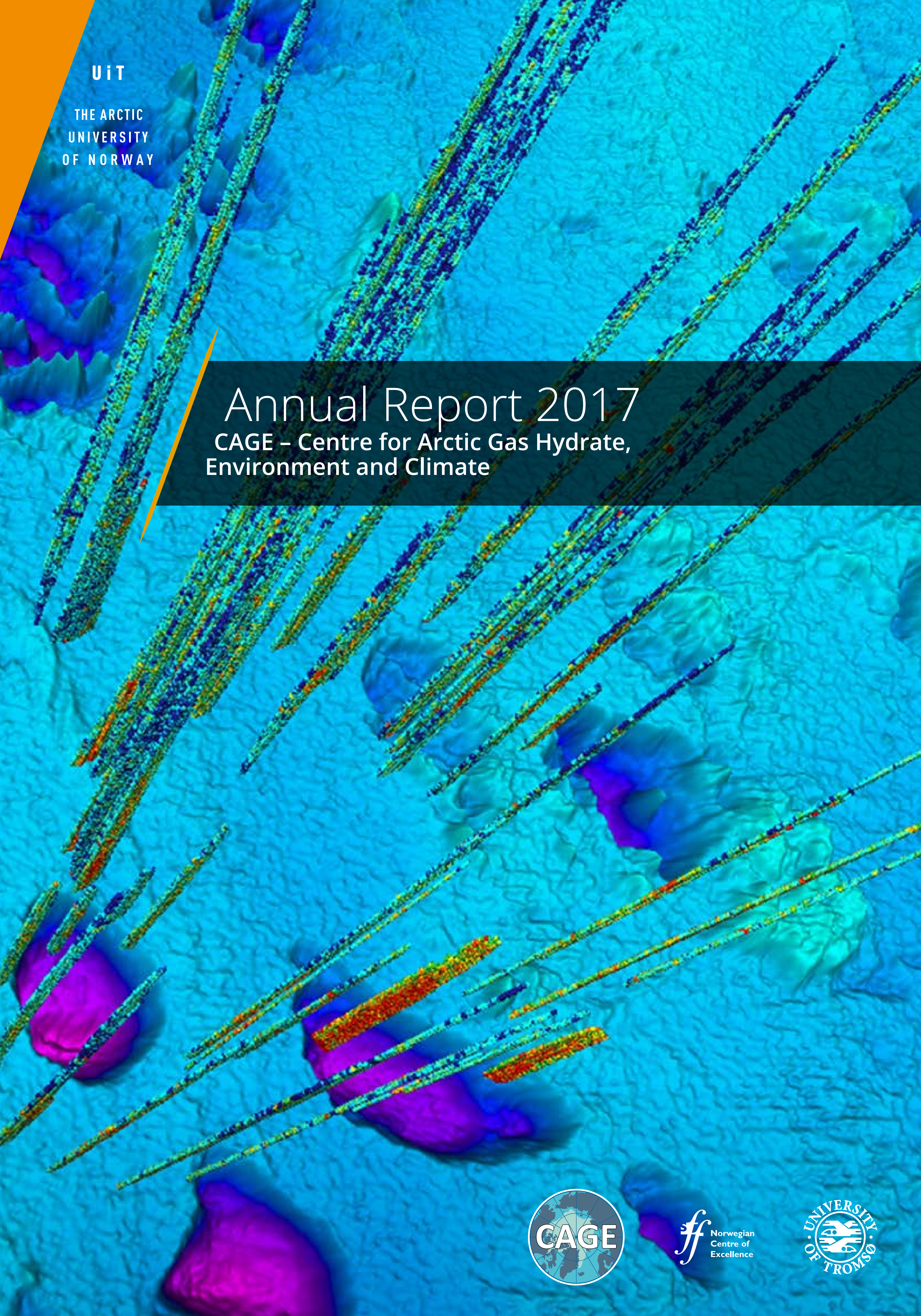
Modifications:
This version of the annual report has been modified from the original published in 2018.
Below is an overview of the changes made.

- Impact factor values have been removed from page 30-31 (Publications list)

UiT

THE ARCTIC UNIVERSITY OF NORWAY



# Annual Report 2017

## CAGE – Centre for Arctic Gas Hydrate, Environment and Climate

CAGE

Norwegian Centre of Excellence

# Words from the Director

CAGE has completed its first five-year phase as a Centre of Excellence. During this short time, the centre has established itself as a world leader in gas hydrate-related environmental and climate research. This achievement was recognised by our highly successful midway-evaluation in 2017, where significant funding was secured from the Norwegian Research Council for another five years.

## Methane – a greenhouse gas more potent that $CO_2$

Methane is the second most important greenhouse gas after $CO_2$. It has a short life time, but when integrated over 20 years it has a warming effect over 80 times greater than that of carbon dioxide, triggering very rapid warming. In the Arctic vast amounts of methane are trapped at shallow depths below the seafloor as gas hydrates, ice-like frozen mixtures of gas and water. Current ocean warming makes these greenhouse gas reservoirs vulnerable to thawing. CAGE is investigating what this could mean for Arctic climate and environment in the future.

## Scientific highlights

CAGE has had several successful research cruises with the UiT Research Vessel Helmer Hanssen in 2017. A major objective has been demonstrating the suitability of the high-resolution P-cable 3D seismic equipment for time-lapse 4D investigations of the linkage between gas hydrates, fluid migration and environmental change. Furthermore, seafloor observatories deployed in the Arctic Ocean for a year, have been successfully recovered, providing vital datasets on seasonal water-column methane dynamics.

Our focus on high-latitude petroleum provinces as a specific gas hydrate setting has generated significant scientific and public interest. We have examined the interaction of huge ice sheets with underlying petroleum reservoirs, that results in highly concentrated gas hydrate accumulations located at shallow sub-bottom depths. Our conceptual model for large-scale abrupt methane ejections in such settings was published in Science, and is highly relevant also for potential future destabilization of gas hydrate reservoirs associated with contemporary ice sheets of Greenland and Antarctica.

> *Our focus on high-latitude petroleum provinces as specific gas hydrate setting has generated significant scientific and public interest*

Our results furthermore indicate that the amounts of carbon trapped in gas hydrates in Arctic petroleum provinces are underestimated, and that the continental shelf of the Barents Sea could be prone to significant gas hydrate destabilization due to warming oceans.

Due to the important role of microbes in regulating gas emissions into and through the water column, microbiology has taken an increasingly important role in CAGE. We are taking this a step further with our plans for the "Ice-Cold Microorganisms Laboratory" (ICOM), which will be a unique platform for long-term experiments of the microbiological response to methane dynamics in a changing Arctic.

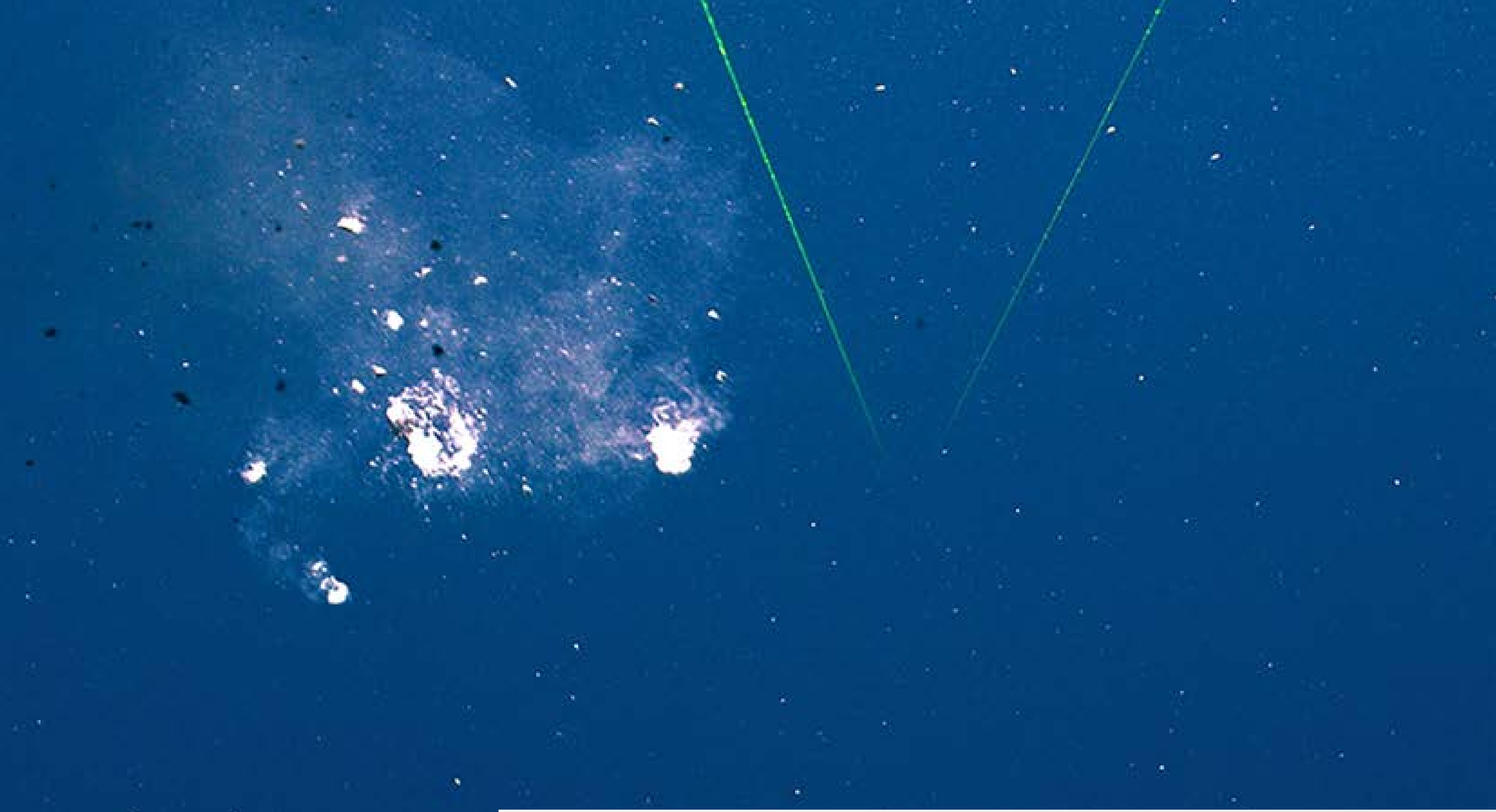
## Looking ahead

CAGE has had great success in combining development of innovative technologies with interdisciplinary, cutting edge research, and our strong collaboration with both industry and academia, nationally and internationally has been important. Our future research directions will follow and expand from this successful path. We will continue to integrate knowledge, techniques and expertise from different scientific fields to investigate the complex environmental and climatic systems of the warming Arctic.

The new ice-going Research Vessel Kronprins Haakon opens up new areas of the frozen Arctic Ocean, expanding the opportunities for pan-Arctic research on Arctic gas hydrates, environment and climate. It is also the perfect platform for training the new generation of experts on a changing Arctic in our PhD Research School.

Karin Andreassen

Prof. Karin Andreassen, *Centre Director*



# Contents



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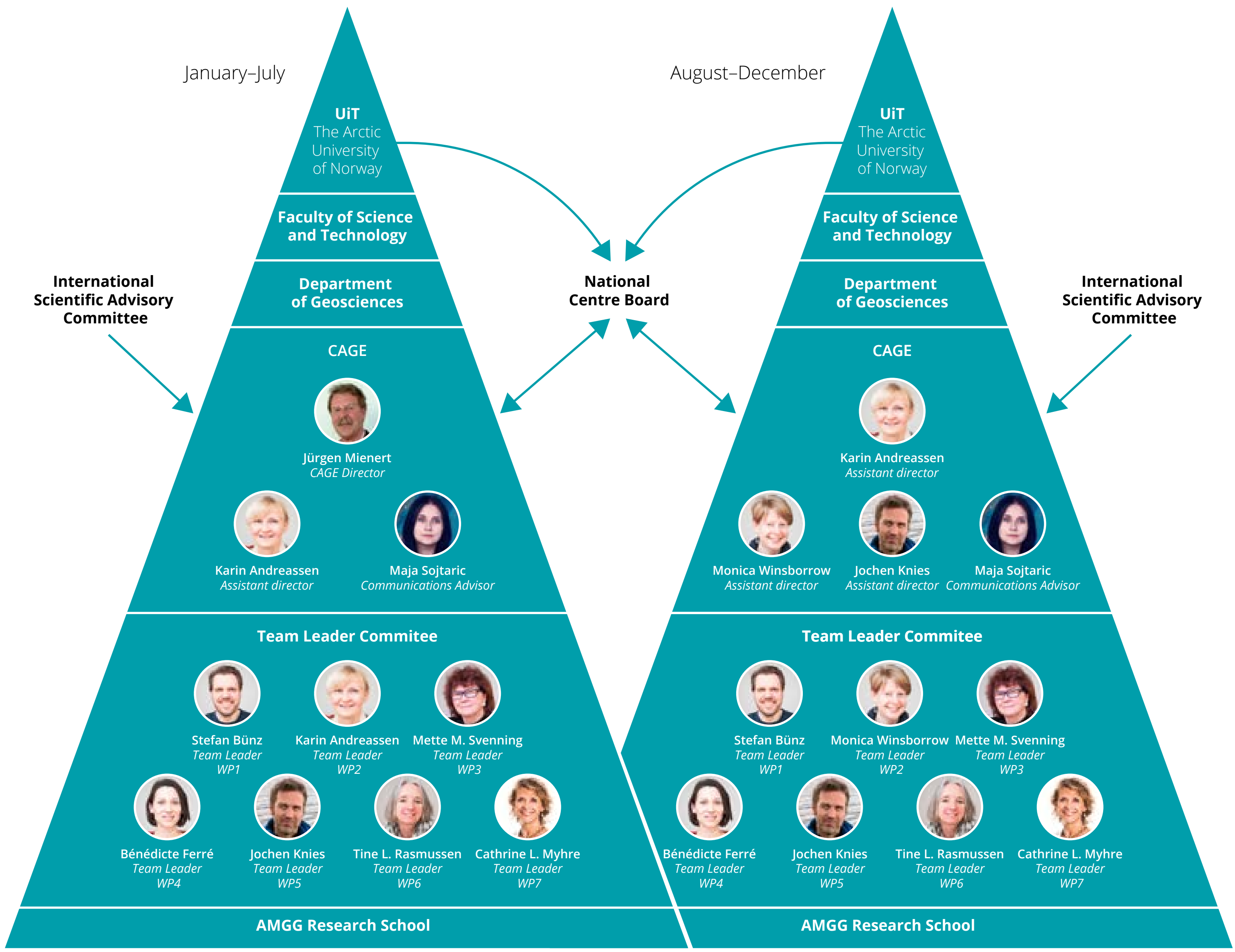
*Cover illustration: Methane release associated faults fractures and acoustic anomalies in 3D seismic. Illustrated by A.P. Faverola; Photo page 2: Karin Andreasesen; Photo page 3: Gas hydrates dissociating in the water column in the Arctic Ocean. Photo by Giuliana Panieri, CAGE.*

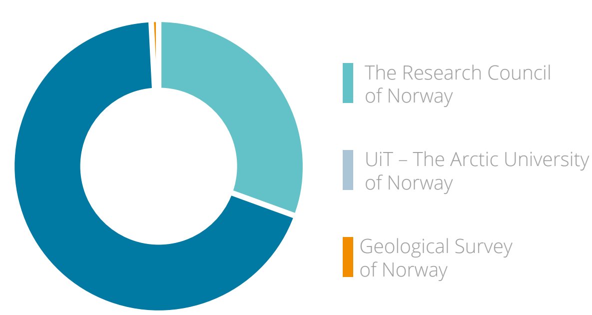

*Editorial team: Maja Sojtaric & Karin Andreassen. Design and layout by Torger Grytå, Department of Geosciences, UiT – The Arctic University of Norway.*

# Organisation chart of the centre




# Funding 2017

| Funding (1000NOK) | Amount | Percentage |
|---|---|---|
| The Research Council | 15 084 | 30.6 % |
| UiT The Arctic University of Norway | 33 786 | 68.6 % |
| Geological Survey of Norway | 368 | 0.7 % |
| **Total** | **49 238** | **100 %** |

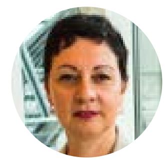


# The centre board

The centre board is responsible for overseeing the strategy for research, training, economy and patent developments at the centre of excellence. The board also oversees operational aspects including the relationships to the University, institutes and industry. Director of CAGE, Professor Jürgen Mienert, reports to the centre board.

**Kenneth Ruud**
*Chairman*
*Prof., Pro-Rector for Research and Development, UiT*

**Morten Hald**
*Prof., Dean NT-faculty, UiT*



**Nalan Koc**
*PhD, Research Director, Norwegian Polar Institute*

**Morten Smelror**
*PhD, Adm. Director, Norwegian Geological Survey*

**Ingrid Schjølberg**
*Prof., Director, Ocean Science Technology NTNU*

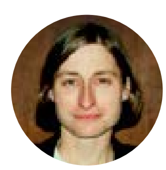
**Kristina Helland-Hansen**
*Vice President Exploration, Statoil*

# Scientific advisory committee

CAGE has an international scientific advisory committee that gives advice on stratigic scientific issues and consists of distinguished experts in their fields.

**Prof. Antje Boetius**
*Alfred-Wegener Institute for Polar Research, FRG*

**Prof. Georgy Cherkashov**
*Institute of Mineral resources of the Ocean, RUS*



**Dr. Carolyn Ruppel**
*United States Geological Survey, USA*

**Dr. Jerome Chappelaz**
*Research Director, CNRS, Grenoble, FR*

**Prof. Doug Connelly**
*National Oceanography Centre, Southampton, UK*

WORK PACKAGE 1

# Gas hydrate and free gas reservoirs

## Stefan Bünz, *Team Leader*

Professor Stefan Bünz has 20 years of experience in marine geology and geophysics with specific research expertise in: gas hydrates, fluid flow systems, shallow gas anomalies and geohazards, high-resolution 3D/4D and multi-component seismics, $CO_2$-storage in petroleum provinces, seafloor ecosystems, ultra-slow spreading ridges, and tectonic and non-tectonic faulting.

## Members:

Joel Johnson
*Associate Professor (USA)*

Peter Franek
*Postdoctoral Researcher*

Alexey Portnov
*Postdoctoral Researcher*

Sunil Vadakkepuliyambatta
*Postdoctoral Researcher*

Shyam Chand
*Researcher*

Andreia Plaza Faverola
*Researcher*

Giacomo Osti
*PhD Candidate*

Sunny Singhroha
*PhD Candidate*

Alexandros Tasianas
*PhD Candidate*

Espen Valberg
*PhD Candidate*

Malin Waage
*PhD Candidate*

Kate Waghorn
*PhD Candidate*

## About:

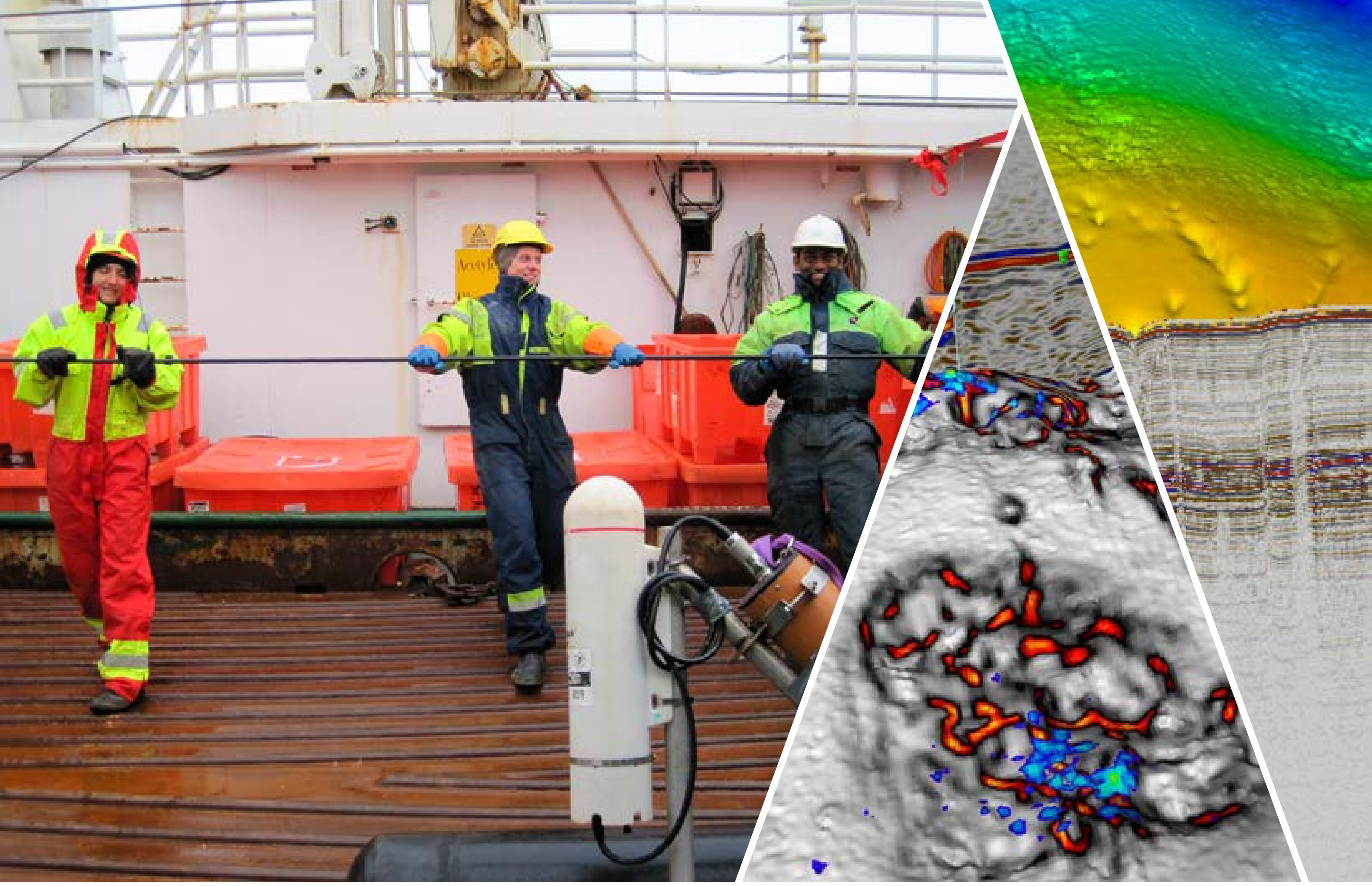
Among the greatest uncertainties in the Arctic marine gas hydrate system is the amount and stability of frozen methane in sub-seabed sediments. Equally important is the amount of this methane that has or will be released, potentially impacting ocean life and climate. In our work package we have developed innovative, high-resolution geophysical acquisition, processing and interpretation techniques. Combining these with inverse modelling enables us to detect, image and assess marine methane hydrate reservoirs across the Arctic.

## Main questions:

- How much carbon is stored in today's methane hydrate and free gas reservoirs in the Arctic and how much is susceptible to climate change?
- At what rates, by which means and under which circumstances is methane expelled from sub-seabed reservoirs to the seabed?

## Major aims:

- Identify and quantify gas hydrate and free gas reservoirs in the Arctic.
- Develop technologies for direct detection of gas hydrate in marine sediments.
- Understand the spatial and temporal dynamics of gas hydrate reservoirs under changing environmental conditions using high-resolution 3D seismic imaging, sediment drilling and sampling, as well as heat flow measurements and modelling.
- Understand the genesis, mechanisms and governing geological processes of fluid flow.
- Acquire high-resolution 4D time-lapse data to quantify fluid flows through fractured systems.



We focused on investigating deep and shallow gas hydrate and methane release sub-seabed features in two areas offshore of North West Svalbard and in the Barents and Kara Seas.

Research cruises with UiT's R/V Helmer Hanssen provided unique high-resolution 3D and 4D seismic datasets of gas hydrate systems spanning a range of environments from an Arctic shelf to a deep-water system.

We cooperated with the Norwegian Petroleum Directorate (NPD) and the wider hydrocarbon industry, which provided us with exclusive access to commercial geophysical data. This gave us the opportunity to investigate deeper sediment formations where thermogenic gas from petroleum reservoirs migrates upwards into the gas hydrate stability zone (GHSZ).

Close collaboration with Russian colleagues provided data from the Kara Sea at a marine gas release site near Yamal Peninsula. The Yamal Peninsula has received worldwide attention due to the natural blowout craters in onshore permafrost.

## Main achievements 2017

1. Gas hydrate modelling showed that the Barents Sea shelf could be prone to significant gas hydrate destabilization due to warming oceans.

2. Correlation between seismic observations and integrated gas hydrate stability zone modelling showed that the amount of carbon trapped in gas hydrates is underestimated in Arctic petroleum provinces.

3. Demonstrated that high resolution P-Cable 3D seismic data is suitable for time-lapse 4D seismic investigation of sub-seafloor fluid migration and expulsion through faults and fractures.

4. Detected micro-seismicity in ocean-bottom seismometers and used this to examine intensity of seepage periods

5. Integration of P-Cable 3D seismic with electromagnetic data and seismic velocity models indicated high amounts of gas hydrates, free gas and authigenic carbonates within active chimneys.

*Deployment of P-Cable system from Research Vessel Helmer Hanssen.*

*Pockmark at MeBo drilling site in Vestnesa.*

*Three-dimensional composite figure of Vestnesa Ridge gas hydrate system.*

*Photos & illustrations: Andreia Plaza Faverola, CAGE.*

WORK PACKAGE 2

# The role of ice ages

## Monica Winsborrow, *Team Leader from August 2017*

Monica Winsborrow is a researcher at CAGE. Her research focuses on the reconstruction of past ice sheets, working to understand the processes and mechanisms that control their evolution and dynamics, and examining their environmental impacts. She holds a PhD in Physical Geography from the University of Sheffield, UK and worked in both academia and industry before joining CAGE in 2014. She became team leader and assistant director of CAGE in August 2017.

## Karin Andreassen, *Team Leader until August 2017*

Karin Andreassen is a professor in marine geology and geophysics at UiT. Her research career spans more than 25 years investigating the long-term development of the Barents Sea and the wider Arctic, focusing on ice sheet dynamics and subglacial landforms, sediments and processes, gas hydrates, shallow gas and fluid flow spanning from glacial to interglacial conditions.

## Members:

**Alun Hubbard**
*Professor*

**Leonid Polyak**
*Professor*

**Chris Stokes**
*Visiting Professor (UK)*

**Henry Patton**
*Postdoctoral Researcher*

**Nikolitsa Alexandropoulou**
*PhD Candidate*

**Emilia Daria Piasecka**
*PhD Candidate*

**Calvin Shackleton**
*PhD Candidate*

**Mariana da Silveira Ramos Esteves**
*PhD Candidate*

**Pavel Serov**
*PhD Candidate*

## About:

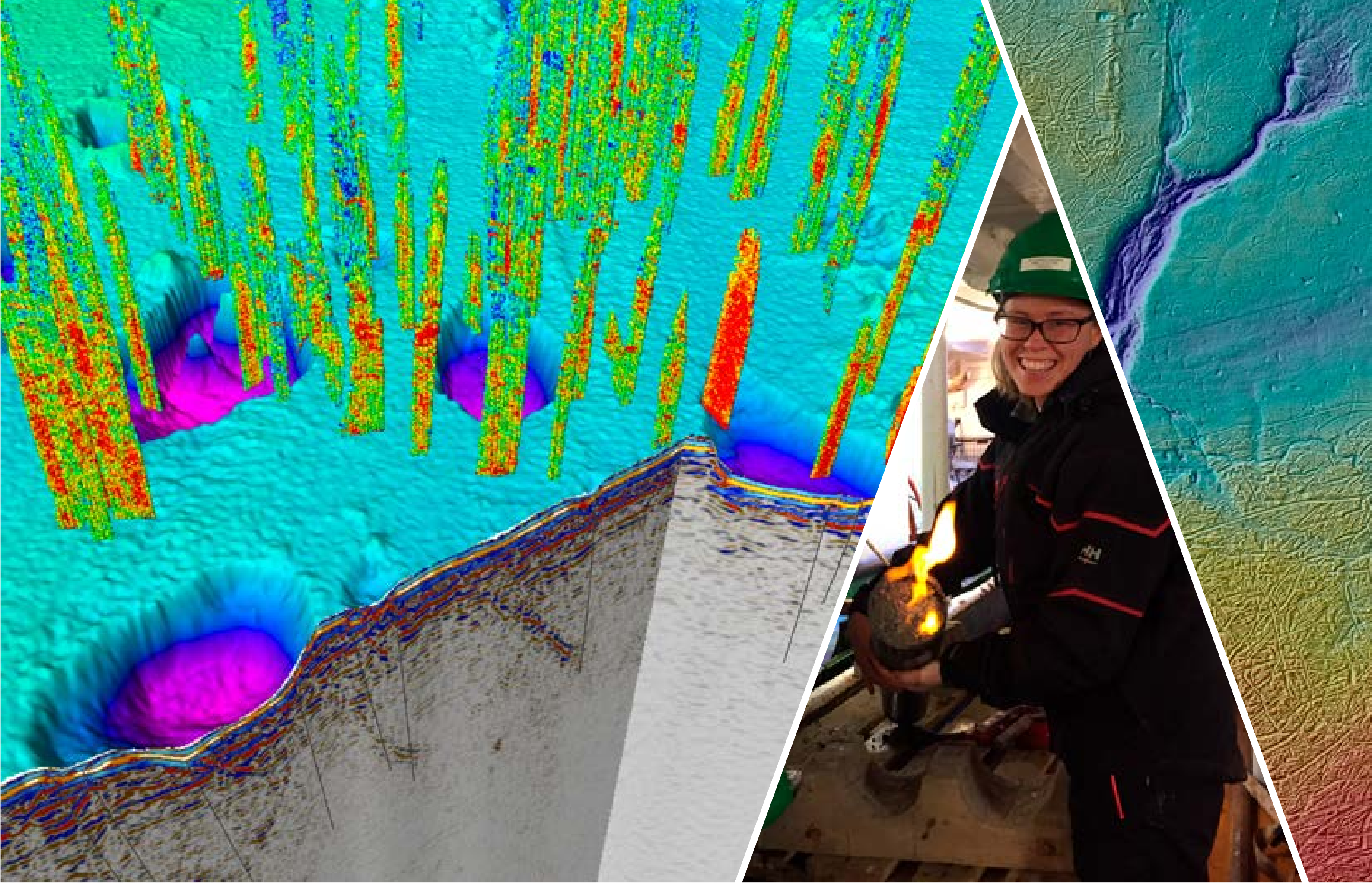
Vast quantities of methane are sequestered as shallow gas hydrates across the Barents Sea shelf. Deep thermogenic sources continually feed these gas hydrate reservoirs, which exist where there are low temperatures and high pressure. We propose that these hydrate reservoirs were much thicker, more extensive and stable under the extreme conditions of past ice ages. As the massive ice sheet loaded the Barents seabed, it created persistently high pressure and low temperature subglacial regimes. We combine state-of-the-art marine geophysical data with high-resolution numerical ice sheet modelling. This provides us with extraordinary insights into the long-term variability of methane storage and release, forced by glacial advance and retreat over the past 2.7 Ma. Our new understanding is crucial to improve the prediction of present and future greenhouse gas release from today's Greenland and Antarctic ice sheets.

## Main questions:

- How does the subglacial footprint of ice sheets impact on deep fluid flow and gas hydrate dynamics?
- How does the thickness, extent and volume of gas hydrates change through the ice ages?
- What impact did glaciations have on the Arctic environment?

## Major aims:

- Determine, through modelling and empirical observations, the key processes, interactions and fluxes between gas hydrates and ice sheets.
- Model the long-term impact of past glacial cycles on hydrocarbon systems.
- Isolate critical subglacial controls on past ice sheet and ice stream behaviour and dynamics.
- Develop stratigraphic and environmental frameworks for key CAGE study areas.
- Develop stratigraphic and environmental frameworks for key CAGE study areas with an extension into the Norwegian sector of the Arctic.



Numerical models require accurate constraints provided by high quality empirical data. We continue to acquire state-of-the-art geophysical datasets from strategic field sites across the Norwegian- Barents Sea and Arctic.

Our work package is in a world leading position to implement models of past glacial cycles and processes. We can assess their concomitant impact on subglacial gas hydrate dynamics in unprecedented accuracy and detail.

## Main achievements 2017

1. Developed an innovative, climatically coupled ice-sheet model simulation reconstructing the evolution of the Eurasian ice-sheet complex over the past 37,000 years, constrained by an established empirical framework detailing the timing and dynamics of glaciation.

2. Investigated suite of giant seafloor craters and gas hydrate pingos in the Barents Sea, and establish a novel model for their formation based on a coupled ice sheet-gas hydrate reconstruction. The results were published in Science.

3. Advanced understanding of the Barents Sea ice sheet deglaciation sequence from high-resolution marine geophysical datasets

4. Validated high-resolution ice reconstruction against glacial-isostatic response history of the Barents Sea in collaboration with Durham University (UK).

5. Modelled the postglacial response of Arctic Ocean gas hydrates to climatic warming.

6. Developed an interactive outreach project incorporating ice sheet modelling at Nordnorsk Vitensenter, funded by KLIMAFORSK programme at Research Centre of Norway (see page 29).

7. Karin Andreassen succeeded professor Jürgen Mienert to the position of the director of CAGE. Monica Winsborrow was appointed the work package leader and the assistant director of CAGE.

*Methane craters and flares in the Barents Sea.*

*Gas hydrate on fire in a sediment core.*

*Braided meltwater channel in the central Barents Sea.*

*Photo & illustrations: Andreia Plaza Faverola; Karin Andreassen; Calvin Shackleton/MAREANO.*

# Cold loving microbes in a warming Arctic

## Mette Marie Svenning, *Team Leader*

Professor Mette Marianne Svenning is an internationally recognized expert on methods for isolation and cultivation of methane oxidizing bacteria (MOB), and has a culture collection of representative MOB from Arctic and sub-Arctic regions. Svenning has extensive fieldwork experience from Arctic (Svalbard) and sub-Arctic regions. This includes leadership, management and coordination of fieldwork, methane emission measurements, vegetation analyses and sampling for microbial and molecular studies in the laboratory.

## Members:

**Helge Niemann**
*Assoc. Professor (20%)*

**Friederike Gründger**
*Postdoctoral Researcher*

**Wei-Li Hong**
*Postdoctoral Researcher*

**Arunima Sen**
*Postdoctoral Researcher*

**Michael Carroll**
*Researcher*

**Vincent Carrier**
*PhD Candidate*

**Pavel Serov**
*PhD Candidate*

**Emmelie Åström**
*PhD Candidate*

## About:

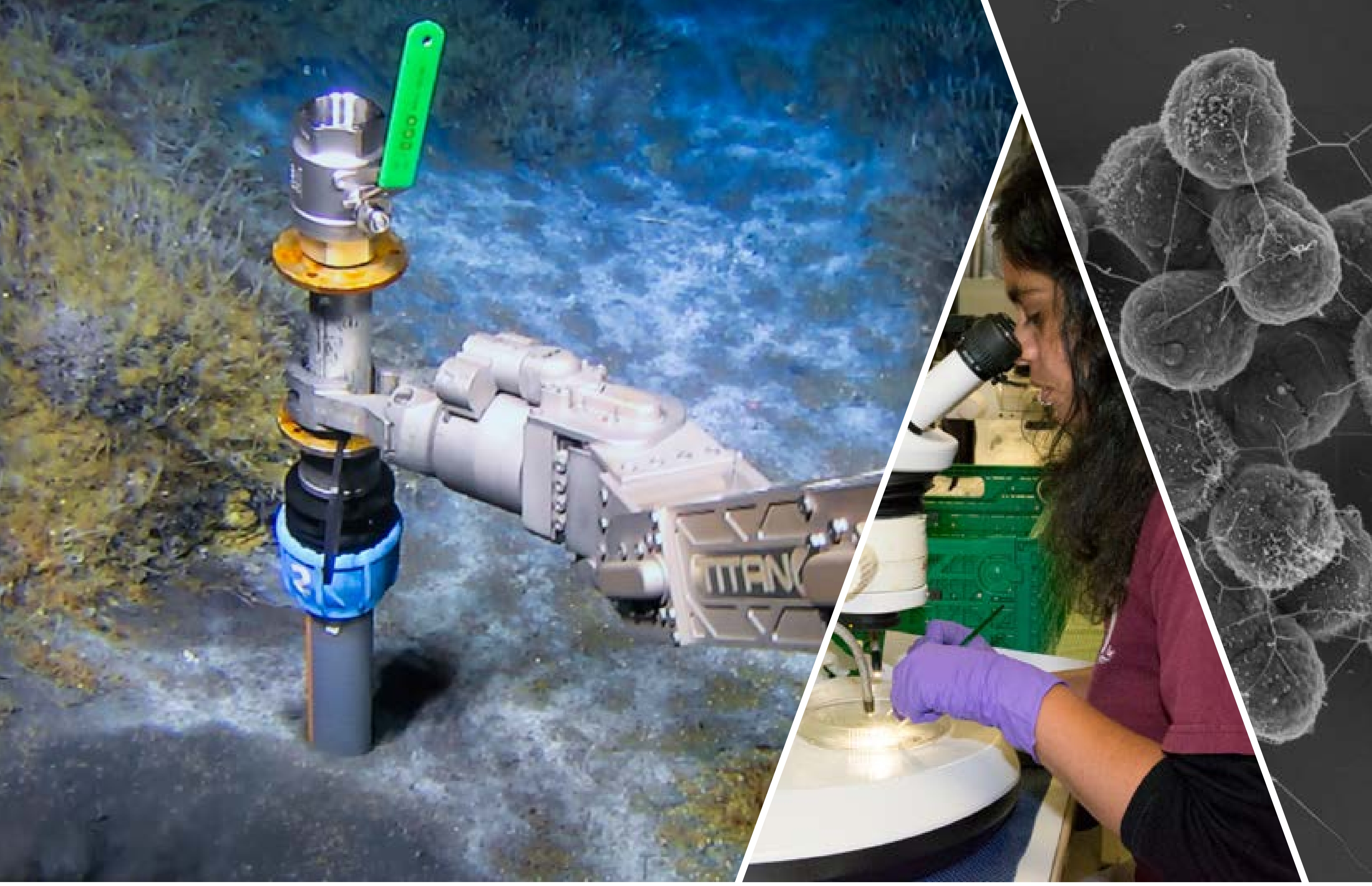
The central scientific objective of the group is to elucidate the role of the seafloor and the water biological community in mediating the release of methane from sediments to the ocean and atmosphere.This includes benthic organisms, communities, microorganisms and food web structures in order to understand the range of biological responses to varying intensities of methane seeps from the Arctic marine sediments. Our studies are linked to, and coordinated with, geochemical, sedimentological and water column studies of the CAGE team. In the coming years, WP3 will emphasize microbiology and the sensistivity of cold adapted microbial sub-seabed ecosystem's importance for methane emissions. A new and unique infrastructure, the Ice-Cold Microorganisms Laboratory (ICOM), will be a novel tool to address biodiversity, activity and evolution of cold loving microbes.

## Main questions:

- How is life on the seabed affected by methane release from gas hydrate dissociation?
- What is the role of the seafloor biological communities in mediating the exchange of methane from seafloor sediments into the water column?
- How do the sub-seabed microbial communites and networks respond to changes in temperature and substrate availability?
- How active is the methane oxidising filter in the water column?

## Major aims:

- Understand habitat characteristics and locations of seep communities.
- Document the characteristics of microbial communities in sediments and the water column, including methanotrophic activity and community composition.
- Decipher life cycles of macrobenthic and microbial communities, along with the ecological structure and function of communities and food webs associated with seafloor methane emissions.
- Understand responses and evolution of cold seep biological communities.
- Get in-depth knowledge of the cold seep microbial structures, adaptations and evolution.




We have accuired knowledge of cold seep biological communities in the Arctic. Images of the seabed and the fauna at methane release sites were correlated with physical and geochemical parameters for development of methane associated communities.

Prof. Svennings culture collection of MOBs from Arctic and sub-Arctic regions currently represents one of the research platforms of Work Package 3: addressing adaptive mechanisms to Arctic ecosystems by molecular physiology; combining laboratory experiments with genomics. Another main research platform of Svenning's group is biodiversity and activity of microbial communities, and their involvement in organic carbon degradation and $CH_4$ emission.

## Main acievements 2017

1. Established a new collaboration with The Faculty of Biosciences, Fisheries and Economics, to better account for the role of microbial communities related to ecosystem structure and methane release from the seabed.

2. Received an infrastructure grant from Tromsø Research Foundation (TSF) to establish the Ice-Cold Microorganisms Laboratory (ICOM). The new lab facility will allow CAGE to conduct experiments and get new insights into how microbial communities work in ice-cold environments.

3. Alexander Tøsdal Tveit was awarded a substantial starting grant from TSF for his project: Cells in the cold. The project is closely related to the new lab.

4. Categorized cold seep communities in the High Arctic. These highly specialized communities are found in very close proximity tofocused methane emissions. They differ clearly from communities in other seep-associated areas.

5. Discovered a new genus and two new species of bivalves at active methane seeps and pockmarks along the western and southern margins of the Svalbard shelf.

6. Discovered that methane oxidising bacteria are acting as an extremely potent methane filter, dependant on environmental factors. They are able to utilize methane in the water column and prevent it from reaching the atmosphere.

7. The microbial community composition at cold seeps has been characterized by DNA sequencing. Large parts of this community belongs to still undescribed microbes.

*ROV Æegir taking samples from an what appears to be a microbial mat on the ocean floor offshore Lofoten.*

*Postdoc Arunima Sen examining siboglinid worms in the microscope on board RV G.O. Sars.*

*Methane oxidising bacteria from the water column.*

*Photos: Maja Sojtaric; Mette Svenning.*

# Gas in the water column

## Bénédicte Ferré, *Team Leader*

Bénédicte Ferré is a physical oceanographer whose research activities span from sediment resuspension and transport to oceanographic data associated with methane release. She holds a PhD degree in Marine Science from the University of Perpignan, France. Ferré was a post-doctoral researcher at the United States Geological Survey in Woods Hole, USA, before joining the Department of Geosciences at UiT - The Arctic University of Norway as a researcher in 2008 and CAGE as a team leader in 2013.

## Members:

**Dr. Helge Niemann**
*Assoc. Professor (20%)*

**Dr. Anna Silyakova**
*Researcher*

**Knut Ola Dølven**
*PhD Candidate*

**Pär Gunnar Jansson**
*PhD Candidate*

**Manuel Moser**
*PhD candidate*

**Muhammed Fatih Sert**
*PhD Candidate*

## About:

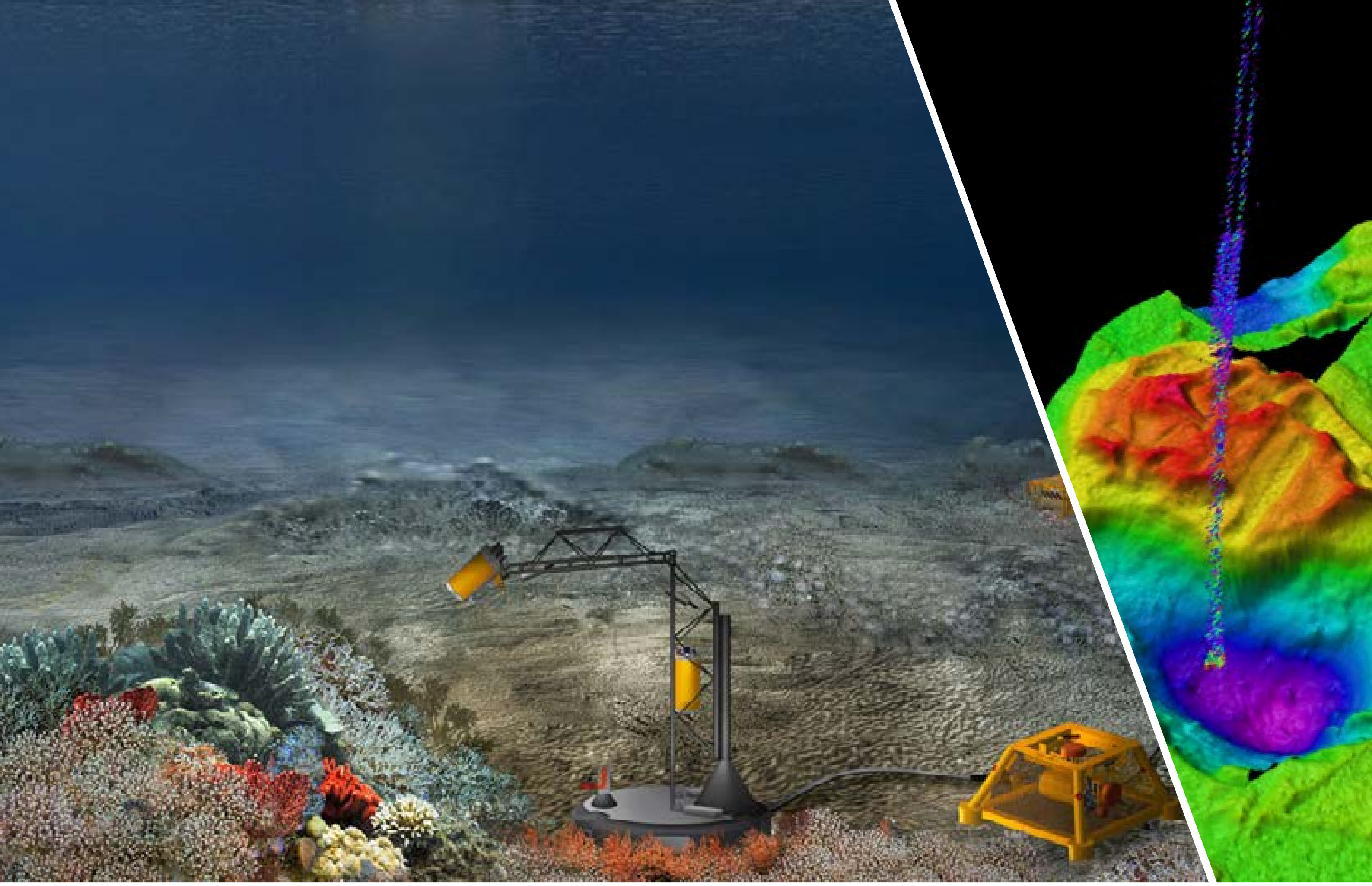
The effects of methane release on Arctic ocean life and climate are still unclear. Methane transport into Arctic oceans takes place via bubbles or in dissolved form from dissociating gas hydrate under the seafloor. However, seasonally stratified water and current dynamics can limit vertical methane diffusion. Our aim is to determine and understand the potential transport processes of hydrocarbon gases from the seabed to the atmosphere. This is achieved primarily by deciphering long-term (multiyear) physical and chemical oceanographic measurements using state-of-the-art technology at key High Arctic methane release sites , as well as through numerical modelling.

## Main questions:

- How much of the methane released from the seafloor reaches the upper water column and/or the atmosphere?
- Over what horizontal and vertical distances do ocean currents transport methane plumes?
- What is the variability of the methane release and what are the processes involved?
- What are the interactions between the physical, chemical and biological processes that affect methane transport?
- What is the effect of methane seeps on the Arctic Ocean biogeochemistry?

## Major aims:

- Observe and model the transport of methane plumes.
- Determine the amount of dissolved methane beneath the seafloor boundary layer.
- Determine and model methane fluxes from the seafloor to the sea surface.
- Determine physical and chemical boundary conditions of the bottom water that modify methane seep activities.
- Investigate and compare water column biogeochemistry at and around active methane flares.



We developed two ocean floor observatories (K-Landers) together with Kongsberg Maritime in 2014–2015, that have allowed us to deploy multi-sensor technology at key Arctic sites over annual timeframes. With such advanced equipment it is possible to continuously measure environmental changes associated with methane release at remarkable resolutions.

The K-Landers demonstrate a successful cooperation between maritime industry and research teams, that is crucial in establishing pioneering, cross-disciplinary research for Arctic Ocean climate systems.

While the ocean observatories monitor the seafloor, a continuous recording system onboard our research vessel RV Helmer Hanssen (in co-operation with NILU, Norwegian Institute for Air Research) measures the release of methane into the atmosphere. This allows us to quantify local and regional atmospheric methane fluxes, as well as to investigate how changes in ocean stratification can regulate methane release through the water column into the atmosphere.

## Main achievements 2017

1. Successfully recovered the two observatories that were deployed in October 2016 offshore Western Svalbard and in the central Barents Sea

2. A collaboration with GEOMAR based on 11 hydro-acoustic surveys shows no evidence of increase in seafloor methane emissions offshore Svalbard from 2008 to 2014

3. Methane measurement under and above the young sea ice were performed during the N-ICE2015 expedition, where the Norwegian Polar Institute's RV Lance was frozen into and drifted with the sea ice at 80°N for several months. Results are discussed in close collaboration with co-authors, and we aim to submit the results by summer 2018.

4. We are estimating methane driven dissolved organic matter dynamics by comparing biogeochemistry at and outside methane seepage areas. To do so, many water samples were taken at different locations during the 2017 summer cruises.

5. We are developing a new tool for predicting the fate of seafloor-emitted methane using a two-phase gas model in one dimension. This numerical model incorporates a wide range of bubble sizes and flatness, coupling between free and dissolved gases, turbulent vertical mixing, direct escape of bubble gas to the atmosphere and equilibration of dissolved gases with the atmosphere.

6. Within the project LoVe (Lofoten-Vesterålen), we are working to develop a cabled observatory on an active methane seep. This project is led by the Institute for Marine Research, Bergen.

7. We have been awarded a collaborative grant within the project SIOS (Svalbard Integrated Arctic Earth Observing Systems) to deploy a K-Lander to continue our time series offshore Svalbard.

*LoVe cabled ocean observatory system offshore Lofoten and Vesterålen.*

*Crater area methane flares.*

*Illustrations: Statoil/Havforskningsinstituttet; Alexey Portnov, CAGE.*

WORK PACKAGE 5

# Methane seepage history

## Jochen Knies, *Team Leader*

Jochen Knies is a senior researcher at the Geological Survey of Norway. He holds a 20% postion at CAGE, where he is currently assistant director. His research expertise integrates marine geochemical and environmental investigations along formerly glaciated continental margins in the Arctic. Knies holds a PhD degree in Marine Geology from the University of Bremen. His broad professional experience includes, among others, a position as postdoctoral fellow at the Alfred Wegener Institute for Polar and Marine Research (AWi), Germany, and a visiting professor position at the University of Hawaii, USA.

## Members:

Giuliana Panieri
*Associate Professor*

Karl Fabian
*Researcher*

Aivo Lepland
*Researcher*

Shyam Chand
*Researcher*

Soma Baranwal
*Postdoctoral Researcher*

Terje Thorsnes
*Researcher*

Tobias Himmler
*Postdoctoral Researcher*

Pierre-Antoine Dessandier
*Postdoctoral Researcher*

Wei-Li Hong
*Postdoctoral Researcher*

Deniz Koseoglu
*PhD Candidate*

Katarzyna Melaniuk
*PhD Candidate*

Simone Sauer
*PhD Candidate*

Andrea Schneider
*PhD Candidate*

Kärt Paiste
*PhD Candidate*

Haoyi Yao
*PhD Candidate*

## About:

To understand the environmental factors that drive methane seepage we need to better constrain the timing of methane release throughout the geological past. To do this we use authigenic carbonates and microfossils to develop records of palaeo-methane seepage for sites around the Arctic. We then assess the influence of various environmental conditions, for example sea ice extent and glacial isostatic adjustment, on methane seepage history.

## Main questions:

- How can we quantify hydrocarbon leakage from "fossil" seep sites and accurately determine the timing of leakage during the geological past?
- What are the environmental conditions that drove past methane release?

## Major aims:

- Establish geochemical markers and time constraints for "abnormal" methane ocean - atmosphere conditions and links to climate scenarios during the geological past.
- Develop palaeo-ice sheet climate models in cooperation with work packages 1 and 2 that can be used to determine and calibrate the ages and amounts of methane release associated with authigenic- derived carbonates in the Arctic.
- From collaborations with the hydrocarbon industry, we will use borehole samples to establish long-term records of methane release.


The recovery of methane-derived authigenic carbonates from shallow drillings on Vestnesa Ridge provide evidence for persistent methane leakage over the last two glacial-interglacial cycles. It confirms the impact of ice ages on Arctic fluid flow systems far beyond the present continental shelf areas.

## Main achievements 2017

1. Identified a new cold-seep site off the Lofoten margin with enormous production of methane-derived biomasses and stable isotopic composition of methane below -115 ‰, one of the lightest ever measured methane values in high northern latitudes. The ultimate source of methane is still uncertain, but the system in 800 m water depth is strongly influenced by meteoric waters, likely sourced from outcropping sedimentary strata.

2. Documented a highly dynamic fluid flow system in the Barents Sea with shut on/off modes on a year-to-year basis. Preliminary observations suggest that natural methane leakage from the seafloor is widespread and sedimentological features like craters, pingos and carbonate crusts, indicate to be long-lived. This site will be further inspected by remotely operating vehicle and seafloor observation during the coming years to provide answers to these phenomena.

3. Developed a full understanding of variable methane gas fluxes to the seabed preserved in calcareous organisms. We have established a classification of visual and mineralogical characteristics of the exterior and interior test wall microstructure of the benthic foraminiferal species Cassidulina neoteretis having experienced different degrees of diagenetic alteration during past methane emission events.

4. Documented that the ongoing and past methane emissions at the gas-hydrate bearing fluid flow systems south of Spitsbergen is due to episodic ventilation of deep reservoirs rather than global warming-induced gas hydrate dissociation.

*Collecting carbonate crust from a canyon off the Lofoten margin.*

*Carbonate crust hosts different life forms.*

*A detail of the remotely operated vehicle Ægir – the Norwegian national infrastructure.*

*All photos: Maja Sojtaric.*

# Methane, $CO_2$ and ocean acidification

## Tine Lander Rasmussen, *Team Leader*

Tine Rasmussen is a professor at the Department of Geosciences, UiT The Arctic University of Norway. Her research interests include palaeoceanography, palaeoclimate, palaeoecology, micropalaeontology, focused on abrupt climate and oceanographic changes including long palaeo time series from Arctic and sub-Arctic areas. She holds a PhD degree in marine science/micropalaeontogy from Aarhus University in Denmark, and has professional experience from among others, from Woods Hole Oceanographic Institution (USA), Lund University (SWE) and Copenhagen University (DK).

## Members:

**Kasia Zamelczyk**
*Researcher*

**Mohamed Ezat**
*Postdoctoral Researcher*

**Ulrike Hoff**
*Postdoctoral Researcher**

**Chiara Consolaro**
*Postdoctoral Researcher*

**Siri Ofstad**
*PhD Candidate*

**Naima El Bani Altuna**
*PhD Candidate*

** Sadly, Ulrike Hoff - a valued member of our team, passed away on Dec. 28th 2017.*

## About:

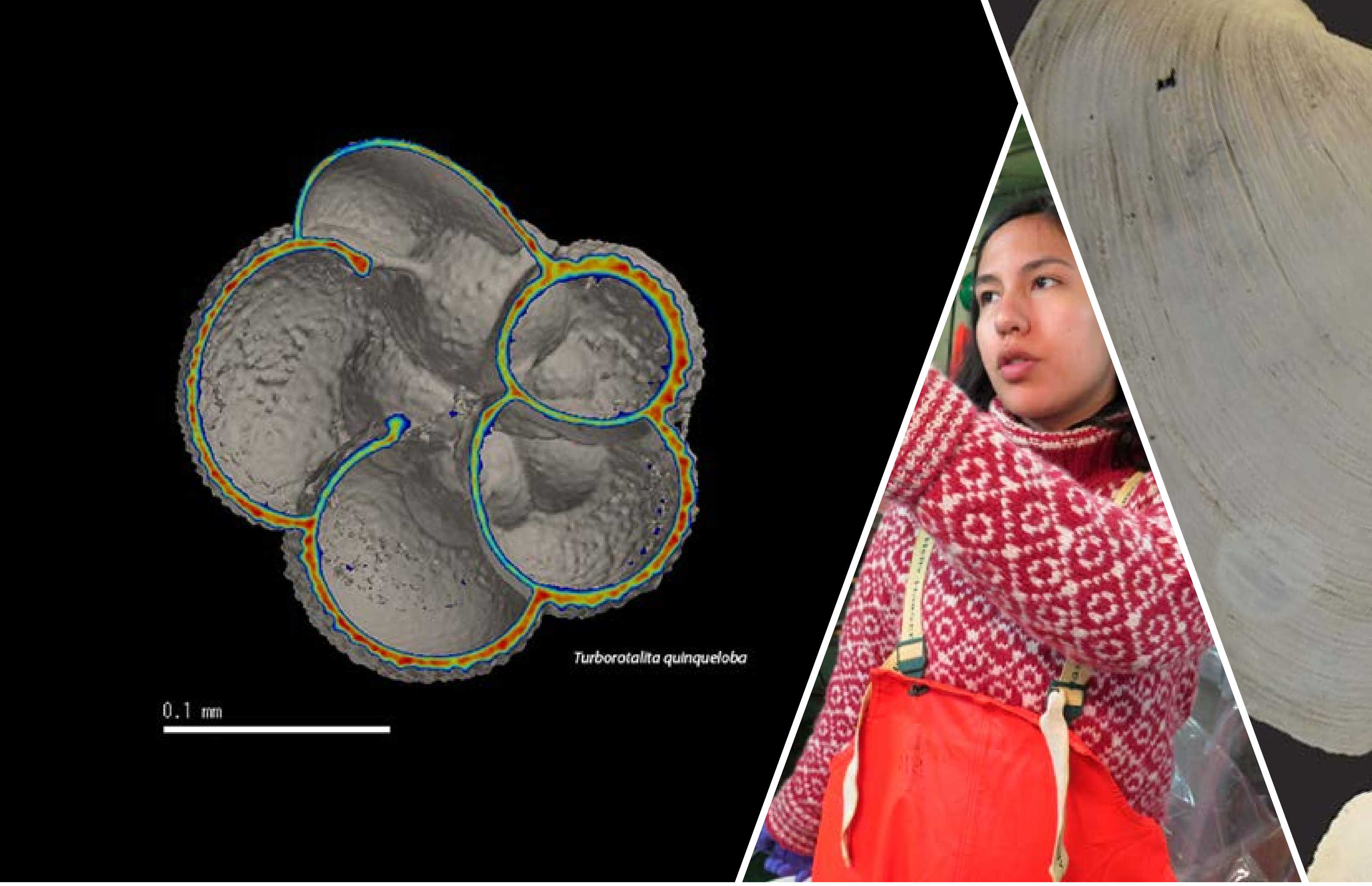
We investigate methane seep areas by annual sampling in order to document changes in both methane release and related ocean acidification. Methane oxidizes to $CO_2$ and can potentially cause ocean acidification. Isotopic records from measurements of foraminiferal shells and quantitative fauna analyses are amongst our proxies for recording changes due to methane emissions. Studies of living and fossil foraminiferal distribution patterns, may indicate the degree of methane release through time. Also abundance of the benthic foraminiferal communities in methane seep areas, and geochemical analyses of stable isotopes and sediment chemistry contribute in that respect. We also investigate areas largely unaffected by methane as control areas.

## Main questions:

- Can we quantify variations in past methane release?
- Is there a relation with climate (ocean temperature) variability or not?
- Does methane release contribute to ocean acidification?

## Major aims:

- Investigate methane release in relation to past climate and ocean temperature changes.
- Apply multi-proxy techniques to reconstruct high-resolution climate and greenhouse gas records.
- Detect and quantify planktic foraminiferal responses to changes in ocean chemistry due to methane release, increasing atmospheric $CO_2$ and ocean warming.
- Provide robust records useful for modelling and forecasting future changes as a result of ongoing changes in the polar ocean.




Insights into past and present ocean conditions depend on improving existing standards and established methods. Our methods comprise: analysis of sediment and foraminiferal fauna/diatom flora carbon-14 datings; isotope analyses; elemental analyses organic geochemistry and biomarkers from dinoflagellate and diatom productivity. Integration of these methods allowed us to publish a benchmark paper in Nature Communications.

## Main achievements 2017

1. Dated increase in release of methane at Vestnesa Ridge to the last deglaciation, beginning during Heinrich event H1 at ca. 17,000–16,000 years. This correlated with major surface bottom water warming and rapid retreat of the Svalbard-Barents Sea Ice Sheet.

2. Observed that methane release from Vestnesa Ridge culminated during the warm Bølling and Allerød interstadials 15,600–13,000 years ago. There were no significant changes in the composition of the benthic foraminiferal faunas between seep and non-seep sites. The faunas were controlled more by changes in ocean circulation, sedimentation patterns and temperature.

3. Analyzed $CO_2$ records for the the past 135,000 years, that show that the Nordic seas acted as a $CO_2$ source during the end of cold Heinrich events. This happened at the same time as the the permanent sea-ice cover disappeared and bottom water temperatures reached their maximum.

4. Investigated for the first time methane seeps in the Barents Sea that indicate extreme productivity of non-calcareous planktic organisms, and poorer preservation of planktic foraminifera and pteropods.

5. Described a new species of chemosynthetic bivalve and found the northernmost occurrence of another known chemosynthetic bivalve species. They seem linked to periods of slightly warmer bottom water conditions.

6. Performed correlation analyses of benthic foraminiferal faunas in the North Atlantic for the glacial period and found that the majority of species respond to bottom water temperature changes at c. 1700 m water depth.

7. $^{14}C$ dating of different benthic foraminiferal species revealed speciesspecific ages and gave new details of the ventilation history of Nordic seas overflows during the last glacial period.

*Image of T. quinqueloba from the crater area generated by the MXCT scanner, the red signifies more dense calcite while blue is less dense.*

*Siri Ofstad on a research cruise aboard Helmer Hanssen.*

*Archivesica arctica. A new species of chemosynthetic bivalve species first described from Vestnesa Ridge (Hansen et al., 2017).*

*Photos: Siri Ofstad; Giuliana Panieri; Tine L. Rasmussen.*

WORK PACKAGE 7

# Methane emissions to the atmosphere

## Cathrine Lund Myhre, *Team Leader*

Cathrine Lund Myhre is a senior scientist at the Department of Atmospheric and Climate Research, at NILU – Norwegian Institute for Air Research. She studies natural and anthropogenic greenhouse gases and aerosols, including their sources, concentrations and long-term trends. Lund Myhre's focus is on the Sub-Arctic and Arctic regions. She holds a PhD in Physical Chemistry from the University of Oslo, Norway. Lund Myhre coordinated the project MOCA (Methane Emissions from the Arctic OCean to the Atmosphere) at NILU, funded by the Norwegian Research Council, and connects the hydrate research done at CAGE with atmospheric science. The MOCA project is a collaboration between UiT/CAGE, NILU - Norwegian Institute for Air Research, and the Center for International Climate and Environmental Research – Oslo (CICERO).

## Members:

**Jürgen Mienert**
*Professor CAGE*

**Bénédicte Ferré**
*Team Leader, CAGE*

**Sunil Vadakkepuliyambatta**
*Postdoctoral Researcher, CAGE*

**Gunnar Myhre**
*Senior Researcher, CICERO*

**Ignacio Pisso**
*Senior Scientist, NILU*

**Stephen M. Platt**
*Scientist at NILU*

**Norbert Schmidbauer**
*Senior Scientist, NILU*

**Andreas Stohl**
*Senior Scientist, NILU*

## About:

The MOCA project investigates the release of methane from the ocean to atmosphere, and the potential effects this greenhouse gas may have on increased radiative forcing and subsequent global warming. The project combines state-of-the-art atmospheric and oceanographic measurements to investigate this powerful greenhouse gas. We also integrate this empirical data with atmospheric models, such as the FLEXPART Lagrangian transport model or OsloCAM3, to achieve impact scenarios for present and future climate change. MOCA contributes to understanding present atmospheric effects of methane released from Arctic seabed sediments.

## Main questions:

- Does methane release from the seabed into the ocean reach the atmosphere?
- What are the climatic implications of seabed methane seepage?

## Major aims:

- Measure and estimate natural methane emissions from the Arctic Ocean floor to the atmosphere.
- Describe the climatic impact and radiative forcing (direct and indirect effects) from seabed methane emissions under present-day as well as future atmospheric compositions.

Centre for Arctic Gas Hydrate, Environment and Climate

Norsk institutt for luftforskning
Norwegian Institute for Air Research

*Methane Emissions from Arctic OCean to the Atmosphere: Present and Future Climate Effects*

The atmosphere group uses observation data to constrain models and understand the processes influencing ocean-atmosphere exchange and addresses the question of whether methane from the ocean is an important issue for the future climate.

## Main achievements 2017

1. Collected atmospheric gas measurements over a three-year period, including 2017, from across large areas of the Arctic Ocean and Barents Sea from the RV Helmer Hanssen. The continuous measurements include methane, $CO_2$, CO, in addition to offline sampling for isotope analysis and quantification of trace gases such as ethane and propane.

2. Modelled methane emissions from gas hydrates over the Arctic Ocean over the 21st century. The model indicates that methane emissions from hydrate dissociation may not be a major driver of global warming.

3. Discovered repeated instances of unexpectedly high methane concentrations along North Svalbard towards the Arctic Ocean. This region is characterized by active methane seeps and water mass stratification very close to the sea surface (>15m). Release of methane from the ocean to atmosphere may be higher in these less stratified water masses. Further work and collaboration between CAGE and NILU relies on new funding as the MOCA project ended in April 2017.

4. Submitted the MOCA final report to the Research Council of Norway. The report was accepted by the program comittee, December 2017.

*Zeppelin atmospheric observatory, Svalbard.*

*Sensor measuring methane and other greenhouse gases on board RV Helmer Hanssen.*

*Photo: Jerzy Strzelecki; CAGE.*

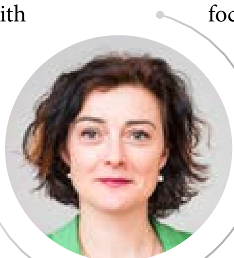
# Arctic Marine Geology and Geophysics Research School (AMGG)

The Research School, led by CAGE staff in cooperation with the Department of Geosciences at UiT – The Arctic University of Norway, aims to train PhD students and young scientists in the field of Arctic marine geology and geophysics.

The training focuses on the development of Arctic continental shelves and margins, including topics such as glacial processes and products, fluid emissions and gas hydrates, palaeoclimate and – oceanography, energy and environment and geo-hazards. The PhD trainee school offers scientific cruises to the Arctic; relevant seminars about climate and environmental change; field trips to terrestrial fluid emission sites; specialized workshops with national and international participants; and training courses for a new generation of scientists.

## Giuliana Panieri, *AMGG Leader*

The research school is led by Associate Professor Giuliana Panieri from CAGE, with coursework developed in close collaboration with the Department of Geosciences, UiT The Arctic University of Norway.



## Annual workshops and teaching cruises

A highlight of the AMGG calendar is the annual meeting, where students have the opportunity to develop collaborations and receive critical feedback by presenting their work to their colleagues and invited academic experts. Another important annual event is our AMGG cruse onboard UiT's RV Helmer Hanssen, led by scientists from CAGE and the Department of Geosciences This allows PhD and Master students to gain valuable experience in the acquisition and interpretation of state-of-the-art marine datasets.Target areas include the Fram Strait, the Barents Sea and areas around Svalbard.

In 2017 the AMGG PhD teaching cruise focused on gas hydrate deposits and methane seepages in several sites across the Barents Sea. During the cruise students were introduced to all aspects of data collection, processing and interpretation

AMGG also offers workshops, lectures and exercises on a wide range of scientific disciplines focusing on theoretical and practical applications of geomarine research from the sub-seafloor, the seabed, and the water column. Examples of the topics covered include: sedimentary processes and palaeo environments on glaciated continental margins; fluid flow; ocean acidification and anthropogenic impacts.

## Bubbles 2017 – A main event on the AMGG calendar

The "Bubbles 2017 – The Role of Methane in Marine and Terrestrial Environment" International Training School, took place at CAGE and Department of Geosciences 6–15 June 2017. The workshop was sponsored by AMGG, CAGE, and the national Research Schools ResClim and CHESS.

Several internationally recognized experts contributed to the workshop, offering insights into the latest methane and gas hydrate- related research. The main aim of Bubbles 2017 was to provide a thorough and interdisciplinary introduction to the role of methane in marine and terrestrial environments (e.g. permafrost), from generation, migration, consumption and impact on the seafloor, water column and finally into the atmosphere.

> *Bubbles 2017 promoted the development of an international community of early career scientists*

Bubbles 2017 promoted the development of an international community of early career scientists, developing their research skills in state-of-art techniques and methods for detecting and monitoring methane emissions.

The workshop encompassed lectures and practical exercises (e.g. seismic interpretation, modelling of the gas hydrate stability, microbial experiments, micropaleontology exercises), with poster sessions every afternoon.

Students from Norway, Sweden, Germany, USA, New Zealand, Italy, France, Spain, Russia, Taiwan, Costa Rica, and China attended Bubbles 2017.

## High score on evaluation

At the end of the school the students were asked to complete an evaluation form and here are some of their comments:

*I learned a lot, great opportunity to meet others interested in marine methane and learn about other students' research;*

*I liked the content, learned a lot I can incorporate into my current and future research. I am motivated to find a PhD program to continue in academia;*

*I am 100% satisfied, well organized and well-planned school with many interesting participants from all around the world and fantastic training team.*

*An iceberg spotted during the AMGG cruise.*

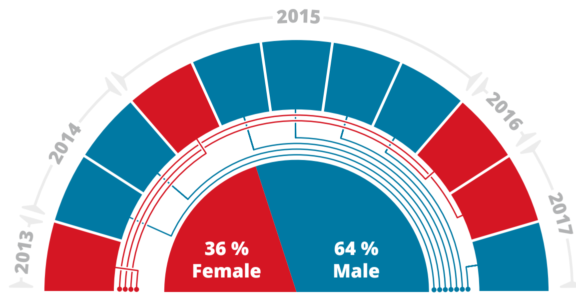
*PhD candidate Espen Valberg sampling sediments during the AMGG cruise.*

*Group photo, Bubbles international school.*

*Students relaxing in the sun durting Bubbles 2017.*

*The evaluation of the Bubbles 2017 shows that students were satisfied with the programme.*

*Photos: Giuliana Panieri; Torger Grytå.*




## List of PhD dissertations

### 2013

**Safronova, P.**
*Distribution, depositional environment and post-depositional deformation of Cenozoic gravity-induced deposits along the western Barents Sea continental margin.*
Supervisor: Andreassen, K.

### 2014

**Faust, J.C.**
*Environmental response to past and recent climate variability in the Trondheimsfjord region, central Norway - A multiproxy geochemical approach*
Supervisor: Knies, J.

**Vadakkepuliyambatta, S.**
*Sub-seabed fluid-flow systems and gas hydrates of the SW Barents Sea and North Sea margins*
Supervisor: Bünz, S.

### 2015

**Chauhan, T.**
*Late Quaternary paleoceanography of the northern continental margin of Svalbard*
Supervisor: Rasmussen, T.L., Noormets, R.

**Ezat, M.**
*North Atlantic–Norwegian Sea exchanges during the past 135,000 years: Evidence from foraminiferal Δ14C, d11B, d18O, d13C, Mg/Ca and Cd/Ca*
Supervisor: Rasmussen, T.L., Groeneveld, J.

**Gudlaugsson, E.**
*Modelling the subglacial hydrology of the former Barents Sea Ice Sheet*
Supervisor: Andreassen, K., Humbert, A.

**Jessen, S.P.**
*Ice rafting, Ocean circulation and Glacial activity on the western Svalbard margin 0–74,000 years BP*
Supervisor: Rasmussen, T.L.

**Portnov, A.D.**
*Role of subsea permafrost and gas hydrate in postglacial Arctic methane releases*
Supervisor: Mienert, J., Cherckashov, G.

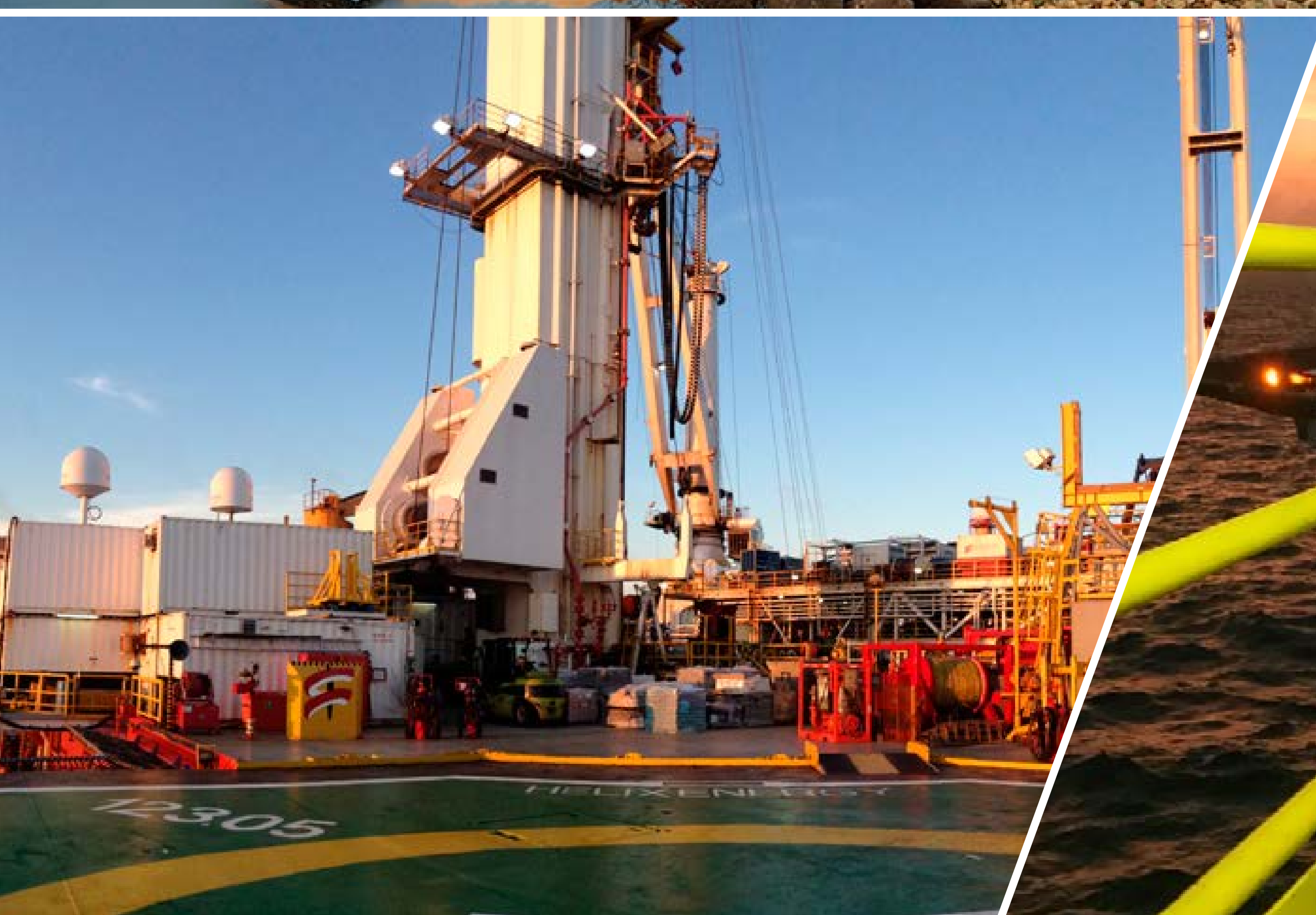
### 2016

**Sauer, S.**
*Past and present natural methane seepage on the northern Norwegian continental shelf*
Supervisor: Knies, J., Mienert, J.

### 2017

**Sztybor, K.**
*Late glacial and deglacial paleoceanographic and environmental changes at Vestnesa Ridge, Fram Strait: challenges in reading methane-influenced sedimentary records*
Supervisor: Rasmussen, T.L.

**Tasianas, A.**
*Fluid flow at the Snøhvit field, SW Barents Sea: processes, driving mechanisms and multi-phase modelling*
Supervisor: Bünz, S.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**Calvin Shackleton**
*PhD Candidate*


**Alexey Portnov**
*Postdoctoral Researcher*


**Mohamed Ezat**
*PhD Candidate*


**Chris Stokes**
*Visiting Professor*

# Training, international exchange and guest scholarships 2017

PhD students at CAGE receive standardised training and diplomas from UiT The Arctic University of Norway and our Research School, Arctic Marine Geology and Geophysics (AMGG). We also welcome PhD students from other institutions for training, through established exchange programmes and relevant scientific networks. Our PhD students and Postdocs also participate in training programmes with colleagues at internationally acclaimed science institutions. In addition we welcome guest scholars from all over the world, who are interested in establishing networks with CAGE scientists.

## Calvin Shackleton, *PhD*

From February 2017 until January 2018 I stayed at the Lamont Doherty Earth Institute (LDEO), University of Columbia, New York, USA. The 11-month stay was beneficial to my PhD work, and for networking and future collaboration with the researchers there. Their expertise in Greenlandic and Antarctic glaciology complemented my work very well, and regular discussions, meetings, and paper reviews with the researchers there allowed me to expand my knowledge of present-day glacial systems and place my work on palaeo-ice sheets in a wider, and more contemporary context. While there I got the opportunity to run an outreach stall on the movement of glacial ice at the LDEO open day, attended by 2300 people including prospective students, teachers, researchers, and media representatives. The overall experience of living and working in New York was fantastic, and I am grateful for the opportunity to collaborate with the scientists there and work at such a prestigious research centre. Now that I am back in Tromsø, collaboration between myself and several LDEO researchers will continue, as I plan the final papers for my PhD.

## Alexey Portnov, *Postdoctoral Researcher*

From March 2017 until March 2018 I worked in the Ohio State University in the School of Earth Sciences where I joined the gas hydrate drilling project GOM$^2$conducted in the Gulf of Mexico. This gave me a unique opportunity to work on the semi-submersible drilling rig with world-leading scientists from several US universities, including The Ohio State University, University of Texas at Austin, Lamont Doherty Earth Observatory. Additionally, I had full access to the 3D seismic and well logging data from the Gulf of Mexico drilling cite, which led to one journal publication and several conference abstracts.

> *One of the important achievements during my stay was significant expansion of professional network*

One of the important achievements during my stay was significant expansion of professional network, which will inevitably lead to future collaborations. Overall, I got an excellent opportunity to compare the fundamental approaches to gas hydrate research in the Arctic and tropical regions by the European and American geological schools. I believe, this will be useful for my future career related to research in both the Arctic regions and elsewhere.

## Mohamed Ezat, *Postdoctoral Researcher*

In 2017, I have received 3.3 million NOK from the Research Council of Norway and the COFUND Marie Sklodowska-Curie actions under the EU FP7. This grant provides me with an opportunity to work at one of the most advanced labs at University of Cambridge for the next two years followed by a third year at CAGE, UiT. I aim to use this grant to pursue a better understanding of the sensitivity and response of the Arctic Ocean to climate change.

I will look at how different components of the Arctic Ocean climate system act and interact at times that were both warmer and colder than today. The lab facilities at Cambridge allow for a high-level precision and detail in analysis of foraminifera shells. We have some materials to work on from the central Arctic Ocean, and I have also applied to join an IODP expedition to hopefully collect more. My PhD and post-doctoral work at CAGE have awarded me many opportunities to do interesting science, and the research atmosphere is very inspiring!

## Chris Stokes, *Professor University of Durham*

I was a Visiting Researcher at the Centre for Arctic Gas Hydrate, Environment and Climate (CAGE) for 6 weeks in Spring 2017. This visit enabled me to strengthen long-standing collaborations with colleagues at CAGE, primarily Prof Andreassen and Dr Winsborrow and our Ph.D. student (Emilia Piasecka), but it also enabled me to meet and network with other staff and postgraduates in CAGE. This led to some fruitful meetings to discuss recent and future projects, particularly in the area of ice sheet dynamics. I was also able to finish two research papers during my visit, including one with a co-author from UiT The Arctic University of Norway.

*Calvin Shackleton at Lamont Open Day outreach event.*

*The drilling rig Q-4000 in the Gulf of Mexico.*

*Alexey Portnov on a research cruise in the Gulf of Mexico.*

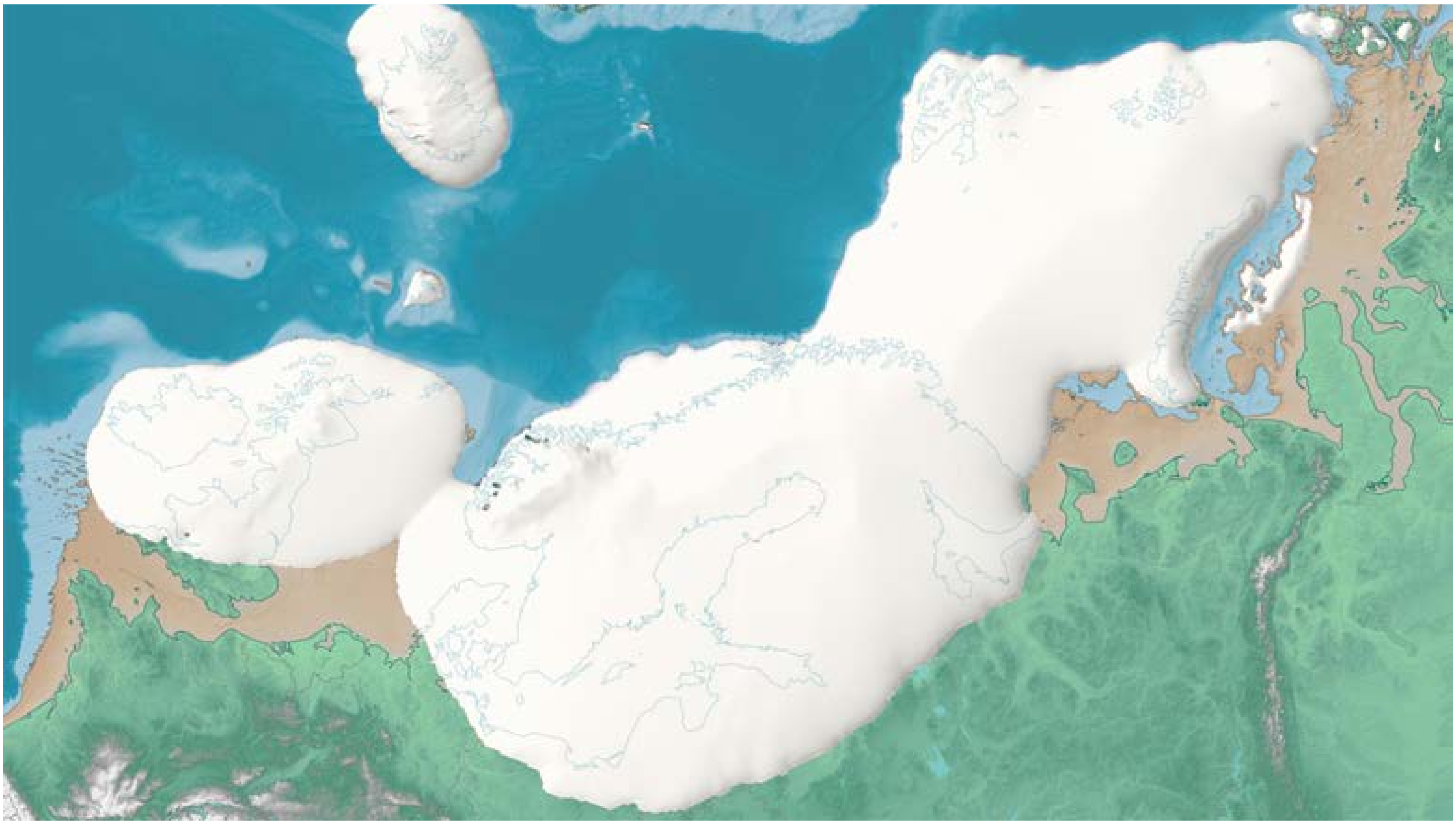
*Photos: Mariana Esteves; Alexey Portnov; Private.*

# First hand exploration of gas hydrate provinces

We have completed 31 expeditions on research vessels in the Arctic regions since 2013. In 2017 we ventured on research cruises to Barents Sea, Yermak Plateau, Vestnesa Ridge and Lofoten. Our scientists have also participated on expeditions on US drilling vessel Q-4000 into the Gulf of Mexico, and Korean ice breaker Araon into Canadian Arctic.

Our field research encompassed technologies such as remotely operated vehicles, seabed photography, and seabed drilling campaigns. In 2017 the new icebreaker Research Vessel Kronprins Haakon was also delivered to the Norwegian wharf in Bergen. It will be fully operational and available to scientists in Tromsø, including CAGE, in 2018.

| Simone Sauer and Haoyi Yao collecting water samples. Photo: Giuliana Panieri | Research vessel G.O. Sars deploying ROV Ægir off Lofoten. Photo: Maja Sojtaric |
| Sunset off Lofoten. Photo: Maja Sojtaric | Ann Cook and Alexey Portnov on board Q-4000. Photo: Private | Deploying the P-Cable. Photo: Andreia Plaza Faverola |
| PhD candidate Malin Waage with burning hydrate. Photo: Pavel Serov | Wei-Li Hong extracting porewater from sediment cores. Photo: Maja Sojtaric |
| Gas hydrate in sediment core. Photo: Karin Andreassen | PhD students collecting core samples on board RV Helmer Hanssen. Photo: Giuliana Panieri |
| Detail from ROV Ægir. Photo: Maja Sojtaric |



# 22,500
## YEARS AGO

During the Last Glacial Maximum, it would have been possible to ski across the ice continuously for 4500 km: from the far South Western isles in Britain to Siberia.

Maja Sojtaric, *Communications Advisor*

She writes our press releases, manages media contact and maintains our social media distribution, as well as arranging workshops in communication.

# International attention and novel outreach efforts

2017 was indeed an eventful year for CAGE, with scientific results garnering immense attention, and a new outreach project aimed at school children creating synergies beyond science.

Our focus on narrating our excellent results to the general public, industry, stake holders, and media plays an important role in our overall strategy for the centre.

This strategy has so far been fruitful – in 2017 alone we have had over 450 media mentions, the majority of them shining a light on our published scientific results. We also ventured into the realm of data visualisation for children in 2017 – developing an interactive installation and webpage, together with Nordnorsk vitensenter, the science centre in Tromsø.

## Science paper bonanza

CAGE aims for high exposure of our results by distributing them through press releases to the general public. The effectiveness of this approach was demonstrated by extremely wide attention attracted by our Science paper on massive methane craters in the Barents Sea that was published in June 2017.

We provided a content package to the press office at Science – a press release with quotes and several stunning images. All content was developed in-house by our communications advisor and the scientists involved in the paper.

Close cooperation with the press office at Science ensured that the content was distributed widely. In turn, this resulted in massive attention, which first author Karin Andreassen was willing to take head on.

Throughout the year she has been interviewed on numerous occasions, and made herself available to journalists and inquisitive peers alike. The effort has resulted in over 100 unique news articles published worldwide on the abrupt methane release in the Arctic. News outlets as diverse as The Washington Post, The Atlantic and Mashable covered this story.

> *CAGE aims for high exposure of our results by distributing them through press releases to the general public.*

As far as wider communication of fundamental CAGE research goes, the Science paper proved that given the results are of global interest, scientific publications are sound, and scientists are willing to make an effort to engage with the media, a lot can be gained.

## ICEMAP – an innovative take on data visualization for kids

Our second example is something completely different: development of an interactive installation, together with the Nordnorsk vitensenter, a science activities centre in Tromsø.

An enormous ice sheet covered most of northern Eurasia around 24,000 years ago. CAGE had received funding from the Research Council of Norway in the autumn of 2016 to develop an interactive map-based story, ICEMAP, based on recently published model reconstructions of this last ice age. Two CAGE scientists, Henry Patton and Alun Hubbard, were instrumental in the development of the map visualizations.

Through 2017, a multi-layered interactive webpage – icemap.no – as well as a physical installation at the Science Centre in Tromsø, were developed together with illustrators, communicators, exhibition and graphic designers, engineers and web developers.

From February 2018 children and teachers could interact with the ice age simulation to explore how the ice sheet grew and melted, and experience how the changing environment around Europe affected our narrator Lenny Lemming, a cartoon avatar that travels through thousands of years of climate change.

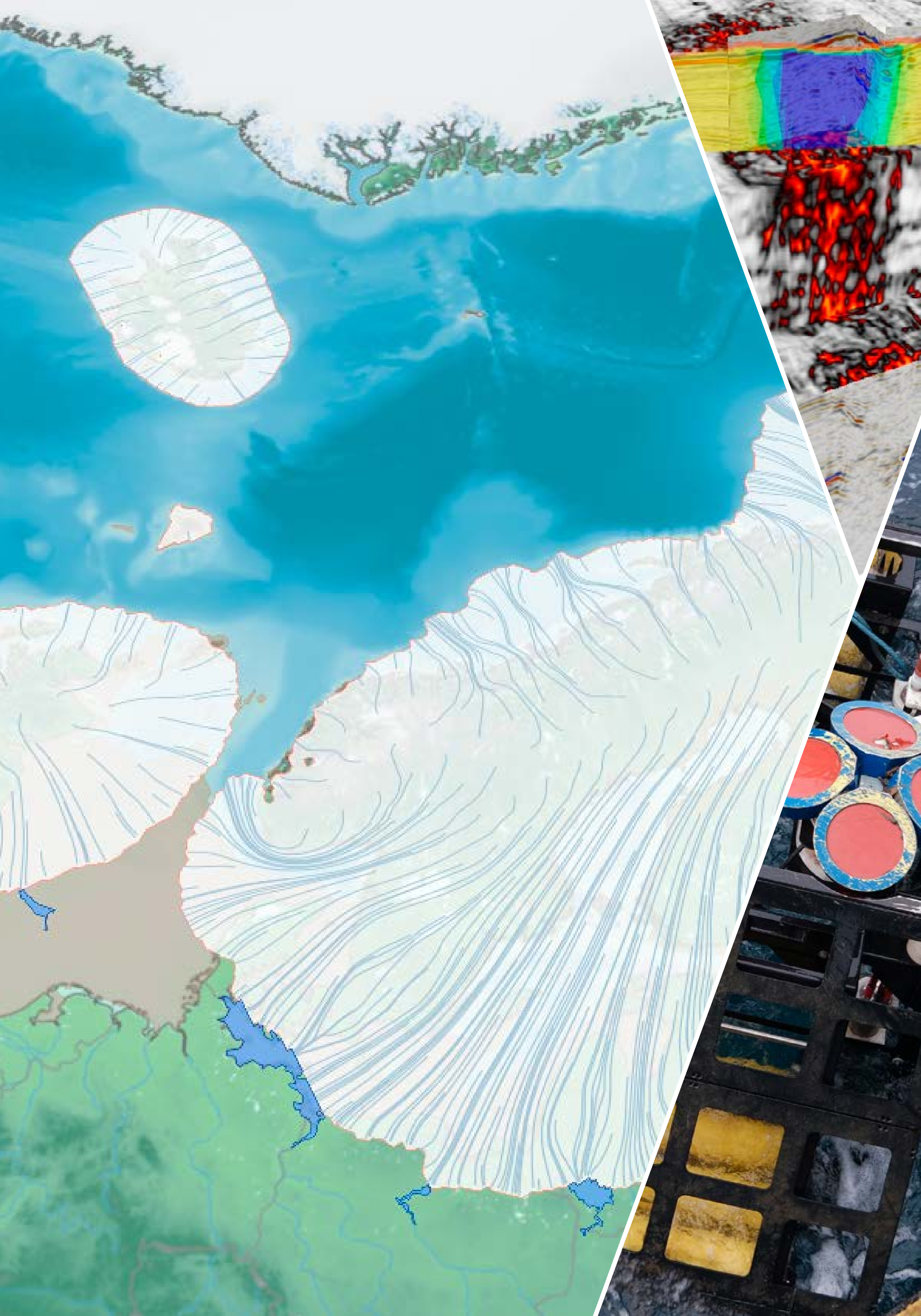
ICEMAP is an innovative take on data visualisation, combining a cutting-edge numerical ice-sheet reconstruction with narrative illustrations to convey knowledge about how the complex natural world around us functions, changes and leaves a lasting geological legacy.

ICEMAP project was managed by CAGE senior communications advisor Maja Sojtaric. Visit: https://icemap.no

*Map of the ice cover over Europe during the last ice age.*

*Lenny the Lemming traveling through the ice age.*

*Illustration: Henry Patton; Alice Kvalvik.*



# The CAGE tool box – Technology, innovation and research

The success of CAGE builds upon the integration of world-class empirical and numerical technologies to study Arctic sub-seafloor and ocean-bound methane as potential driver of future climate change. With access to the new icebreaker RV Kronprins Haakon, this tool box will be applied in permanently ice-covered regions, allowing for the first-time detailed studies of potential amplifiers for global change, including melting of submarine gas hydrate systems in the Arctic and accumulation of free methane gas below the still ice-covered ocean.

Analogous to these dramatic changes today, we will use our tool box to find the controlling mechanisms for build-up and release of submarine gas hydrate systems in the Arctic and provide answers to what extent methane escape from sub-seafloor reservoirs has influenced Arctic and global climate perturbations.

## Ocean observatories

The ocean observatories (K-Landers) developed in a collaboration between Kongsberg Maritime and CAGE were deployed and recovered four times offshore Svalbard and in the Barents Sea, providing unprecedented multi-sensor data on Arctic methane seepage and the physical and chemical properties of the ocean. These give CAGE insights into the frequency of methane release and how this is influenced by ocean conditions, as well as on ocean acidification processes and trends.

## CAGE video-camera system

In 2015 CAGE started a collaboration with WHOI (Woods Hole Oceanographic Institution) to develop a towed video-camera system. This digital imaging equipment provides real-time HD video and images of the seafloor, real-time digital depth and altitude, and allows visually guided water column (Niskin bottles) and sediment (multicores) sampling. In addition to dedicated digital imaging campaigns, the CAGE video-camera system plays a vital role in planning ROV operations. The system has been deployed at several methane sites in the Barents Sea in 2017.

## 4D seismic using P-cable

CAGE uses UiT's national infrastructure P-cable seismic system, which CAGE members have been involved in developing. Studies of gas hydrates, shallow gas and geological structures in sediments near the seafloor are ideal targets of our P-cable seismic system. By collecting 3-Dimensional (3D) P-cable data at the same study area over multiple years we are able to monitor spatial and temporal variations (4D) in the movement of fluids in the sediments. The unprecedented resolution of the P-cable seismic provides CAGE with a unique opportunity to investigate the processes and drivers that regulate past and present gas hydrate and fluid flow systems.

## National facility for stable isotope analyses

CAGE has established a stable isotope laboratory, equipped with a MAT 253 Isotope Ratio Mass Spectrometer, at the Department of Geosciences, UiT. The laboratory is an integral part of our palaeoclimatic, oceanographic, geobiological and carbon cycling research, and is a part of the national infrastructure FARLAB (Norway's national facility for advanced isotopic research). The lab will eventually become one of the few laboratories in the world where scientists can analyze clumped isotopes, a ground-breaking method that allows extremely precise palaeoclimate reconstructions.

## Fully automated palaeomagnetic laboratory

CAGE partner, the Norwegian Geological Survey (NGU), has installed a fully automated 2 G Cryogenic Magnetometer at their facilities in Trondheim. This equipment gives us the ability to significantly improve the stratigraphic framework of carbonate-poor Arctic sediments by analyzing changes in the polarity, intensity and direction of the geomagnetic field of the Earth over the past millions of years, enabling us to develop a precise chronology for the climate of the past. It furthermore, provides a powerful means to trace variations in methane seepage in the sub-seafloor sediments over timescale of millions of years.

## Numerical ice sheet modelling

Numerical modelling is a valuable tool that can be used to explore the role ice sheets have played in shaping and driving changes in the Arctic environment. At CAGE we have developed a high-resolution, 3D reconstruction of the last glacial cycle to have affected the Eurasian continent, constrained and tested against a variety of up-to-date empirical datasets. Data-rich outputs derived from these modelling experiments inform us how the ice sheet developed and impacted with its surroundings through time, including the evolving pattern of crustal warping, hydrological routing and storage, broad-scale climate distributions, and subglacial temperature-pressure conditions.

*Ice sheet numerical model output.*

*Gas chimney.*

*Detail from ocean observatory.*

*Photos & illustrations: Henry Patton; Stefan Bünz; Benedicte Ferré.*

# Publications list 2017


**Andreassen, K., Hubbard, A.L., Winsborrow, M., Patton, H., Vadakkepuliyambatta, S., Plaza-Faverola, A., Gudlaugsson, E., Serov, P., Deryabin, A., Mattingsdal, R., Mienert, J., Bünz, S.** *Massive blow-out craters formed by hydrate-controlled methane expulsion from the Arctic seafloor*. Science, 2017 (0036-8075) 356 (6341) p. 948-953

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**Bjarnadóttir, L.R., Winsborrow, M., Andreassen, K.** *Large subglacial meltwater features in the central Barents Sea*. Geology, 2017 (0091-7613) 45 (2) p. 159-162

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**Chand, S., Cremiere, A., Lepland, A., Thorsnes, T., Brunstad, H., Stoddart, D.** *Long-term fluid expulsion revealed by carbonate crusts and pockmarks connected to subsurface gas anomalies and palaeo-channels in the central North Sea*. Geo-Marine Letters, 2017 (0276-0460) 37 (3) p. 215-227

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**Cremiere, A., Strauss, H., Sebilo, M., Hong, W.-L., Gros, O., Schmidt, S., Tocny, J., Henry, F., Gontharet, S., Laverman, A.M.** *Sulfur diagenesis under rapid accumulation of organic-rich sediments in a marine mangrove from Guadeloupe (French West Indies)*. Chemical Geology, 2017 (0009-2541) 454 p. 67-69

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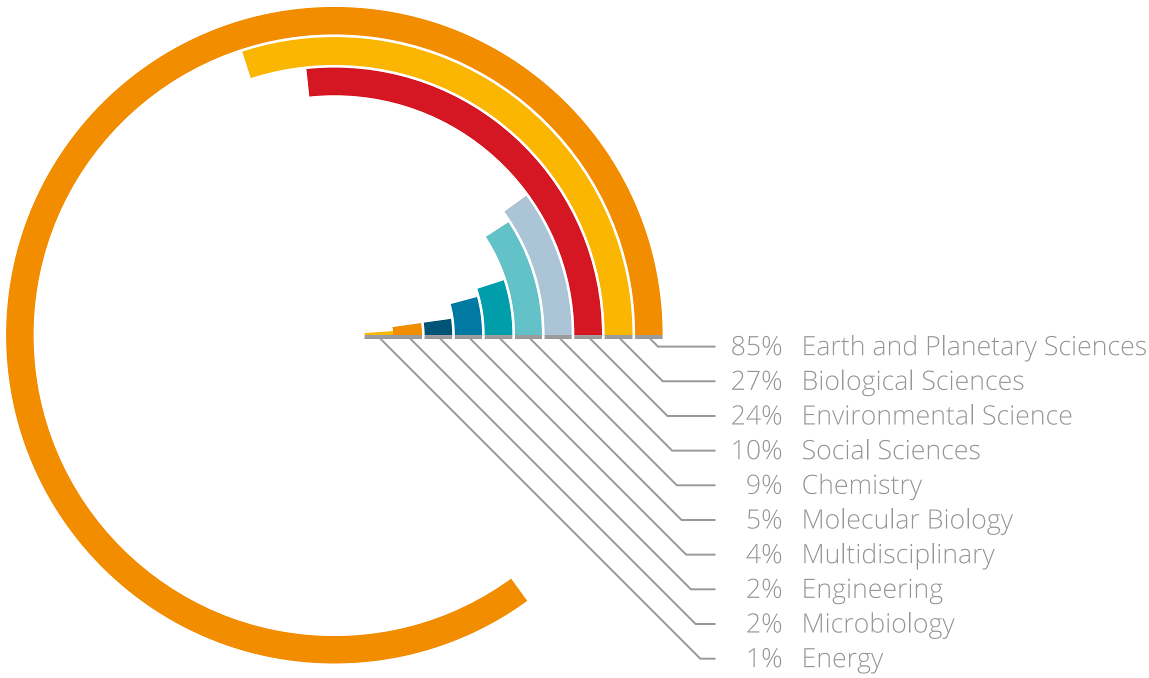
## Subject area, publications

Source: Scopus




## Publications

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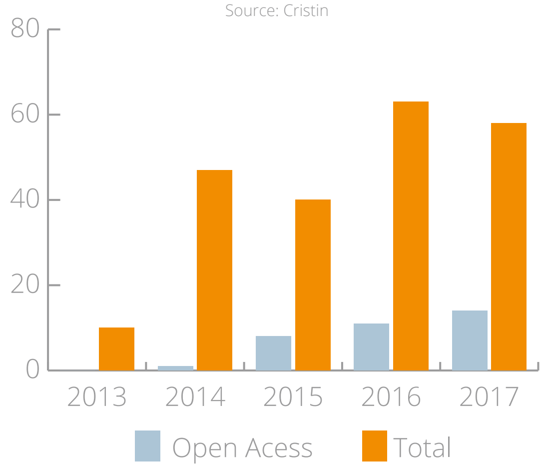


## Presentations

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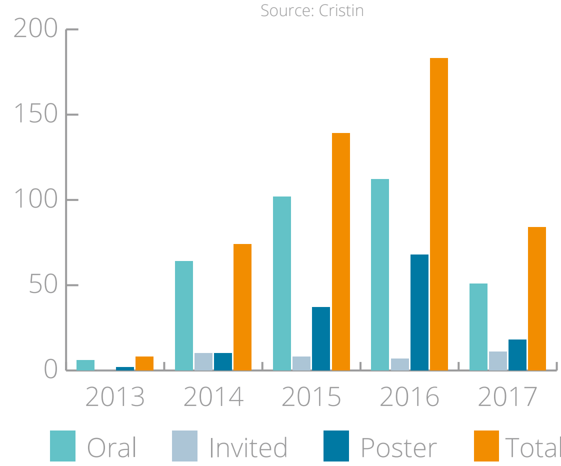


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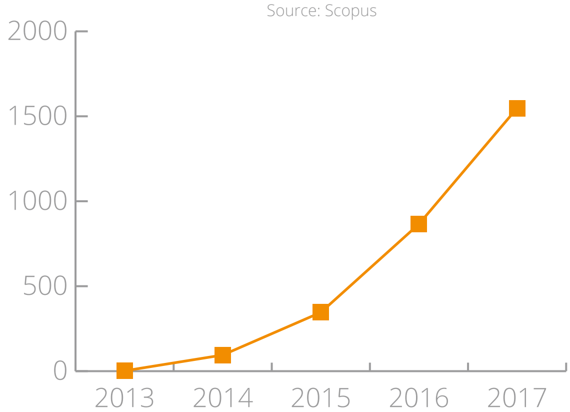


## PhD and Master thesis

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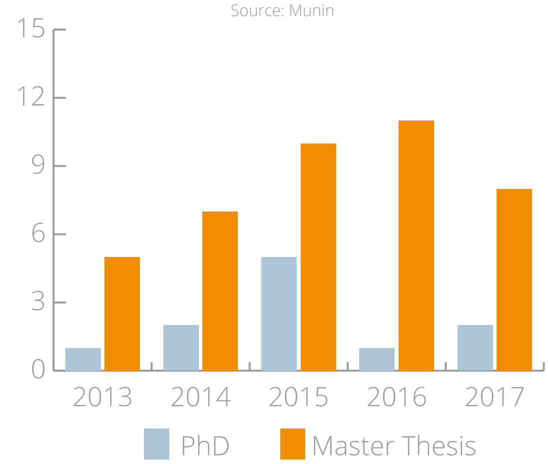

# International collaboration 2013–2017

Our research is connected with international scientific communities that are outlined as important collaborators by Norwegian Research Council and Norwegian Ministry of Foreign Affairs. We participate in several EU projects and actions such as: STEM CCS on carbon capture; COST MIGRATE on hydrate quantification; and FIXO3 on environmental observations and technologies. We also lead the PACT project funded by NRCs INDINOR program. It examines how Arctic Ocean warming affected monsoons in the past, in collaboration with Indian institutions NCAOR and Birbal Sahni Institute of Paleobotany. In addition to that we collaborate on papers with relevant colleagues from all over the world.

## International collaborations on publications

(2013 to present)

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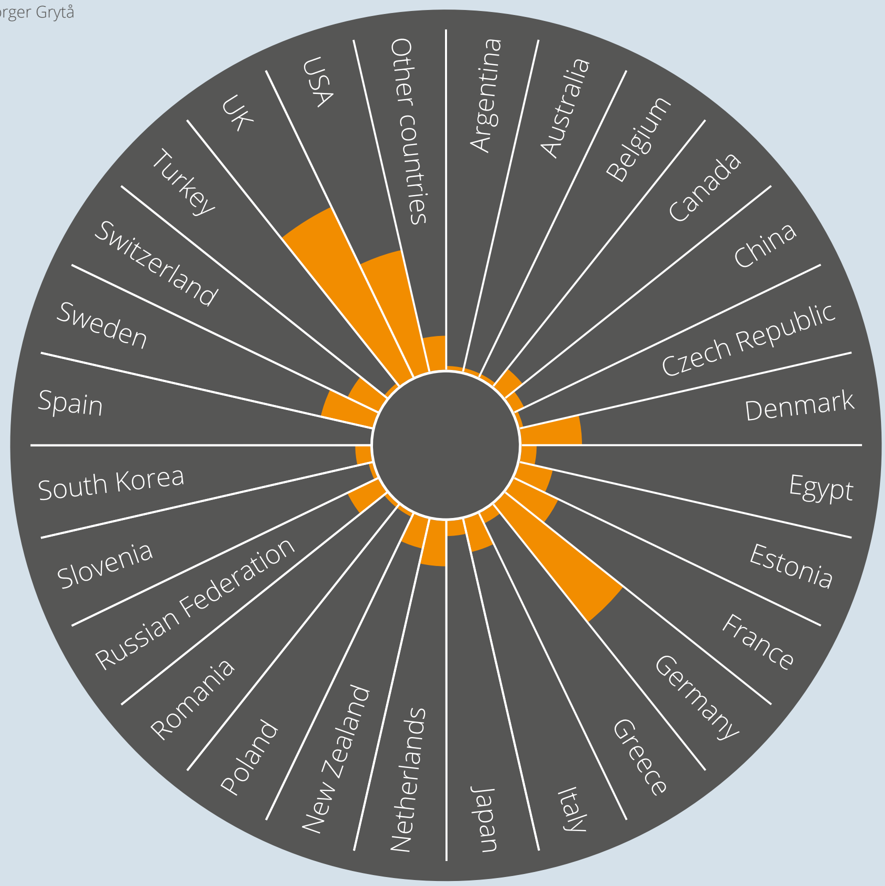
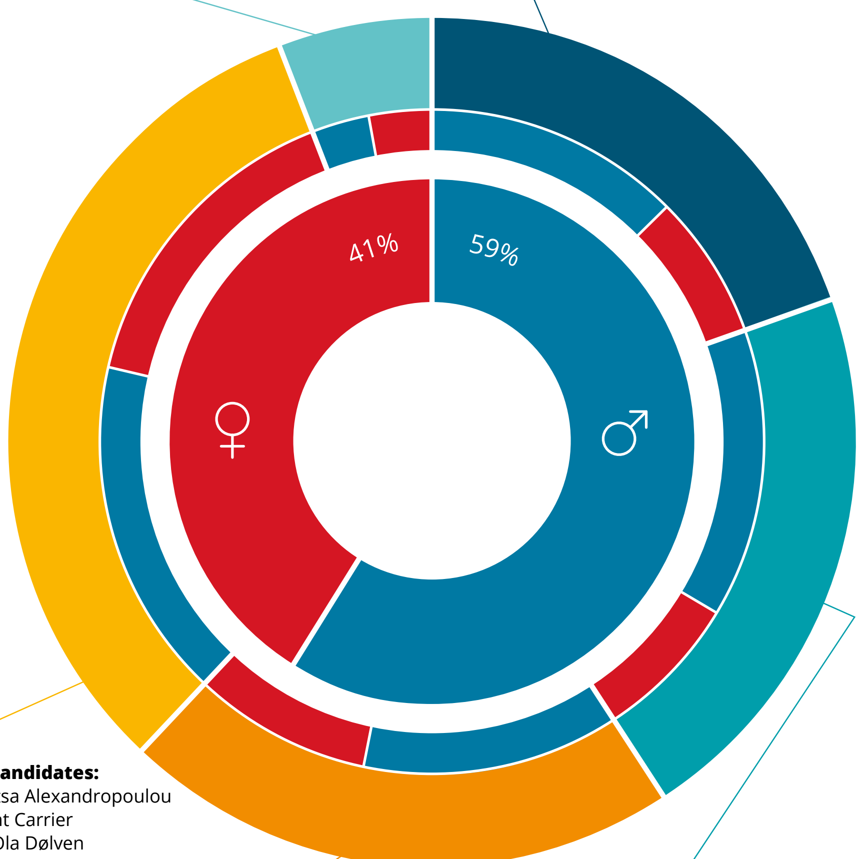


# Full list of personnel at the centre

We consistently work towards gender equality in our staff. 5 out of 7 of our work package leaders are women. Our over all staff numbers also show that we perform way above the average 21 percent women in STEM fields in OECD countries, and significantly above the average of 16 percent in Norway. More than 60 percent of our staff are PhD students and early-career scientists.

**Senior scientific staff:**
Jürgen Mienert, Professor
Karin Andreassen, Professor
Tine L. Rasmussen, Professor
Alun Hubbard, Professor
Mette Svenning, Professor
Stefan Bünz, Professor
Giuliana Panieri, Associate Professor
Helge Niemann, Associate Professor.
Jochen Knies, researcher/vice director
Monica Winsborrow, researcher/ vice director
Leonid Polyak, Adjunct Professor (USA)
Jens Greinert, Professor (FRG)
Joel Johnson, Associate Professor (USA)
Chris Stokes, Visiting Professor (UK)

**Adminstrative and technical staff:**
Matteus Lindgren, Engineer
Fabio Sarti, Data Manager
Maja Sojtaric, Senior Advisor
Tonje Merete Moe Winther, Executive Officer




**PhD Candidates:**
Nikolitsa Alexandropoulou
Vincent Carrier
Knut Ola Dølven
Naima El Bani Altuna
Mariana da Silveira Ramos Esteves
Pär Gunnar Jansson
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Katarzyna Melaniuk
Manuel Moser
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Kärt Paiste
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**Tobias Himmler**
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**Aivo Lepland**
*Researcher*


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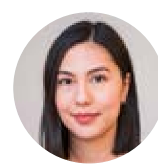
**Siri Ofstad**
*PhD Candidate*


**Giacomo Osti**
*PhD Candidate*


**Simone Sauer**
*Postdoctoral researcher*


**Andrea Schneider**
*PhD Candidate*


**Andreas Stohl**
*Researcher, NILU*


**Chris Stokes**
*Visiting Professor*


**Monica Winsborrow**
*Researcher – Assistant director – Team leader WP2*


**Malin Waage**
*PhD Candidate*

**Karin Andreassen**
*Professor*
*Director CAGE*

**Soma Baranwal**
*Postdoctoral Researcher*

**Stefan Bünz**
*Professor*
*Team Leader WP1*

**Vincent Carrier**
*PhD Candidate*

**Michael Carroll**
*Researcher*

**Shyam Chand**
*Researcher*

**Chiara Consolaro**
*Postdoctoral Researcher*

**Mariana da Silveira Ramos Esteves**
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**Mohamed Ezat**
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**Karl Fabian**
*Researcher*

**Andreia Plaza Faverola**
*Researcher*

**Bénédicte Ferré**
*Researcher*
*Team Leader WP4*

**Peter Franek**
*Postdoctoral Researcher*

**Jens Greinert**
*Professor*

**Ulrike Hoff**
*Postdoctoral Researcher*

**Wei-Li Hong**
*Postdoctoral Researcher*

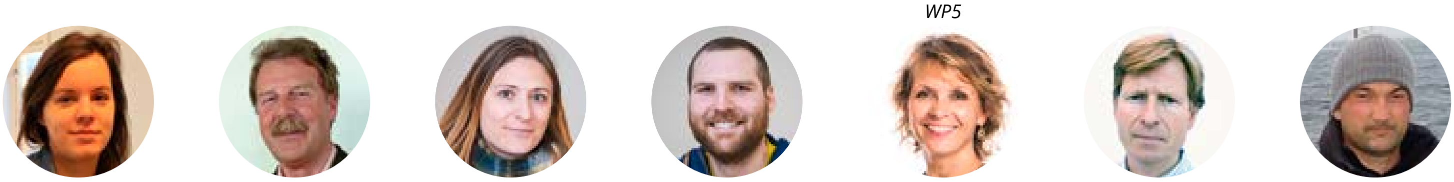
**Alun Hubbard**
*Professor*

**Pär Gunnar Jansson**
*PhD Candidate*

**Jochen Knies**
*Researcher – Assistant director – Team Leader WP5*

**Joel Johnson**
*Associate Professor*

**Deniz Koseoglu**
*PhD Candidate*



**Katarzyna Melaniuk**
*PhD Candidate*

**Jürgen Mienert**
*Professor*

**Tonje Merete Moe Winter**
*Executive officer*

**Manuel Moser**
*PhD candidate*

**Cathrine Lund Myhre**
*Researcher*
*Team Leader WP7*

**Gunnar Myhre**
*Researcher, CICERO*

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*Assoc. Professor (20%)*

**Giuliana Panieri**
*Associate Professor*

**Henry Patton**
*Postdoctoral Researcher*

**Emilia Daria Piasecka**
*PhD Candidate*

**Leonid Polyak**
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**Alexey Portnov**
*Postdoctoral Researcher*

**Tine Lander Rasmussen**
*Professor*
*Team Leader WP6*

**Fabio Sarti**
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**Calvin Shackleton**
*PhD Candidate*

**Arunima Sen**
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**Sunny Singhroha**
*PhD Candidate*

**Muhammed Fatih Sert**
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**Anna Silyakova**
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**Maja Sojtaric**
*Senior advisor, communications*

**Mette Marie Svenning**
*Professor*
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**Alexandros Tasianas**
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**Terje Thorsnes**
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**Kärt Peiste**
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**Espen Valberg**
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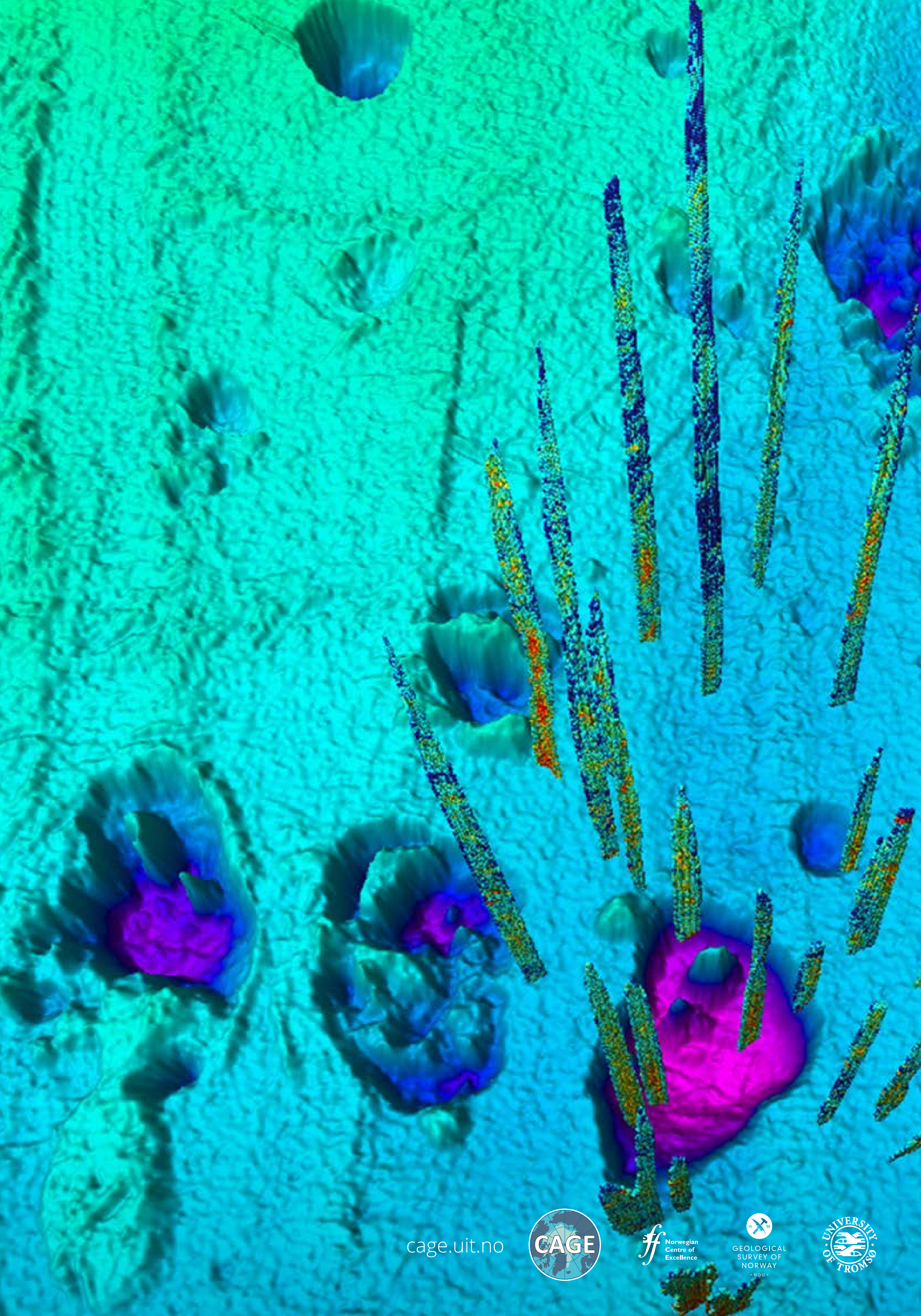
**Kate Waghorn**
*PhD Candidate*

**Haoyi Yao**
*PhD Candidate*

**Katarzyna Zamelczyk**
*Researcher*

**Emmelie Åström**
*PhD Candidate*



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