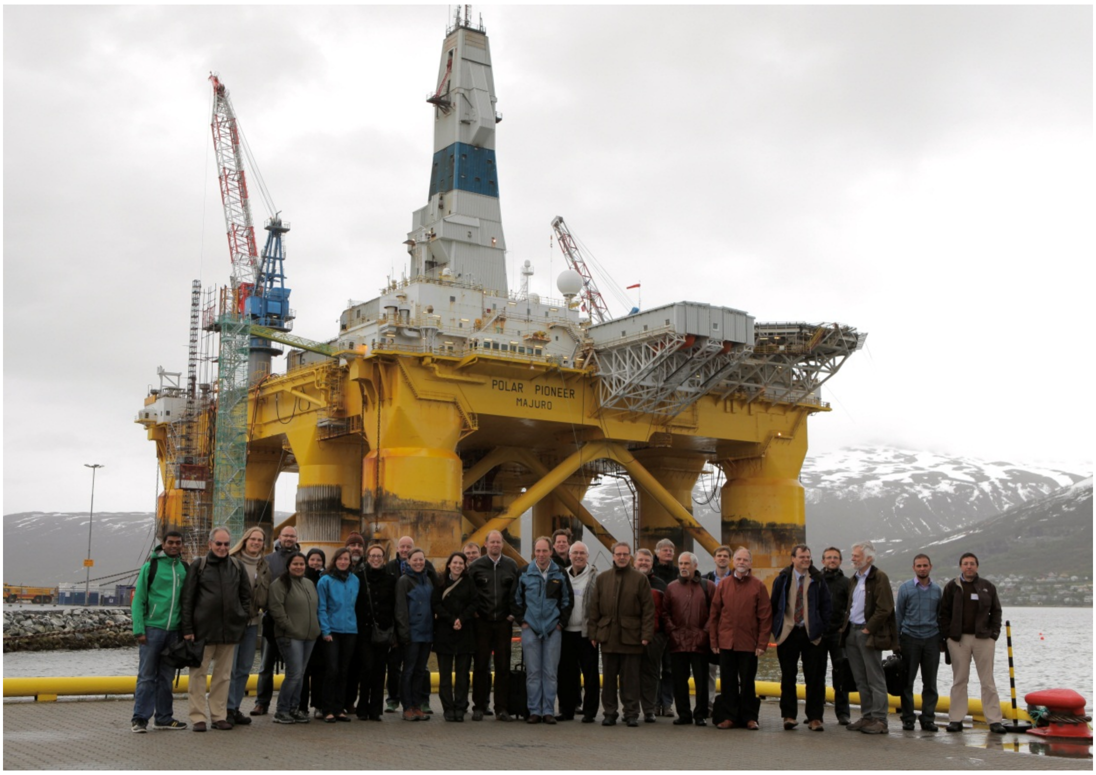
# Deep sea and sub seafloor frontier

# Workshop report WP5

# "Geofluids and gas hydrates:

Fluid flow in Arctic continental margins and ocean ridges"




30-31 May 2011

University of Tromsø, Tromsø, Norway

Juergen Mienert

## Abstract

About 40 scientists from Europe and USA met in Tromsø on May 30-31, 2011 to raise scientific questions about fluid flow and methane hydrate in Arctic regions and to discuss potential drilling targets and technologies to answer these questions. One of the primary goals of this workshop was to develop a report towards a programme for conducting scientific drilling into fluid escape pathways in Arctic continental margins and sedimented ocean ridges, and to develop synergies with national and international ocean observatory programs. Drilling into fluid release areas has never been done before, but it is of regional and global relevance providing opportunities for fundamental, forefront interdisciplinary research involving geophysics and geology, geochemistry, biogeochemistry, microbiology and biology. All global climate change scenarios forecast a large and irreversible change in Arctic Ocean regions. Coupled ocean – atmosphere modeling predicts already significant warming of shallow Arctic seas by several degrees Celsius for surface-waters by the year 2050. Recent marine geophysical research has identified various methane hydrate provinces in Arctic regions, and determined some bounds such as ocean temperature for their thermodynamic stability. New discoveries at the seabed and beneath show vigorous methane venting from gas chimneys. Understanding past and present fluid leakage, associated geological and biological processes and the effects of climate change on the Arctic seabed region in general, and on the stability of gas hydrate and release of geofluids in particular, is therefore both a scientific challenge and of high societal relevance. Drilling into selected fluid-escape chimneys will increase our understanding in climate, environmental, energy and ecosystem research. However, such a drilling campaign has yet to be developed.

**Convenors:** Juergen Mienert and Angelo Camerlenghi

**Organisation:** Kai-Rune Mortensen and Benedicte Ferre

# I. Scientific questions

Fluid flow studies in Arctic continental margins and ocean ridges concentrate in regions of 70 degrees northward. One of the main questions is: How much methane hydrate is there in the shallow subseabed and how much methane is released into the water from methane hydrates? It was noted that that our present technologies have clear limitations. Electromagnetic (EM) surveys are not very precise in locating gas hydrate and fluid, and inversion models are with industry and input data are problematic. Only few inversion codes are with academia (NOCS, Rocksource in Bergen). Thus, a combination of ocean seismometer (OBs) that allow to use p- and s-wave velocity anomalies to model the amount of gas hydrates and free gas in areas mapped by EM and 3D seismic and drilling is needed for a better quantification. A need exists to drill several areas in order to characterize the whole margin from high to low flux regions. This will allow to calibrate the geophysical signals better from which we infer the methane hydrate and free gas concentrations remotely.

A calibration of geological models is needed but how many drilling locations are actually needed remains open? How much water and how much gas are moving in the margin - ocean ridge setting? Hydrothermal circulation cells have most likely different sizes and the influence on western and eastern Svalbard ridge segments may be very different depending on subsidence and sediment load on ridge segments. The GHSZ shoaling occurs at two ends: at the shelf (pressure decrease due to water depths) and ocean ridge (geothermal gradient increase due to heat flow). What the hydrate effects on the geothermal gradients are is to be determined. What is the effect on annual and long term ocean temperature changes on hydrates and geothermal gradients? We need to start building and integrating geophysical, geochemical, and biological and hydro-acoustic base line data from climate sensitive methane hydrate regions.

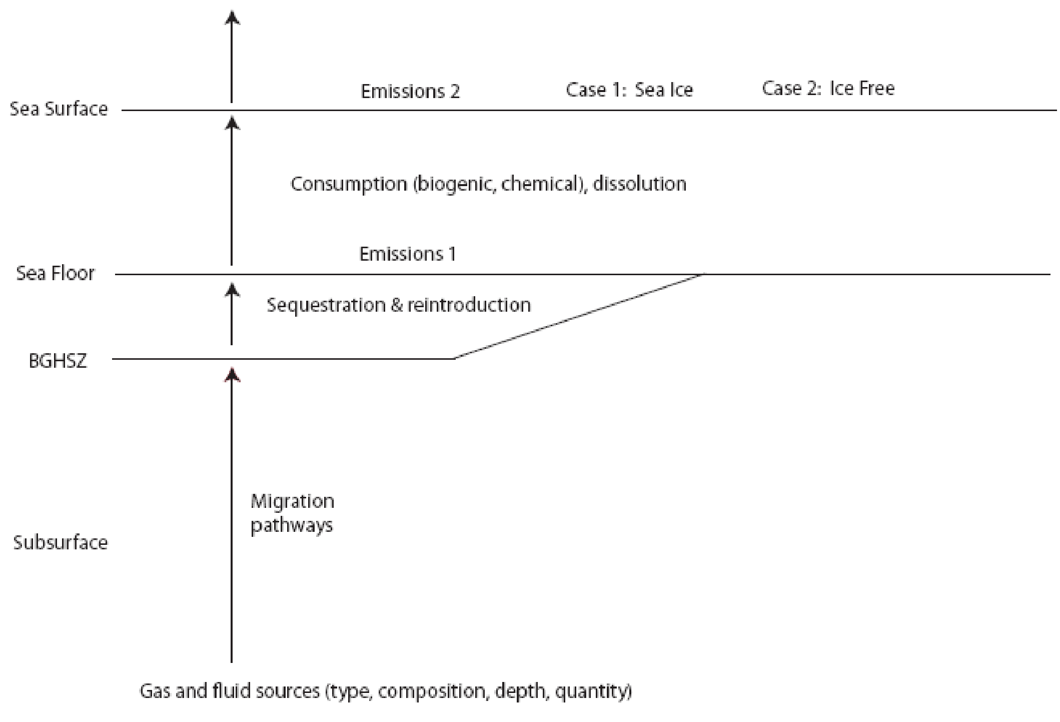
What is the offshore permafrost model for the Arctic shallow seas and Svalbard? The shelf – slope areas is the most affecting and mots rapidly changing system due to ocean temperature changes. What are the lead and lag times for dissociation and methane release on the shelf? How much methane from the seabed goes to the water column and how much leaves the ocean to atmosphere? We need to trace methane recorded in the atmosphere back to the various source areas and leakage systems. What is the geological portfolio: source areas of pipes and gas chimneys? How does the plumbing system of permafrost and gas-hydrated non-permafrost areas work. What is the actual area of the gas hydrate extent and occurrence in the GHSZ?

On the deep water areas of ocean ridges we need to learn more about the serpentinisation and methane producing processes? Her we may use best the tracer Helium3 to identify the source areas. Can we identify the different fluid release system classes? What are the timing of processes of the migration of fluids/gas through the deeper formations and the shallow GHSZ? What are the diagenetic and phase changes related to kinetics of gas and fluids?

**Seabed and water column:** What are today's boundary conditions at the seafloor and how do they change in the next decade? Well designed and integrated water column physical and chemical studies, seabed surveys and subseabed source studies are needed. Where the methane in the ocean bottom water does comes from and how does it change through the water column? We need to find the methane in the water column and trace it back to the sources? What are the isotopic compositions of the authigenic carbonate and microfauna at seep sites that will allow to use paleorecords? Paleo-seep monitors of Cenozoic hydrocarbon releases in formerly ice sheet dominated regions such as the Barents Sea are key areas in which we need to choose a range of simple to more complex geological setting to understand the fluid flow hydrate system changes in glacial and interglacial times. We wish to determine their response time and develop theories of the boundary conditions and how do they change through time. Changes of gas compositions during subseabed migration and upflow in the ocean are also critical parameters for building up a matrix of water depth (shelf to ridges) and sub-seabed source depth in relation to gas flow.

**We need to use the whole continuum of geophysics, real-time observations and modeling to understand the margin fluid flow and methane hydrate system (Figure 1)**, and to answer: What is the hydrology of the ocean ridge - margin system in which methane hydrate builds up or dissociates at unknown rates and times? What are the areas where we can use seabed drilling tools and go from there to drilling from DV *Joides Resolution* in seasonally ice-free areas?

Figure 1: Schematic diagram of fluid emissions



An important aspect of the workshop was the discussion of pan-Arctic research activities involving USA, Russia, Canada and Norway where activities in methane hydrate studies have some priorities for unconventional energy and climate-related methane hydrate research. At the same time collaboration with colleagues from countries interested in Arctic geoscience and sharing infrastructure and ship time is certainly of high interest as well. Figure 1 was prepared by the technological working group showing that the flux of methane through the sub seasurface and from dissociating methane hydrates, the methane emission at the seabed to the water column and the emission from the water column to the atmosphere remains of key importance for assessing the contribution of methane fluxes from the Arctic to the global methane emissions in the next decade. Monitoring in both space and time the ongoing processes in response to various anthropogenic and natural forcing factors will provide urgently needed knowledge about the Arctic methane systems, where marine geologist, observational scientists and modelers need to collaborate.

**Working group I:** Juergen Mienert (Marine Geologist, UiT, Norway); Graham Westbrook (Marine Geophysicists, University of Birmingham, UK); Tim Collett (Marine Geologists, United States Geological Survey, Hydrate Energy, USA); Matthew Hornbach (Marine Geophysicists, Rice University, Texas, USA), Mads Huuse (Marine Geologists, University of..; UK) Achim Kopf (Marine Geologists, University of Bremen, MARUM, Germany); Jouvier Escartin (Marine Geochemist/Geologist, CNRS, IPBGP, Parics, France), Rolf Birger Pedersen (Marine Geologists, University of Bergen, Norway), Dirk de Beer (Marine Geochemist, Alfred-Wegener Institute for Polar Research, Germany), George Papatheodorou (Marine Geologists, University of Patras, Greece) et al.

## II. Technology

It was felt that developing efficient and relatively inexpensive seafloor drilling and integrated specific drilling platforms can dramatically accelerate research. Work on a pan Arctic drilling campaign can start immediately with existing tools in the top of the slope and the shallow shelf seas, which is the critical area. Identify natural laboratories that are considered to characterize a larger area, which can be studied in detail using short-range research drilling tools. Scientist should determine what % of the information they need that can be obtained by shallow drilling and which information requests deep drilling. The use of deeper drilling capability can integrate academic and industry needs. Feasible technologies and their importance are summarized as follows:

1) Remote Sensing /Geophysics
   - Mapping
     - High resolution
     - Low resolution
   - Satellite
   - Airborne
   - Ship
   - Geophysics (Towed / AUV / ROV /seafloor mounted)

3D seismics
Multibeam bathymetry
Side-scan
EM
Acoustics (Midwater)
Imagery
Multi system platforms

2) Subseafloor sampling
   Drilling
      Down hole logging & measurements
      Coring
         Pressurized corer
         Vibro
         Gravity
      Pressurized vibro & gravity core equipment
      Seabed drilling capability
      Platform specific support
      Fluid and gas sampling & better technologies
3) In-situ measurements
   Observatories
   CORK
   $CO_2$, $CH_4$ probes
4) Oceanography
   Water chemistry
   ADCP
   Gliders with docking stations
5) Modeling (Integrated multiparameter)
   Gas
   Fluid
   Geotechnical
6) Infrastructure (energy & communications)
   Technologies applied to ice-covered areas
   Subsea permafrost s

**Working Group II:** Tom Feseker (Geologist/hydrogeologist, University of Bremen, MARUM, Germany); Michael Max (Geologist/geophysicist; Hydrate Energy International, USA); Tim Freudenthal (Geologist, University of Bremen, MARUM, seabed drill rig, Germany); Maria Ask (Rock mechanicstress measurements/deformation, Vice Chair EDP (IODP) co-leader of work package 7 LCU, Sweden); Rokas Kubilius (student, Fisheries Acoustics, Bergen University & METAS, Norway); Achim Kopf (Geologist; MARUM, Univ. of Bremen, Germany; Marine geotechnics/Seagoing technology, coordinator of $DS^3F$); BreTerje Torkelsen (Technical Director, METAS - Marine Ecosystem Technologies AS, Norway); David Smith (Head of Marine Operations; British Geological Survey, ECORD Science Operator, IODP, United Kingdom).

## Permafrost and Gas Hydrates using Research Downhole Logging and Coring Technologies (with a Special Focus on the Beaufort Sea Shelf )

**Rapporteur: T.S. Collett**

It is generally believed the thermal conditions conducive to the formation of permafrost and gas hydrate have persisted in the Arctic since the end of the Pliocene (about 1.88 Ma). Maps of present day permafrost reveal that about 20% of the land area of the northern hemisphere is underlain by permafrost (Fig. 2). Geologic studies and thermal modeling of subsea conditions also indicate that permafrost and gas hydrate may exist within the continental shelf of the Arctic Ocean. Subaerial emergence of portions of the Arctic continental shelf to current water depths of 120 m during repeated Pleistocene glaciations, subjected the exposed shelf to temperature conditions favorable to the formation of permafrost and gas hydrate. Thus, it is speculated that "relic" permafrost and gas hydrate may exist on the continental shelf of the Arctic Ocean to present water depths of 120 m. In practical terms, onshore and nearshore gas hydrate can only exist in close association with permafrost, therefore, the map in Fig. 2 that depicts the distribution of onshore continuous permafrost and the potential extent of "relic" sub-sea permafrost also depicts the potential limit of onshore and nearshore gas hydrate.


Figure 2. Distribution of permafrost in the Northern Hemisphere (source of permafrost data: http://nsidc.org/data/ggd318.html). Shown are the areas of onshore continuous permafrost (dark blue) and offshore possible relic permafrost (light blue) under which conditions maybe favorable for the occurrence of gas hydrate.

Recent studies have shown that the sediments beneath the continental shelf of the Arctic are undergoing some of the most dramatic warming on earth. This warming is a product of the sea level rise at the end of the last ice age, when relatively warm water (mean bottom temperatures >-1.8° C) transgressed across the much colder arctic shelf (mean annual surface temperatures <-12° C). The thermal disturbance generated by this transgression is still propagating down into subsurface sediments causing warming and the melting/decomposition of both permafrost and gas-hydrate-bearing sediments. There has been little consideration of the geologic processes (ie, sediment strain, gas and fluid flux) that can result from this significant change throughout the Arctic.

Scientific drilling of a destabilized permafrost and dissociating gas hydrate accumulation on the Arctic shelf would be of great benefit in characterizing the distribution of gas hydrate in the Arctic and unveiling the thermal and hydrogeological processes that control methane release from destabilized permafrost and gas hydrate. It would provide important clues as to the interplay between permafrost-associated gas hydrate in Arctic shelf sediments and global climatic change. Arctic marine basins to be considered in any future study should include those of the Beaufort Sea, Chuckchi Sea, East Siberian Sea, Laptev Sea, Kara Sea, and Barents Sea.

Work along the Svalbard Margin has for the first time linked contemporary methane emissions with the warming and breakdown of gas hydrates. In addition, work on the East Siberian shelf has documented high concentrations of methane that may in part be attributed to methane hydrate degradation. On the U.S. Beaufort Sea Shelf new maps of permafrost distribution produced from industry legacy seismic data and new USGS data imply that a significant portion of the shelf methane hydrate may have already dissociated. Recent ROV observations and sediment coring on the Canadian Beaufort Sea Shelf have documented methane venting from the seafloor in several distinct environments. Gas was observed venting near the shelf edge at relatively low rates, but over a widespread area. Conversely, vigorous gas venting from a focused vent was observed at the Kopanoar "pingo-like-feature" (PLF). The location of the vent sites on both the mid-shelf and near the edge of the slope is consistent with gas flux from decomposing relict permafrost and gas hydrate.

The Arctic PPG in 2001 recommended to drill a destabilized permafrost-associated gas hydrate accumulation on the Arctic shelf with a view to characterizing active processes of methane release. It was envisioned this could be achieved through drilling a series of transects across the shelf, from an outer shelf position at the former limit of permafrost, to an inner position where permafrost has seen relatively little change (reference site possibly on land). Drilling objectives should include determining the distribution of permafrost, gas hydrate and associated free gas, to establish the nature of the thermal regime, to investigate active gas transport processes and fluxes, to develop models of methane release from destabilized permafrost-associated gas hydrate accumulations.

## One year direct observations on volcanic activity of a cold seep, the Håkon Mosby Mud Volcano (HMMV)

**Rapporteur: D. de Beer**

A long-term observatory for mud eruptions (LOOME) was positioned for a year on the HMMV. The HMMV expels methane-rich fluids by active mud volcanism.
The HMMV has a diameter of 1500 m and consists of three concentric habitats: a central area with very soft warm mud originating from subsurface sediments, a surrounding area covered by white mats of sulfide oxidizing bacteria, and a peripheral area with hydrates colonized by symbiotic tube worms. Several studies have shown that the high upflow velocity of porewater in the central area controls the anaerobic microbial process rates. Measurements with temperature loggers showed that the volcano has periods of increased activity in an area of at least 50 m in diameter. Our observatory consisted of sensing units that measured (1) temperature and seismics deep in the sediment, (2) dynamics of temperature and chemistry at the sediment surface, and (3) units measuring in the water column (time lapse camera, CTD and scanning sonar). It was deployed July 26, 2009, and recovered September 27, 2010. Intensive auxiliary biogeochemical and microbiological measurements were performed before and after the deployment. The data and bathymetric maps showed that several eruptive events occurred along with massive movements of mud. We will integrate all available data, and present an overview of the events leading to and following a sudden eruption. Insight in the mechanisms and frequency of such events are important in understanding the process of mud volcanism and the development of the biological filters against methane emission.

## Long-term monitoring and quantification of fluid outflow at the seafloor using photomosaics: An example from the Lucky Strike Hydrothermal field

**Rapporteur J. Escartin**

Seafloor imagery is routinely acquired with autonomous and remotely operated vehicles. These data are key to understand fluid outflow at the seafloor (e.g., hydrothermal vents, cold seeps), providing constraints on their geometry and distribution, the links to other structures, or the associated ecosystems that they may sustain. Full scientific exploitation of such data has been hindered to date by the size of these datasets, and inherent difficulties in their processing and visualization. Long-term monitoring of these systems is a key to understand the dynamics and links to other processes both in the water column and below the seafloor (e.g., currents, deformation, magmatic events), nut these are largely based on time-series of physical (e.g., temperature) or chemical parameters (pH, redox, oxygen) that necessarily discrete and partial; a full characterization through image mosaics would provide the adequate context to better interpret instrumental data.

Here we present a series of geo-referenced and co-registered photomosaics of the Lucky Strike hydrothermal field (Mid Atlantic Ridge, 37°N), acquired in 1996, 2006, 2008 and 2009). These datasets are the implementation of new image processing techniques [1, 2] specifically tailored to generate giga-mosaics in the underwater environment; these include correction of illumination artifacts and removal of the edges between individual images in the mosaic so as to obtain a continuous and uniform image. The technique allow us to generate mosaics over large areas (order of 1 km square [e.g., 3]), with the possibility of co-registration of imagery from different surveys for temporal change studies. In the case of the Lucky Strike field, the mosaics were generated using 60,000 electronic still images, extending over a surface of 800 x 800 m, and with a pixel resolution of 5 to 10 mm. This scale of observation also allows a direct link to high-resolution microbathymetry acquired near the seafloor.

Resulting mosaics provide us with a first and most complete view of the distribution of hydrothermal activity at the Lucky Strike area. It also allow us to identify different types of hydrothermal outflow, the geometric links between these, and their relationship to other geological features such as faults or deposits that may control the fluid paths. Comparison of the photomosaics acquired in different years also allow us to identify the evolution of hydrothermal activity at specific sites) and at the scale of the hydrothermal field, indicating that there is a general decline in the intensity of the hydrothermal activity at time-scales of 10 years and less. This decline is not apparent in the instrumental records (e.g., temperature time series at individual vents), thus demonstrating the need and complementarity of imaging and instrumental monitoring. The imagery is also a powerful tool for the installation of instrumentation and infrastructure associated with seafloor observatories, such as the one now operating at Lucky Strike.

These results demonstrate that gigamosaicing can be routinely performed to characterize sites of interest (cold seeps, gas outflows, CO2 storage sites), and that it is a powerful tool to monitor temporal change in these areas at time scales of 1 to 10s of years that are required to understand the dynamics of fluid flow in the sub-seafloor.

## The impact of seasonal bottom water temperature change on the gas hydrate stability zone

**Rapporteur: T. Feseker**

The discovery of numerous gas seeps on the upper slope off western Svalbard in a depth range of 150 to 400 m by Westbrook et al. (Geophys. Res. Lett., 36, L15608, 2009) has led to the hypothesis that submarine gas hydrates are dissociating in response to warming of the West Spitsbergen Current. In order to test this hypothesis and plan further investigations including the drilling of gas hydrates in this area within the framework of ECORD/IODP, it is essential to understand the dynamics of the gas hydrate stability zone with respect to changes in bottom water temperature.

Water column temperature measurements obtained from CTD casts between 1975 and 2008 indicate temperatures ranging from 0 to 5 °C at 300 to 450 m water depth during the summer season. Linear regression yields a general warming trend of approximately 0.033 °C per year. Published model scenarios thus imply a linear increase from 2°C to 3°C over a period of 30 years, which results in a shift of the gas hydrate stability limit at the seafloor from around 360 to around 400 m water depth and a horizontal retreat of several hundred meters.

However, continuous observations from moorings show that the long-term warming trend is overlain by seasonal water temperature variability on the order of several degrees, and heat flow measurements revealed high thermal conductivity of the shallow sediments. As a result, seasonal temperature changes propagate deeply into the sediments. Numerical simulations of transient heat transfer in a vertical cross-section of the slope show that seasonal bottom water temperature changes result in large shifts of the gas hydrate stability zone, which may cause periodic formation and dissociation of shallow gas hydrates. Consequently, further studies are required to distinguish between seasonal and long-term changes in the assumed gas hydrate system off Western Svalbard.

## 3D seismic images of fluid flow phenomena of sub-Arctic continental margins: a baseline for Arctic studies

**Mads Huuse**

The offshore recognition of fluid flow phenomena along continental margins is largely driven by the availability of extensive, high-quality commercial 3D seismic surveys. These datasets allow new insights into the subsurface plumbing of hydrocarbon seeps, gas hydrate accumulations, mud volcanoes, pockmarks and sandstone intrusions, which will be presented in this contribution (Fig. 3).

The availability of such surveys in the Arctic is still limited and it would seem logical to apply lessons learned from sub-Arctic continental margins when interpreting seismic images from the Arctic.

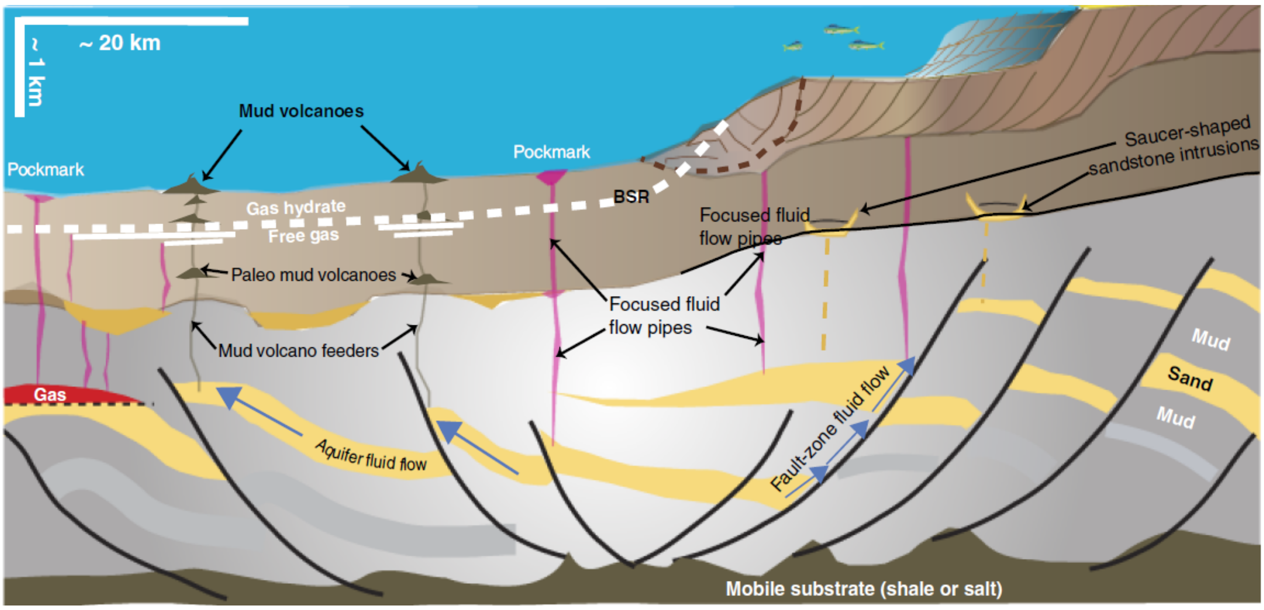



Fig. 3 – Synthesis of fluid flow phenomena along sub-Arctic continental margins with mobile substrates (Huuse et al. 2010: Basin Research).

## Scientific drilling for gas hydrates with the sea floor drill rigs

Rapporteur: T. Freudenthal

Sea floor drill rigs that can be deployed from standard research vessels are bridging the gap between dedicated drill ships that are used for deep drillings in the range of several hundred meters below sea floor and conventional sampling tools like gravity corers, piston corer or dredges that only scratch the surface of the sea floor. A major advantage of such robotic drill rigs is that the drilling action is conducted from a stable platform at the sea bed independent of any ship movements due to waves, wind or currents. At the Marum Center for Marine Environmental Sciences at the University of Bremen we developed the sea bed drill rig MeBo that can be deployed from standard research vessels. The drill rig is deployed on the sea floor and controlled from the vessel. Drilling tools for coring the sea floor down to 70 m can be stored on two magazines on the rig. A steel-armoured umbilical is used for lowering the rig to the sea bed in water depths up to 2000 m in the present system configuration. It was successfully operated on ten expeditions since 2005 and drilled more than 1000 m in different types of geology including hemipelagic mud, glacial till as well as sedimentary and crystalline rocks.

MeBo boreholes be equipped with sensors and used for long term monitoring. The installation of a “MeBoCORK” named long-term borehole monitoring system off Japan during R/V SONNE cruise 222 is planned for June 2012. Depending on the scientific demands, the MeBoCORK will allow in situ measurements of eg. temperature and pressure. The “MeBoCORK” will be equipped with data loggers and data transmission interface for reading out the collected data from the vessel. By additional payload installation on the MeBoCORK with an ROV it will be possible to increase the energy capacity as well as to conduct fluid sampling in the bore hole for geochemical analyses. It is planned to install a prototype of this additional payload with the MARUM ROV QUEST4000M during the following R/V SONNE cruise in July 2012.

## In situ, drilling/sampling and observatory technology in hydrogeologically active and gas hydrate areas

Rapporteur: A. Kopf

In situ measurements, both during the drilling process and long-term after hole completion, have a long tradition in ODP and IODP and serve to identify and characterise fluids in marine sediments. In the shallower sub-seafloor, less sophisticated probes may achieve similar things. In general, the key governing parameters measured include formation pressure (P) and temperature (T), which have been proven very powerful in order to identify fluid flow and gas hydrate processes.

For in situ P and T measurements, the suite of borehole instruments in IODP includes the DVTP, DVTPP, T2P, and - with Riser drill ships – the MDT tool.

Simpler tethered tools for measuring P and T are violin bow or self-contained heat flow probes, pushed or free-falling cone penetrometers (CPTs), and piezometer lances.

If the is situ stress state is to be studied post-cruise, drilling/sampling under in situ conditions comprise a number of devices. In academic or commercial drilling, those include HYACE, Hyacinth, PCS, or FPC, to name just a few.

Devices that do not require the use of a drill ship, but any research vessel of opportunity, are autoclave piston corers, autoclave core barrels for seafloor drill rigs such as MeBo, and the likes.

If P and T are to be monitored in an observatory, the most common, highly versatile and diverse approach in IODP have been CORKs. These could be rather simple, but may incorporate monitoring at numerous levels, packed intervals, fluid sampling, and even real-time data transmission. Apart from the CORK, mini-CORK systems such as instrumented bridge plugs (e.g. SmartPlug, GeniusPlug) or the SCIMPI tool have been developed for areas of active fluid flow, overpressure, and gas hydrate processes. If setting an observatory with a drill ship is not an option, more affordable observatory instruments such as MeBo-CORKs, long-term piezometer probes, or custom-built long-term stations on the seafloor (CAT meters, osmo-driven probes, LOOME, MIMOSA) represent an alternative.

In summary, there is a wealth of in situ techniques that could – more or less – reliably measure the PT conditions in gas hydrate bearing lithologies. In the future, those could be combined with marine electromagnetics, fluid sampling, electrical conductivity, and other techniques. The presentation will review the most prominent developments including some results and will conclude with an outlook.

## Gas-related acoustic anomalies related to shallow gas hydrate formation

**Rapporteur: A. Krylov**

Gas hydrate in arctic environment is typically considered to be related with permafrost. However, investigations of the permafrost-related hydrates require deep drilling. At the same time, increasing interest of the International scientific community to the Arctic has resulted in resent discovery of new shallow gas hydrate occurrences there. The main idea of this study was to forecast potential areas of the shallow gas hydrate accumulation at the Barents and Kara seas offshore Russia.

The calculations of PT conditions of the shallow hydrate formation were based on distribution of measured bottom water temperatures ranging from 0.5 to -1.00C and from 0.0 to -1.50C within the Barents and Kara seas, respectively; assuming the pure methane as a hydrate-forming gas and water salinity of 35‰. As a result, the pressure values (water depth function) required for the shallow gas hydrate formation were obtained allowing to predict the hydrate-prone areas. For the Barents Sea these areas are: South Barents and Frantz-Victoria depressions, Al'banov and Bear Island troughs limited by minimum water depths of 320 m. At the Kara Sea, the minimum water depth required is 280 m indicating the Eastern Novaya Zemlya, St. Anna, and Voronin troughs as the hydrate-prone regions. Beside the P and T that are necessary but insufficient factors controlling hydrate formation, the gas amount enough to oversaturate pore water and, so that cause gas hydrate precipitation has to be present. It is known that focused gas seepage toward the seafloor ordinary controls formation of the shallow gas hydrate accumulations. Shallow gas hydrate formation conditions within fluid discharge areas kinetically most favorable near the seafloor where the greatest pressure and overcooling occur in the sediment since both temperature and equilibrium pressure decrease toward the seafloor (Soloviev and Mazurenko, 2000). Therefore, the problem was to reveal hydrocarbon discharge structures within the areas characterized by required water depths. For the arctic environment (due to relic permafrost presence), free gas seepage is most common. Evidences of the gas seepage may be effectively acquired by seismoacoustic survey. Special studies directed on the search for the gas seeps in the Arctic offshore Russia have not been performed. However, data obtained by the Murmansk Arctic Geological Expedition (MAGE) provide a good net of geophysical profiles over the Barents and Kara seas. Interpretation of the high resolution seismic images allowed revealing various gas-related acoustic signatures in the uppermost sediment. When considering locations of these anomalies with respect to the PT stability conditions, it is appeared to be that gas seepages of different intensity and appearance occur within South Barents Depression, Eastern Novaya Zemlya Trough, and southern part of St. Anna Trough suggesting these areas as the most perspective for the shallow gas hydrate formation.

## Groundwater transport of mineralizing fluids in continental margin sediments

**Rapporteur: M.D. Max**

Concentrations of oceanic natural gas hydrate (NGH) can only form where the concentration of dissolved gas in pore fluids is high enough to drive crystallization. In a three phase system of NGH, water, and free gas, hydrate will form when the driving force for crystallization is great enough either in gas or water media. The source of natural gas is generally from below the GHSZ; migration of gas and fluids controls NGH formation and localization. Although modeling of NGH formation using the local descriptor of 'pore fluid processes' is sufficient for understanding crystallization scenarios, modeling groundwater movement (the geological plumbing system) within sedimentary 'basins' along continental slopes in which NGH may form provides the framework for migration of natural gas.

Oceanic NGH forms within essentially unlithified sediments that are in the early stages of diagenesis and the bulk of the natural gas found in NGH appears to be generated by biological processes. In sediments in passive margins, gravity compaction of sediment appears to be the primary driver of fluid flow. In active margins, tectonics plays a more dynamic part and may also tap thermogenic gases. Local mechanical drivers, such as salt tectonics, also contribute to fluid movement. The groundwater systems related to hydrate formation are expulsive; that is, the water within the sediments is being expelled from the sediment piles as a whole through the seafloor. The amount of water entering the sea must be equal to that expelled from the sediment, which means that observed venting must be a very small fraction of the total water expelled.
Focused groundwater flow and percolation, which is more liable to be related to the formation of concentrations of NGH, can be either through porous strata or along faults that may be either tectonic or generated by groundwater - gas systems that are commonly related to venting. Gas migration that is dominated by diffusion may result in dispersed hydrate over large areas of muddy sediments in which focused flow is primarily along fractures. Exploration for concentrated NGH should focus on modeling the groundwater system within the GHSZ, and for some distance below it to include all groundwater feeders supplying the mineralizing solutions.

## Areal surveys and monitoring of thermogenic gas seepage in shallow coastal waters

### Rapporteur: G. Papatheodorou

Over the last twenty years multiple marine remote sensing surveys have been carried out in Ionian Archipelago (Western Greece) by the Laboratory of Marine Geology and Physical Oceanography and collaborative international institutes. These surveys have revealed a variety of acoustic anomalies in the seabed and evidences of gas venting, suggesting that gas-charged sediments and gas seepages are common phenomena on the seabed. Seabed fluid flows have been reported in a variety of environments such as Pleistocene and present-day fiords-like environments, deltaic environments, lakes, lagoons and shelf environment (Papatheodorou et al., 1993, 2007a,b, Hasiotis et al 1996, Christodoulou et al., 2003).

The Western Greece is one of the main hydrocarbon-prone areas of Greece. Petroleum fields occur in deep carbonates and clastic sequences from the Jurassic to the Eocene, belonging to the external Ionian tectonic unit of the Hellenides. Deep faults act as preferential pathways for the upward migration of natural gas, producing gas seeps along the Ionian coast both offshore and onshore. Geochemical analyses of gas seepages have been shown the thermogenic origin of the natural gas.

Katakolo bay, located at the Western Peloponnesus, has attracted the interest of scientists due to the vast seepage occurring in the harbour and can be considered as a unique natural laboratory to study gas seepage by a long or short term monitoring. Offshore bubbling plumes are widespread throughout the area. The bubbles issuing from cracks in the seabed are of the order of 10 - 20 cm in diameter. The seepage is considered as thermogenic methane (Etiope et al., 2006a,b). Extensive bacterial mats (Beggiatoa sp.) have been found on the seafloor at these seep sites. Furthermore, extensive onshore seeps have been observed in the area of Katakolo and mainly around the harbour.

Detailed repetitive oceanographic surveys have been carried out by the UPAT with the collaboration of INGV for the study of spatial (horizontal and vertical) distribution of $CH_4$ and $H_2S$ in the Katakolo bay in the framework of HYPOX project. The data incorporated results from the deployment of MEDUSA (a towing multiparametric module) in Katakolo bay. MEDUSA data showed that there is a clear correlation between intense gas seepage and oxygen concentration reductions. Based on all these data, Katakolo bay proved to be an excellent site for short-term-monitoring and studying gas seepage and the effect of these on $O_2$ reduction.

The selection of the monitoring site was based on all available data regarding the gas flux measurements, gas composition and origin, oceanographic parameters of seawater and geotechnical properties of the seafloor. The monitoring site is located inside the harbor of Katakolo in an area which is more or less unaffected by the vessel traffic. The site is located within a thermogenic gas seepage area where active faults are intersected.

For the short-term monitoring in Katakolo bay the Gas Monitoring Module (GMM) developed in a previous EU project (ASSEM) was deployed. GMM is based on a multiparametric approach in which the detection of gases ($CH_4$, $H_2S$, $O_2$) is associated with that of key physicochemical factors, i.e. temperature, pressure and conductivity. Gas detection is based on the use of oxygen, methane and hydrogen sulphide sensors commercially available. All sensors have a unique time reference and are controlled by a dedicated data-acquisition system (Marinaro et al., 2006).

The benthic station GMM was deployed on 21 September 2010 in the Katakolo harbor and lasted 3.5 month (101 days, up to 31 December 2010. The preliminary GMM data analysis has shown a good correlation between the measurements of two methane sensors with no shift in sensors signals. The preliminary results also show eight main methane peaks associated with oxygen drops. The preliminary results also show a series of main periods of oxygen depletion, apparently related to enhanced seepage.

## The significance of sub-seabed supply of gas to bubble plumes from the seabed

**Rapporteur: G.K. Westbrook**

Information on the lithostratigraphic control of methane gas and hydrate in the continental margin of west Svalbard has been derived from the interpretation of data from multichannel seismic reflection, ocean-bottom seismometers, sonar and coring acquired in 2008. The presence of methane gas in the middle and lower continental slope is revealed by a prominent bottom-simulating reflector (BSR) in predominantly contourite sediments, which are penetrated, especially along the crest of the Vestnesa Ridge contourite drift, by gas chimneys that periodically emit plumes of gas bubbles. Methane hydrate occurs a few metres below the seabed in the pockmarks at the tops of the chimneys. Near the top of the continental slope, many bubble plumes occur just landward of where the upper boundary of the methane hydrate stability zone intersects the seabed, at about 400-m water depth. These plumes are probably fed, in part at least, by methane released by dissociating hydrate. Numerical modelling of temperature, hydrate formation and dissociation, and gas and fluid flow demonstrates that this can occur in response to a 1°C seabed warming over the last thirty years, where the top of hydrate is less than a few metres beneath the seabed in the zone from which the hydrate stability zone has withdrawn. A clear BSR is not observed within the shallow, predominantly glacigenic sediments of the upper continental slope in water depths shallower than about 700 m, but the presence of free gas at sub-seabed depths greater than the predicted base of the hydrate stability zone is indicated by high-amplitude negative-polarity reflectors above zones of reduced signal frequency, with localised negative-polarity scatterers in the zone of bubble-plume occurrence. These deeper sediments are contourites or other well-bedded marine sediments, within which gas migrates upslope beneath the shallow glacigenic sediments, supplying gas to the hydrate stability zone and to the continental shelf beyond. Seismic velocity models for the upper slope show strong local velocity reduction beneath reflectors that are too deep to be at the base of the hydrate stability zone, whereas farther down the slope, velocity decreases immediately beneath the BSR in the contourites. The glacigenic sediments have a higher seismic velocity, resulting from their poor sorting with consequent low permeability, than the contourites, which are well sorted with high permeability. From these observations we infer that gas migration in the glacigenic sequence is confined to permeable interbeds and fractures cutting through the glacigenc units. This gives a heterogeneous distribution of gas and hydrate occurrence and, hence, non-uniform spatial and temporal patterns of methane release from the seabed, with lateral displacement of locations of seabed emission of gas from shallow gas sources.

## The Norwegian Gas Hydrate Resource Potential

**Rapporteur: E.S. Andersen**

*Need for Natural Gas*
Natural gas is becoming an increasingly important energy source for the world economy, because the gas burns cleanly, causing few pollution problems. The world marketed energy consumption is, according to US Energy Information Administration (EIA) projected to grow by as much as 50% by 2030. Unfortunately, production of conventional and unconventional natural gas cannot keep pace with the growth in demand. The development of new, cost-effective resources such as methane hydrate can play a major role in moderating price increases and ensuring adequate future supplies of natural gas.

*Hydrate Driver*
It is the potential of gas hydrates to become a major energy resource that is the primary driver for the rapidly accelerating international investment in gas hydrate research, especially by countries with limited hydrocarbon resources.
The prospects for production from marine gas hydrates greatly improved when researchers identified extensive gas hydrate accumulations in sand reservoirs in the Gulf of Mexico and

offshore southeastern Japan. What made these deposits attractive for gas extraction is their permeability, which appears to enable gas hydrate to accumulate to very high concentrations (typically 60 to 90 % of the pore space). In addition, the permeability present in sand reservoirs may be the key to producing methane from gas hydrate reservoirs with existing drilling and production technologies.

*Statoil's Role in Unconventional Hydrocarbon E&P*
Recently Statoil took a position in petroleum production from shale formations onshore USA (i.e., the Marcellus and Eagle Ford shale plays). Statoil is also evaluating other unconventional value chains, such as coal-bed methane (CBM) and natural gas hydrates. Drilling results during the last 5-10 years have significantly altered the original view on hydrate prospectivity and it is becoming evident that hydrate exploration is no longer a simple Bottom-Simulating Reflector (BSR) hunt. The BSR is useful for delineating the base of the hydrate stability zone, however strong, continuous BSRs may in many places delineate poor reservoir lithologies. Much of the gas hydrate resource in for instance the Gulf of Mexico occurs in discrete sands contained within the zone of hydrate stability and is unrelated to the presence of a BSR.
A successful exploration approach should therefore consider gas hydrate reservoirs as part of the broader petroleum system and take into account sand deposition (reservoir) and hydrocarbon source, migration and trapping. Using this approach, various deep water basins around the world have the potential for commercial development of gas hydrate resources.

*Gas Hydrate Potential in Norway*
Statoil is currently performing a global screening of commercially attractive basins in order to assess the marine resource volumes within potentially producible gas hydrate accumulations. In addition, we want to determine whether gas can be produced from gas hydrate reservoirs through onshore and/or offshore long-term production tests.
Our study also includes assessing the gas hydrate potential of the Barents Sea region, including onshore Svalbard. During the Tromsø Workshop, we would like to discuss and promote a joint academy/industry programme focusing on determining the gas hydrate resource potential in the region. The programme should focus on identification and characterizing gas hydrate at high concentrations in reservoir-quality sands using methods developed by research programmes in e.g. USA, Canada and Japan. Given substantial resource-indications, the programme should consider exploration drilling and field production test experiments.

## References

Christodoulou D., Papatheodorou G., Ferentinos G., Masson M. (2003): Active seepage in two contrasting pockmark fields in Patras and Corinth Gulfs, Greece. Geo-Marine Letters 23: 194-199.

Escartín, J., García, R., Delaunoy, O., Ferrer, J., Gracias, N., Elibol, A., Cufi, X., Neumann, L., Fornari, D.J., Humphris, S.E., and Renard, J., 2008, Globally-aligned photo mosaic of the Lucky Strike hydrothermal Vent Field (Mid-Atlantic Ridge, 37°18.5'N): release of geo-referenced data, mosaic construction and viewing software: Geochemistry, Geophysics, Geosystems, v. 9, p. Q12009, doi:10.1029/2008GC002204.

Etiope G., Papatheodorou G., Christodoulou D., Favali P. and Ferentinos G. (2006a) Gas hazard induced by methane and hydrogen sulfide seepage in the NW Peloponnesus petroliferous basin (Greece). Terrestial, Atmospheric and Oceanic Sciences vol 16. No.4, 1-7.
Etiope G., Papatheodorou G., Christodoulou D., Favali P., Ferentinos G., E. Sokos (2006b) Methane and hydrogen sulfide seepage in the NW Peloponnesus petroliferous basin (Greece): origin and geohazard. AAPG Bulletin v. 90, No. 5, pp. 701-713.
Final Report of the Arctic´s Role in Global Change Program Planning Group (APPG), 2001.
Hasiotis T., Papatheodorou G., Kastanos N. and Ferentinos G. (1996): A pock-mark field in the Patras Gulf (Greece) and its activation during the 14/7/1993 seismic event. Marine Geology, vol. 130, pp. 333-344.
Marinaro G., Etiope G., Lo Bue N., Favali P., Papatheodorou G., Christodoulou D., Furlan F., Gasparoni F., Ferentinos G., Masson M., Rolin J.F., 2006. Monitoring of a methane-seeping pockmark by cabled benthic observatory (Patras Gulf, Greece). Geo-Mar. Letters, doi: 10.1007/s00367-006-0040-4.
Papatheodorou G., Hasiotis T. and Ferentinos G. (1993): Gas charged sediments in the Aegean and Ionian Seas, Greece. Marine Geology vol. 112, pp. 171-184.
Papatheodorou G., Christodoulou D. and G. Ferentinos (2007a) Gas charged sediments and associated seabed morphological features in the Aegean and Ionian seas, Greece". Contribution 13 (in Powerpoint format). In: "Seabed Fluid Flow. The impact on Geology, Biology and the Marine Environment" by Alan Judd and Martin Hovland, Cambridge University Press, Cambridge CB2 2RU, UK, p. 475, (www.cambridge.org/9780521819503).
Papatheodorou G., Christodoulou D., Geraga M., Etiope G., Ferentinos G (2007b) "The pockmark field of the Gulf of Patras: An ideal natural laboratory for studying seabed fluid flow" In: ZELILIDIS, A., PAPATHEODOROU, G. and GERAGA, M. (eds.): Sedimentology of western and central Greece from recent to Triassic. 25th IAS Meeting of Sedimentology, Patras, 2007, Field Trip Guidebook, p. 43-62.
Prados, R., R. Garcia, J. Escartín, L. Neumann, Challenges of close-range underwater optical mapping, IEEE Oceans, submitted 4/11.
Prados, R., R. Garcia, N. Gracias, J. Escartín, L. Neumann, A novel blending technique for underwater gigamosaicing, IEEE Trans. Mechantronics, submitted 4/11.
Soloviev V.A. & Mazurenko L.L. (2000) Sea Floor Venting and Gas Hydrate Accumulation. In: Natural Gas Hydrate in Oceanic and Permafrost Environment. (Ed. M.D. Max), 28, pp. 259-293.

# Appendix 1

## Workshop Agenda

| DS3F Workshop "Fluid flow in Arctic continental margins and ocean ridges" 30 – 31 May 2011 in Tromsø (Norway) | | |
|---|---|---|
| Monday, 30 May | Invited speaker | Title of the talk |
| 09:00 | Jürgen Mienert, UiT (Norway) | Welcome/opening |
| 09:15 | Espen Sletten Andersen, Statoil (Norway) | The Norwegian gas hydrate resource potential |
| 09:45 | Tim Collett, USGS, Hydrate Energy International (USA) | Degrading Permafrost and Gas Hydrates on the Beaufort Sea Shelf with a Special Focus on Research Downhole Logging and Coring Technologies |
| 10:15 | Michael D. Max, Hydrate Energy International (USA) | Groundwater transport of mineralizing fluids in continental margin sediments |
| 10:45 | *Coffee break / posters* | |
| 11:15 | Dave Smith, BGS (UK) | Arctic drilling: success of ACEX and new opportunities using seabed drills |
| 11:45 | Tim Freudenthal, MARUM (Germany) | Scientific drilling with the sea floor drill rig MeBo |
| 12:15 | *Lunch break / posters* | |
| 13:00 | Alexey Krylov, VNIIOkeangeologia (Russia) | Gas-related acoustic anomalies and shallow gas hydrate formation within the Barents and Kara seas |
| 13:30 | Matthew Hornbach, University of Texas (USA) | Anomalous Bottom-Simulating-Reflections at Hydrate Ridge: 3D Evidence for Subsurface Advection Driving Massive Hydrate Formation? |
| 14:00 | Mads Huuse, SEAES (UK) | 3D seismic images of sub-Arctic fluid flow systems: a baseline for Arctic fluid flow studies |
| 14:30 | Stefan Buenz, UIT (Norway) | High-resolution 3D seismic imaging of fluid-flow features in sedimentary basins of Norwegian Arctic continental margins |
| 15:00 | *Coffee break / posters* | |

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|---|---|---|
| 15:30 | Achim Kopf, MARUM (Germany) | In situ, drilling/sampling and observatory technology in hydrogeologically active and gas hydrate areas |
| 16:00 | Javier Escartin, CNRS/IPGP (France) | Characterization and temporal variability at hydrothermal sites from repeated image surveys: Lucky Strike Hydrothermal field, Mid-Atlantic Ridge |
| 16:30 | Rolf Birger Pederson, UoB (Norway) | Hydrothermal activity at the Arctic Mid-Ocean Ridge |
| 17:00 | *End of the first day* | |
| 19:00 | *Conference dinner at Fjellheisen for pre-registered workshop participants* | |

| Tuesday, 31 May | Invited speaker | Title of the talk |
|---|---|---|
| 09:00 | Tom Feseker, University of Bremen (Germany) | The impact of seasonal bottom water temperature change on the gas hydrate stability zone |
| 09:30 | Graham Westbrook, IFREMER (France) and NOCS (UK) | The sub-seabed supply of gas to bubble plumes from the seabed on the upper continental slope of west Spitsbergen. |
| 10:00 | Dirk de Beer, MPI-MM (Germany) | Year long observations on sediment dynamics of the Håkon Mosby Mud Volcano |
| 10:30 | George Papatheodorou (Greece) | Areal surveys and monitoring of thermogenic gas seepage in the Katakolo Bay (Western Greece) |
| 11:00 | *Writing groups* | |
| 16:00… | **Summary of workshop and closing remarks (Jürgen Mienert)** | |