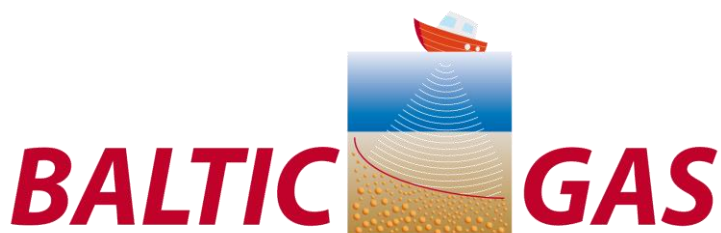


The Y2 BALTIC GAS scientific report

Reporting period: January 1 – December 31, 2010

(compiled by Bo Barker Jørgensen and Henrik Fossing)



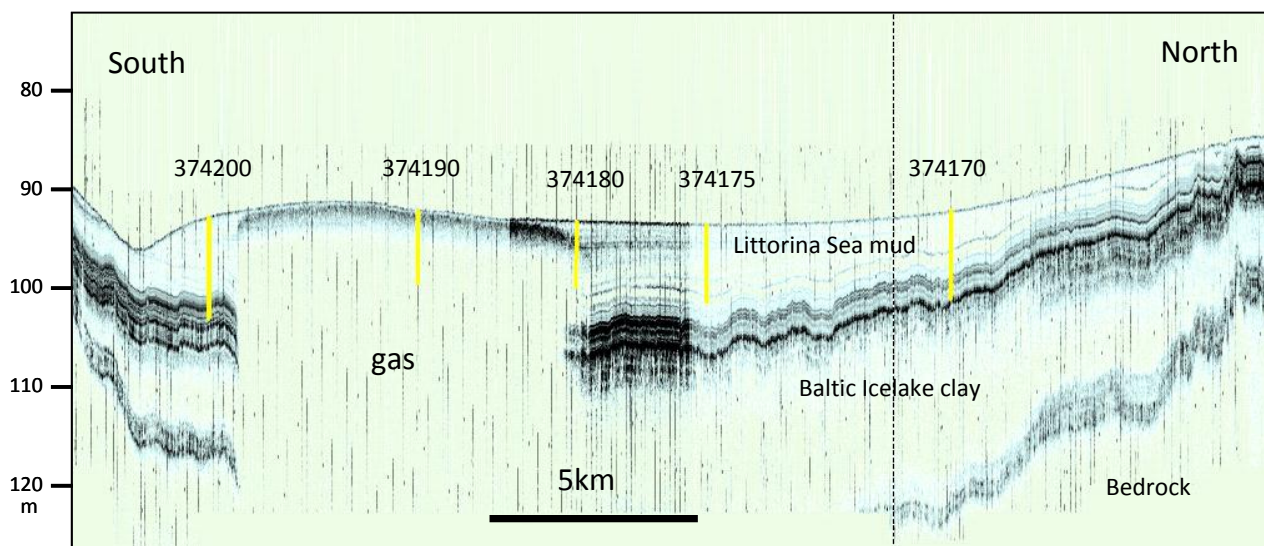
Highlights from the BALTIC GAS projects

Methane formation in the Baltic Sea, which may be sensitive to eutrophication from coastal populations and from river discharge, has led to the accumulation of free gas in the form of methane bubbles beneath the depth of sulfate penetration, several decimeters to meters sub-surface. This “shallow gas” has been detected in hundreds of square kilometres of the Baltic seabed. Although the gas is continuously rising up towards the sediment surface, it is effectively broken down sub-surface when reaching into the sulphate zone. One of the important research challenges in BALTIC GAS is to establish a quantitative and mechanistic understanding of gas accumulation, flux and emission in the seabed. This is done through data mining (WP2), seismo-acoustic measurements (WP3), sediment sampling and analyses of biogeochemical parameters, (WP4) and modeling (WP5). Here we demonstrate the tight coupling between these work packages using three examples.

Seismo-acoustic measurements coupled to biogeochemistry (an example from Bornholm Basin)

On several BALTIC GAS cruises (during 2009 and 2010 organized in WP1) selected areas of the Baltic Sea sea floor was scanned by the use of seismo-acoustic equipment (i.e. echo sounders such as CHIRP or Sparker systems) for the occurrence of free methane gas (WP3). Sound waves penetrate relatively easily into fine grained sediments such as mud, silt, and clay, while penetration depths are limited in sand, gravel and glacial till. Since methane gas in the seabed efficiently absorbs the acoustic energy and thus blanks information about the underlying sediment, shallow gas appears as a more or less homogeneous blank field on a seismic ‘picture’ or ‘scan’.

10 kHz Innomar Parametric Sediment Echo Sounder December 2009



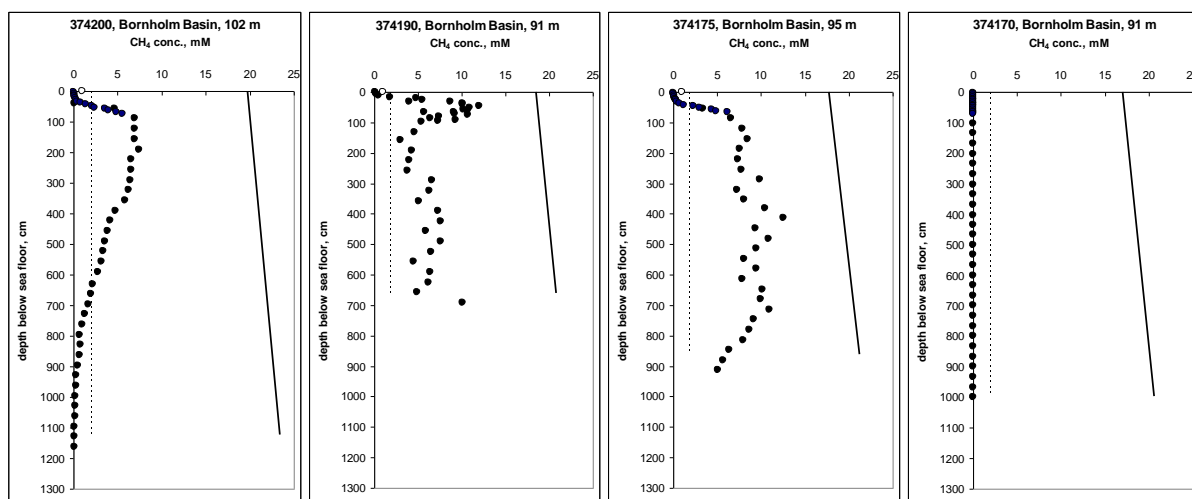


Figure 1. Bornholm Basin transect crossing methane gas saturated sediment at site 374190 at a water depth of about 90 m. Upper panel shows the seismic profile with approximate penetration depth of the GC-corer (yellow vertical bar). Lower panel shows the methane gradient at four sites: 374170, 374175, 374190 and 374200. Site 374180 was positioned at the transition between gas saturated and non-gas saturated sediment but appeared with almost the same CH₄ concentration as Site 374190 and is thus not shown. Solid and dashed lines show *in situ* methane saturation and saturation by 1 atm., respectively.

Figure 1 shows an example from Bornholm Basin (DK) of a seismic transect where methane gas has built up in the approximately 9 m thick Holocene mud layer across a horizontal (south to north) distance of about 8 km. Seismic images recorded like this were used for targeted sampling of sediment cores by gravity coring or other coring, accompanied by immediate sampling of sediment for methane analyses and other sediment constituents comprising – but not limited to – sulfate, sulfide and nutrients (WP4). Particularly during the cruises with *RV Poseidon* (Dec. 2009) and *RV Maria S. Merian* (Aug. 2010) a significant area of the Baltic Sea (from the Arkona Basin in the south west to the Bothnian Bay in the north east) was studied by this approach. The BALTIC GAS cruises have in this way contributed with significant new information on the distribution of methane gas in Baltic Sea sediment (see Mapping of methane distribution in sediments).

Sediment sampling along seismic lines like the one shown on Fig. 1 resulted in several new observations. First of all, the large number of Baltic Sea locations sampled showed an interesting empirical coupling between mud thickness and presence of free gas. Thus, the Holocene mud layer must generally be at least 6 – 8 m thick before free methane gas is able to develop in the sediment. This, however, does not necessary imply that CH₄ will not be present in Holocene mud thinner than about 8 m. Along the Bornholm Basin transect, for example, outside the gas field but still in close vicinity (< 3 km; Station 374175 with a Holocene layer of about 8 m), CH₄ was also present in the sediment, however in concentrations below *in situ* saturation but above saturation at 1 atmosphere (Fig. 1). At such stations no 'blanking' of the seismo-acoustic signal was observed and therefore the signal resembled the seismic picture at stations without CH₄ (e.g. Station 344170 about 9 km north of the gas field with a Holocene layer of about 6 m). Hence, sediment coring was done at all stations in order to specifically detect CH₄ in the sediment.

The CH₄ gradients at Stations 374200 and 374175 were of particular interest because a peak in the CH₄ concentration was observed in the sediment followed by a decrease in CH₄ concentration to near depletion

at the bottom of the sediment cores, about 10 m below sea floor. These CH₄ gradients revealed sediment in non-steady state and implied that CH₄ was gradually building up toward saturation over (geological) times. This hypothesis was tested and confirmed by modeling the methane and sulfur dynamics in the sediment by use of a transport-reaction model as explained in the next section.

Modeling the methane and sulfur dynamics in the sediment by use of a transport-reaction model

We have successfully constructed a mathematical model that can explain the development of free methane gas in the Holocene mud layer in different regions of the Baltic Sea, starting when seawater had forced its way through the Danish Belts and into the freshwater body of the Ancylus Lake some 8,000 years before present (BP) (WP5). This mixing of water bodies gradually formed the brackish Baltic Sea that we know today. The model used is a reactive- transport model coupling solid-aqueous-gas dynamics, organic matter deposition and burial rate, changes in sea level and salinity, and production and consumption of methane through microbial processes (i.e. methanogenesis and sulfate reduction). Under varying conditions the model can be used to track the evolution of organic matter degradation, the resulting effects on the methane balance, and in particular the liberation of free methane gas in Baltic Sea sediment. The model output is verified by *in situ* measurements of sediment biogeochemistry (WP3 and WP4). Here we present an example from the Arkona Basin (Fig. 2).

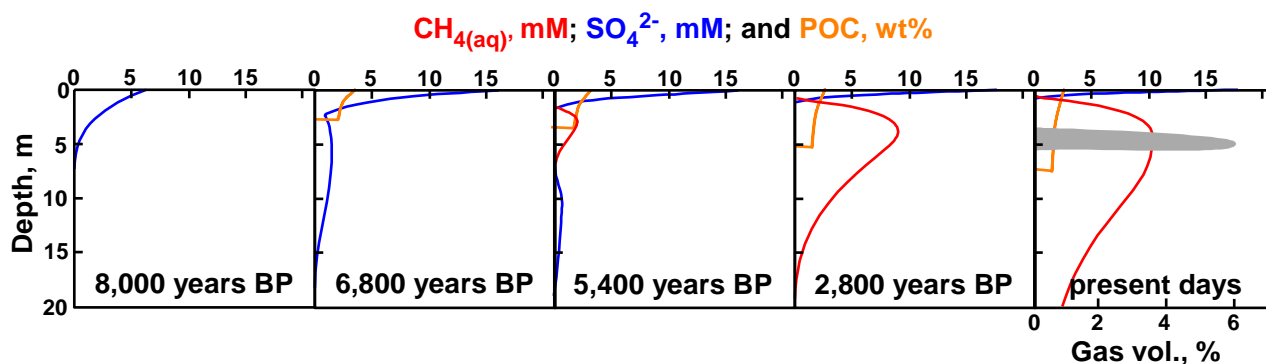


Figure 2. Development in particulate organic carbon (POC, i.e organic matter deposition; brown line), sulfate (SO₄²⁻; blue line), dissolved methane (CH_{4(aq)}; red line), and free methane gas (gray shaded curve) in Baltic Sea sediment starting 8,000 years before present (BP) when the environment gradually turned from limnic to brackish. The maximum penetration depth of POC (brown-orange curve) equals the thickness of the Holocene mud layer. An example from the Arkona Basin modelled by use of a reactive transport model coupling the dynamics of solid-aqueous-gas phases (Redrawn after J. Mogollón, paper in prep.).

The transient model begins 8,000 years BP when the Baltic Sea turned brackish reflected by a gradual increase in bottom water sulfate concentration and concomitant diffusion of SO₄²⁻ into the sediment (Fig. 2). A significant increase in organic matter deposition was simultaneously initiated which has continued until present days resulting in an a steadily increasing thickness of the organic-rich Holocene mud layer. The particulate organic matter (POM) in the Holocene mud was gradually degraded, particularly through the reduction of SO₄²⁻, which narrowed down the SO₄²⁻ penetration into the sediment. CH₄ formation is strongly inhibited in the presence of SO₄²⁻. Therefore, CH₄ production (from POC degradation in the Holocene mud) was not

observed in the sediment before approx. 5,400 years BP at depth where the SO_4^{2-} pool was increasingly exhausted. Since then, CH_4 has been produced in the Holocene mud and gradually increased in concentration associated with an up- and downward diffusion of CH_4 . Through the process of anaerobic methane oxidation the downward diffusing CH_4 completely consumed the deeper reservoirs of SO_4^{2-} in Arkona Basin sediment (between 5,400 to 2,800 years BP; see Fig. 2). Near the sediment surface (at about 1 m in the shown example) similar microbial processes took place when upward diffusing CH_4 met with downward diffusing SO_4^{2-} . However, in surface sediments the pool of SO_4^{2-} was replenished from the Baltic Sea brackish water body and a delicate balance between CH_4 and SO_4^{2-} concentration gradients was observed (in the Arkona Basin example from about 2,800 years ago). The CH_4 pool increased continuously below the SO_4^{2-} rich sediment and ultimately the methane concentration exceeded *in situ* saturation and free CH_4 gas started to build up which has continued until present days (Fig. 2). See also *WP 5: Modeling and data integration* below.

Mapping methane distribution in Baltic Gas sediments

Compilation of biogeochemical data obtained during more than 10 Baltic Gas cruises (WP4) as well as recovered from both published and unpublished CH_4 data (i.e. data mining, WP2) combined with geological and acoustic information (WP3) have been used to map different characteristics of methane in the Baltic Sea: methane distribution and concentration, methane fluxes and consumption and distribution and depth of free gas. Figure 3 shows as an example the coring sites throughout the Baltic Sea and the sediment depth at which the methane concentration reached 1 bar partial pressure. Not included yet are core data from Russian studies in the Baltic Sea, in particular in the Gulf of Finland. The map shows the distribution of the Holocene mud blanket that covers late Glacial and post Glacial deposits.

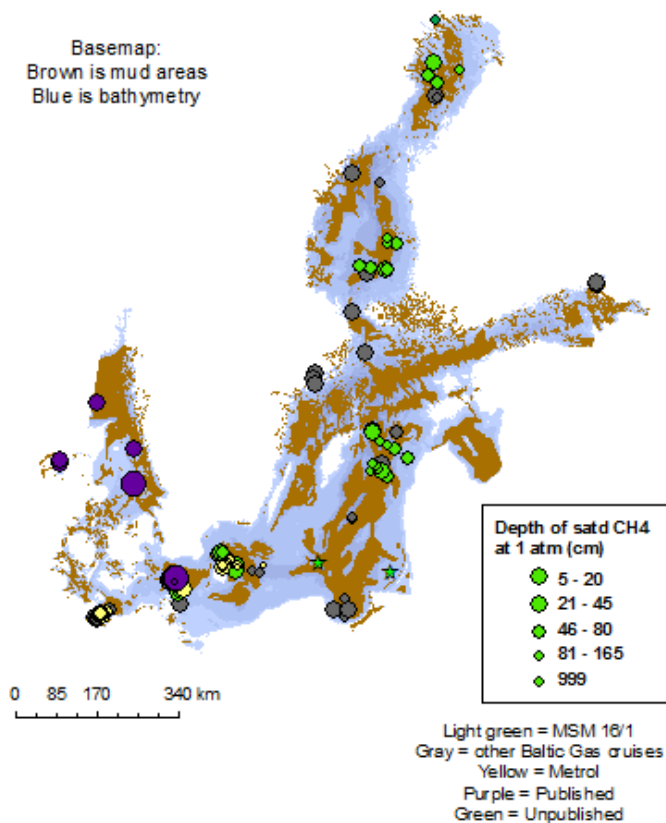


Figure 3. Methane distribution in Baltic Sea sediment.

The map shows that Baltic Gas expeditions have now covered most regions of the Baltic Sea, going from the SW Baltic up through the central basins and into the Bothnian Bay. Included are also some data from the former EU FP5 project, METROL (purple signature). The size of the filled circles shows the depth of 1 bar methane partial pressure. The larger the circle, the shallower the depth of 1 bar methane pressure and, thus, the higher the methane flux. The map shows that high and low methane fluxes are encountered in all parts of the Baltic Sea. There was not a distinct trend due to decreasing salinity, and therefore decreasing sulfate concentration, when going from the Skagerrak to the Bothnian Bay. There was a distinct correlation with the thickness of the Holocene mud blanket, irrespective of location in the Baltic Sea. This correlation is clear from Fig. 1 above.

From the many coinciding recordings of seismo-acoustic zonation of sediments and depth of the sulfate-methane transition we now develop algorithms correlating methane fluxes and gas distribution so that GIS mapping for these key parameters can be extended to the entire Baltic Sea. Such a mapping is one of the main objectives of Baltic Gas and through the process data analysis and interpretation we are gaining a much better understanding for the occurrence of hot spots and deserts for methane fluxes. The geographical variation in fluxes is much greater than first expected and shows that a thorough mapping of the geology of the Baltic Sea and a knowledge of the sedimentation history are critical in order to understand the present-day methane cycle.

WP 1: Project management, coordination and dissemination

(reported by Henrik Fossing, National Environmental Research and Bo Barker Jørgensen, Center for Geomicrobiology, both at Aarhus University, Denmark)

Task 1.1: Management and dissemination

- 1.1.1: Coordination scientific Reports
- 1.1.2: Organizing Workshops or Meetings
- 1.1.3: Establishment of project home-page

Task 1.2: Submission of data to a common database

Task 1.3: Research cruises

- 1.3.1: Identification of target sites
- 1.3.2: GIS based maps of target areas
- 1.3.3: Organizing two weeks cruises

Task 1.4: Ph.D-training program

Deliverables within this reporting period:

- BALTIC GAS Workshops and meetings (reports)

Task 1.1: Management and dissemination

The coordinators have discussed the progress of BALTIC GAS with all WP-leaders, Principal Scientists and Task Responsibles and express that

- all WPs and Tasks are advancing according to original research and financial plan,
- no necessary adaptation of the research plan and schedule of deliverables is presently foreseen,
- no third parties have major influence on the working programme at present, However data mining (Task 2.1) from outside the project partners (i.e. non-BONUS partners i.a. national geological surveys) has turned out to be more difficult than expected as these institutions have no resources to commit themselves to delivery the requested data. In collaboration with Task Responsible Jørn Bo Jensen, the Baltic Gas coordinator Bo Barker Jørgensen has raised additional funds to secure 'third party' dataset for Baltic Gas. A Swedish colleague, now retired from the Swedish Geological Survey, will work as a consultant to provide geophysical data from the Swedish sector of the Baltic Sea.
- no changes in the future working plan are expected,
- no changes are expected for the time frame of deliverables However, it is envisaged to publish mapping of acoustic information and distribution of shallow gas occurrences in a joint report of WP2 and WP3, as the product will be based on data mining as well as new data acquisition.

During the second project year a BALTIC GAS-workshop was organized in cooperation with the hosting institution Stockholm Marine Research Centre (SMF) at The Askö Field Station Laboratory (June 7 - 9, 2010). 24 participants from 11 BALTIC GAS research institutions attended the workshop. A meeting report with agenda and minutes from this workshop was delivered to the BONUS Secretariat and is accessible from the BALTIC GAS home-page (<http://balticgas.net>). This home-page has been up-dated recently with news and with brief information on BALTIC GAS research.

Task 1.2: Submission of data to a common database

In 2010 Hannes Grobe (data librarian of PANGAEA at the Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany) opened [PANGAEA \(http://pangaea.de\)](http://pangaea.de) up to Baltic Gas data of primarily biogeochemical nature. At the same time the BONUS Steering Committee accepted that Baltic Gas scientists use this database rather than SeaDataNet. Importantly, by using PANGAEA we ensure that not only metadata but also the original data are stored and maintained on the long term in an open database.

To ensure a reproducible format in all data sets delivered to the data base and thus facilitate data delivery to PANGAEA a 'data manger' (Henrik Fossing, Aarhus University) was appointed. The data manger receives, coordinates, and keeps track of the delivery of data from the Baltic Gas scientific community to PANGAEA in close dialogue with the data librarian. Several 'test' sets of data sets have tentatively been delivered to PANGAEA to find the best format before data finally have been uploaded to the data base. Presently data from the [RV Susanne A cruise](#) in Aarhus Bay (October 5, 2009) have been submitted to PANGAEA. An example of a data set from a 491 cm long gravity corer comprising 152 data points can be seen when activating this link: <http://doi.pangaea.de/10.1594/PANGAEA.755847>

Task 1.3: Research cruises

Three research cruises with BALTIC GAS participation have been performed during 2010 all organized by BALTIC GAS institutions in cooperation with the coordinator. In order of appearance these cruises were

- RV Susanne A (May 4, 2010) [BALTIC GAS-cruise](#). Chief Scientist: Henrik Fossing, National Environmental Research Institute, Aarhus University, Denmark. 5 participants/ 3 BALTIC GAS institutions. Cruise report published.
- RV Professor Shtokman (June 20-27, 2010) [BALTIC GAS-cruise](#). Chief Scientist: Vadim Sivkov, Shirshov Institute of Oceanology, Atlantic Branch, Russian Academy of Sciences, Kaliningrad, Russia. 2 participants/ 2 BALTIC GAS institutions. [Cruise report published](#).
http://balticgas.au.dk/fileadmin/balticgas/PShtokman_july_2010_cruisereport.pdf
- RV Maria S. Merian (July 31 – August 21, 2010) BALTIC GAS-cruise. Chief scientist: Gregor Rehder, Baltic Sea Research Institute Warnemünde, Germany. 29 participants/ 7 BALTIC GAS institutions. [Cruise report published](#).
http://balticgas.au.dk/fileadmin/balticgas/Merian_cruisereport_2010.pdf
- RC Limada (June 10 - 14) Field study campaign to Himmerfjärden. [BALTIC GAS-cruise](#). Chief Scientist: Volker Brüchert, Department of Geology and Geochemistry, Stockholm University, Sweden. 5 participants/ 2 BALTIC GAS institutions. Cruise report not published.

A brief summary of the research cruises incl. published cruise reports are available at the BALTIC GAS webpage.

Task 1.4: Ph.D-training program

A training BONUS-course *Seismo-acoustic Imaging of Sedimentary and Gas-related Features in the Baltic Sea* organized by University of Bremen, Germany, and University of Szczecin, Poland, took place in the Malkocin Conference Center of the University of Szczecin (Poland) and on board the Polish M/V Navigator XXI during 15-27 July, 2010.

Altogether 20 students participated of which 6 students came from the University of Szczecin (Poland) and 14 students were active in the BONUS-projects: Baltic Gas, Inflow and Hyper comprising the 'BONUS-institutions: Institute of Oceanology of the Polish Academy of Sciences (Poland), P.P. Shirshov Institute of Oceanology of the Russian Academy of Sciences (Kaliningrad, Russia), and University of Bremen (Germany).

During the three-day preparatory course the marine geology of the Baltic Sea was presented by an invited lecture (Jan Harff, IOW/US), and the relevant instruments and survey methods of acoustic surface and sub-surface imagery were introduced to both geophysicist and non-geophysicist participants. Discussions about cruise-planning strategies aimed to acquaint participants with considerations leading to flexibility and successful decisions in scientific cruise management.

The seagoing expedition on M/V Navigator XXI was carried out in the Polish waters of the Baltic Sea. Seismic and side scan sonar data were collected in the Pomeranian Bay, eastern Bornholm Deep and offshore Wladyslawowo during the cruise. During these days, participants gathered experience in equipment handling, data acquisition, processing of seismo-acoustic data, and using preliminary interpretations to aid cruise planning.

The expedition was followed by a two-day post-cruise evaluation workshop. Results were evaluated, put in scientific context, and collected in a preliminary cruise report. Cruise participants presented selected topics in short lectures, highlighting different aspects of new data from the perspective of regional geology. Main scientific results include indications of shallow gas found south of Bornholm, and the mapping of a basement fault zone in the eastern study area.

The course convinced us that a mixture of theory and practice taught in groups produces fruitful discussions between young scientists and enthusiasm as well as knowledge about the selected topic.

WP 2: Data mining and GIS-mapping

(reported by Jørn Bo Jensen, Geological Survey of Denmark and Greenland, Denmark)

Task 2.1: Data mining

- 2.1.1: Searching Baltic Sea methane data in national data-bases
- 2.1.2: Compiling data in a common database

Task 2.2: GIS-mapping

- 2.2.1: Mapping of mined data
- 2.2.2: Mapping of methane flux and distribution in sediments
- 2.2.3: Mapping of hot-spots of present and future CH₄-emission

No deliverables due within this reporting period.

Task 2.1: Data mining

Data mining has been done *within* and *outside* the project partners (i.e. Baltic Gas institutions) and is as such divided into two categories.

Data mining *within* the project partners is in good progress. Besides the already mapped areas in the Danish sector, data from IOW's archives are being processed in the first step concerning the Mecklenburg Bay, Arkona Basin and Bornholm Basin. In these areas no additional data from 'outside' are required but data that are collected during Baltic Gas will be included. In addition, IOW-data from the Polish sector, covering the Stolpe Forechannel and Gdansk Bay as well as data from the Gotland Deep will be processed during the project's third year. Methane distribution in the Russian sector is already mapped by the Russian Academy of Sciences and interpretation of Russian data from the rest of the Baltic Sea is in progress.

Data mining from *outside* the project partners has turned out to be more difficult than expected. An inquiry among geological surveys in the Baltic countries has revealed that search for seismic data and subsequently preparing and handing over these data to Baltic Gas comprise a workload that most geological surveys are not able to handle without additional resources. These institutions have been asked to estimate their costs for data handling but replies are unfortunately lacking. Most promising are responses from Swedish and Finnish institutions whereas seismic data from the Polish sector at present have been dropped as explained below.

The Swedish Geological Survey (SGU) represented by Ingemar Cato was visited for one day in early May 2010 by TR Jørn Bo Jensen. Ingemar Cato found Baltic Gas a very interesting project and Baltic Gas has been provided with maps of Holocene clay and sampling positions containing free gas. However, like the rest of the Baltic Sea surveys, SGU has had no tradition of mapping the distribution of methane gas in the seabed.

Tom Flodén, retired from The University of Stockholm, holds an extensive and scientific valuable database of seismic data from the central Baltic Sea. Tom Flodén has generously offered to share his data with Baltic Gas. However data must be reformatted before transfer to Baltic Gas which requires specific software and knowhow that only Tom Flodén possesses. For a minor cost Tom Flodén has offered to prepare his data for transfer to Baltic Gas and map the methane distribution in the Baltic Sea seabed covered by these data. TR Jørn Bo Jensen and Baltic Gas coordinator Bo Barker Jørgensen are currently discussing how to raise payment to secure this unique dataset for Baltic Gas.

The Geological Survey of Finland (GSF) has been addressed as a Bonus partner (i.e. Inflow) and has replied positively. Thus the TR plans to visit GSF during 2011 to discuss and get access to methane data from the Finnish sector.

The Polish Geological Survey (PGS) has been contacted in writing and asked for information about distribution of methane in the Polish sector seabed. The official answer from PSG is that they cannot supply information free of charge. This implies that Baltic Gas must pay for interpreting the archived Polish data and the subsequent transfer to the project. However, the TR Jørn Bo Jensen is of the presumption that 'mining' methane data from PSG cannot justify an accompanying payment because PSG-data will not contribute significantly to the Baltic Gas database compared to data from the Polish seabed already available within the Baltic Gas group.

Methane distribution data collected during Baltic Gas and 'mined' from the project partners are compiled at GEUS as a basis for GIS-mapping. At present the database holds methane distribution data sampled by Russian, German and Danish institutions and primarily covering the Baltic Sea sectors of these countries. Therefore, it is of particular importance that this database is expanded with Tom Flodén's methane data from the central Baltic Sea.

Task 2.2: GIS-mapping

The GIS mapping continued with integration of geodata derived from literature, reports, and data bases. The GIS ArcGIS 10™ (ESRI) is applied for mapping of mined data. Geodata from geochemical analyses of methane in sediments, pore water data of e.g. sulfate, as well as bottom water data were considered. Furthermore, data about sedimentation or bioturbation rates, as well as fluxes of particulate organic matter reaching the seafloor were integrated into GIS. Maps published in the literature or reports about potential hot-spots for present CH₄-emissions, such as pockmarks or gas flares, were digitized and integrated into the GIS. We have now started with the mining and integration of data considering subsurface structures like fault zones which could be potential conduits for fluids or gases.

In addition, literature references related to the methane cycle in the Baltic Sea were transformed into geodata, allowing a regional – instead of only an alphabetical – representation and analysis. Besides the representation in geographic coordinates, all maps were transformed into the Lambert azimuthal equal-area projection. Whereas the former supports the needs of the BalticGas partners, the Lambert azimuthal projection allows calculation of areas where e.g. free methane gas is observed. For selected areas the spatial coverage of shallow gas was calculated.

The GIS mapping, based on ArcGIS 10, is now converted into the public domain software ArcExplorer™ (ESRI). This will allow BalticGas partners as well as others to work actively with the GIS maps.

WP 3: Gas and seismo-acoustic mapping

(reported by Gregor Rehder, Baltic Sea Research Institute Warnemünde, Germany)

Task 3.1: Mapping and quantification of shallow gas by seismo-acoustic techniques

Task 3.2 Physical characterization of gas-bearing sediments

Task 3.3: Assessment of sites of sediment weakness for recent and future gas ebullition using multidisciplinary seismo-acoustic and sediment property data

Task 3.4: Detection and monitoring of gas bubble propagation through the water column and into the atmosphere in key regions of the Baltic

No deliverables due within this reporting period.

Task 3.1: Mapping and quantification of shallow gas by seismo-acoustic techniques

Single beam echosounder data (38, 200 kHz) in the Russian sector of the Baltic Sea, as well as in an area in Swedish waters north of Gdansk Bay, were gathered during RV Professor Shtokman cruise 103 from June 20-27, and enable a refinement of the areal extent of sediments underlain by shallow gas (~300 km²) and hosting pockmark structures (~1,7 km²) in the Russian sector.

The largest field expedition of the BALTIC GAS project, RV Maria S. Merian cruise MSM 16/1, covering nearly all major basins (Arkona Basin, Bornholm Basin, Gotland Basin, Bothnian Bay and Bothnian Sea), took place from July 30 to August 22. Acoustic information gathered comprises swath bathymetry data, multibeam backscatter data, multi frequency single beam data (5-100 kHz), Parasound data, as well as high frequency seismic data. The sediment acoustic work using the 5-100 kHz signal was focused in the western Baltic (Mecklenburg Bay, Arkona Basin and Bornholm Basin) on shallow gas hot spots, and reconnaissance surveys and detailed studies at newly discovered shallow gas hot spots were performed in the eastern Gotland Basin and northern Baltic Sea. Here, Parasound data were gathered simultaneously along all acoustic profiles. Extensive seismic data acquisition was focused on the known gassy part of the Bornholm Basin, as well as the Piltene depression west of the Gulf of Riga. For seismic data acquisition two streamers in three different configurations were used in order to collect data with high resolution and large offsets, necessary for precise imaging and quantification of shallow gas. In addition, a new method for spatial mapping of shallow gas using low frequency multibeam sonar backscatter signals was demonstrated. The sediment acoustic records were used to select stations for water column and sediment work during the cruise and the simultaneous recording of various systems will allow comparison of the responses of the different systems to the occurrence of shallow gas.

The annual student cruise of the University of Bremen with R/V Alkor AI363 took place during October 4 – 15, 2010, collecting new multi-frequency seismo-acoustic data with the goal of completing the existing data sets imaging shallow gas in the sediments. High spatial resolution surveys were carried out in the Mecklenburg Bay and the Arkona Basin. Data were collected using high-frequency seismic sources (airgun, boomer), fan sweep bathymetric equipment, and the echosounder system of the ship.

Processing and interpretation of the data is currently ongoing, and the integration of the acoustic data in the Baltic Gas common database is in progress. A first forward geo acoustic model based on the BIOT-STOLL theory was developed as a base for the quantification of shallow gas by seismo-acoustic techniques at IOW.

Task 3.2: Physical characterization of gas-bearing sediments

This task is mainly based on the extremely successful coring program performed during the expeditions POS 392 and MSM 16/1. The full core MSCL-loggings of all cores intended for physical property analyses are

finished. The split core logging, core description, subsampling and selected sedimentological analyses are still in progress. Core by core the data are calibrated, processed and used for the geo acoustic models and the interpretation of the seismo-acoustic records. The sediment physical core data will be integrated into the BALTIC GAS common database.

Task 3.3: Assessment of sites of sediment weakness for recent and future gas ebullition using multidisciplinary seismo-acoustic and sediment property data

This task is an end-deliverable of the project and will be based on the mapping of shallow gas occurrences and sites of current methane ebullition. During a brainstorming at the semi-annual meeting in Askö in early summer, it was discussed to use the model efforts within the project to further constrain future zones of weakness based on diagenetic models using external forcing parameters mimicking projected changes (i.e. eutrophication, warming etc.).

Task 3.4: Detection and monitoring of gas bubble propagation through the water column and into the atmosphere in key regions of the Baltic

The technical feasibility of gas bubble detection with WCI multibeam was demonstrated during expedition 392 of RV Poseidon and has been reported. However, continuous observation of the acoustic signals in the water column as well as compilation of existing observations have so far led to the picture that gas ebullition is of minor importance in the Baltic Sea (except for the Kattegat), as is the occurrence of pockmarks hinting to potential gas ebullition (with only one structure found in the Mecklenburg Bay, one in the Arkona Basin, and with the exception of the Pockmark area in the Russian sector). This is in accordance with the general observation of a strong gradient in methane concentration across the pycnocline, which would otherwise be “blurred” by the vertical ascent of bubbles. Based on the work performed within Baltic Gas, it can be argued that the low pressure shallow gas accumulations do not drive methane ebullition, that the few indications of gas seepage point to episodic emission and a strong seasonal bias (i.e. bottom water temperature), and are expected to strongly react to wind-driven water level changes.

WP 4: Biogeochemistry

(reported by Timothy Ferdeman, Max Planck Institute for Marine Microbiology, Germany)

Task 4.1: Methane distribution and geochemical in situ gradients

4.1.1: Sulfur biogeochemistry

4.1.2: Methane biogeochemistry

Task 4.2: Gas emission across sediment-water and sea-air interface

4.2.1: Methane flux and ebullition measurements

4.2.2: Hydrogen sulphide flux

4.2.3: Water column methane and ferry box surface methane measurements

Task 4.3: Methane and key biogeochemical processes

- 4.3.1: Quantify production and breakdown of methane
- 4.3.2: Analyze controls on relevant key geochemical processes
- 4.3.3. CH₄ and H₂S oxidation coupled to water column oxygen consumption

Task 4.4: Holocene evolution of the Baltic Sea ecosystem

No deliverables due within this reporting period.

The second year was characterized by continued sampling of the Baltic Sea to evaluate the distributions of methane, hydrogen sulfide and associated chemical parameters in Baltic Sea sediments (**Task 4.1 and 4.2**). Experiments were run on selected samples to estimate rates of methane turnover and sulfate reduction (**Task 4.3**). Furthermore, samples were collected for the evaluation of the Holocene evolution of the Baltic, including long cores and short cores for dating (**Task 4.4**). Sampling expeditions included:

- A return expedition to Himmerfjärden (Askö Marine Lab, Sweden) in June where scientists and students participated in a field campaign to obtain cores from the Himmerfjärden, an anthropogenically impacted fjord in the north-central basin of the Baltic Sea (**Task 4.1 and 4.2**).
- Extensive sampling of Aarhus Bay was performed during the Aarhus Bay Cruise (ABC2010) onboard RV Susanne A. Long gravity cores and shorter Rumohr Lot cores were taken for further geochemical work-up and for samples for experimental determination of rates (**Task 4.1 and 4.3**).
- The sampling highlight of the year was the major two-leg expedition onboard the German research vessel RV Maria S. Merian over 3.5 weeks in August, 2010. Surface multi-cores and deep gravity cores were obtained from the southern, central and into the northern Baltic reaches accompanied by CTD-casts and sampling of water column. Extensive gas, pore water, solid phase sampling and radiotracer experimentation on the retrieved cores were performed (**all WP4 tasks covered**).
- An off-axis integrated cavity output spectroscopy (ICOS) was installed in November 2009 on the cargo ship Finnmaid (Finnpartner) that commutes regularly between Travemünde (Germany) and Helsinki (Finland) in the Baltic Sea. A 2nd system was built to be used on board of research vessels and successfully monitored the gas concentrations along the ship track during RV Maria S. Merian expedition (**Task 4.2**)

Major research highlights from WP4 include:

- High resolution pore water sampling and analyses from both the RV Poseidon cruise 2009 and the RV Maria S. Merian expedition to Bornholm Basin reveal a deep flux of methane into the underlying clay sediments (as shown on Figure 1). The sink for the methane in these iron- and manganese-oxide rich sediments is not clear. However, radiotracer experiments was started on the RV Maria S. Merian cruise to elucidate mechanisms of the methane oxidation in these deep sediments but results are still underway (**Task 4.1 and 4.3**).

- Experiments combined with stable isotope measurements from samples taken in Aarhus Bay suggest that the sulfur cycle may be active in the methane oxidation process below the sulfate-methane transition zone (**Task 4.3**)
- Solid phase analyses combined with sulfur isotope analyses suggest that a major sink for reduced sulfur in the Baltic Sea appears to be organically-bound sulfur (**Task 4.3**)
- Methanogenesis experiments in the highly organic rich sediments of Himmerfjärden demonstrate that the highest rates of methane production (principally through bicarbonate reduction) are occurring just below the sulfate-methane transition zone. In Himmerfjärden, where sulfate penetration depths are very shallow this leads to a steep gradient of methane towards the surface sediments (**Task 4.3**)
- Continued deployment of floating, lagrangian, methane-gas flux chambers in the littoral regions in Swedish Baltic waters suggest that the littoral regions of the Baltic Sea have been underrepresented in estimates of fluxes of methane gas from the water column to the atmosphere (**Task 4.2**).
- On the RV Maria S. Merian expedition, the methane distribution in the water column was comprehensively assessed, revealing amongst other findings a drastic increase in bottom water methane concentration between the post bloom summer situation and the situation in the winter of 2009, in connection to the occurrence of a benthic nepheloid layer. Very low post-bloom surface pCO₂ values and distinct patterns of surface methane concentrations obtained from the surface survey using ICOS pointed to local sources (**Task 4.2**)
- Alternate dating methods, for instance the use of lead isotopes (lead pollution history) have led to a refined age-model for reconstructing Baltic Sea sedimentation and basin development (**Task 4.4**).

WP 5: Modelling and data integration

(reported by Pierre Regnier, Department of Earth Sciences, Utrecht University, The Netherlands)

Task 5.1: Modelling methane and sulfur dynamics

5.1.1: transport-reaction models

5.1.2: Predictive models (i.e. climate change scenarios)

Task 5.2: GIS-modelling

Task 5.3: Integrating gas, acoustics and biogeochemistry

No deliverables due within this reporting period.

Task 5.1: Modelling methane and sulphur dynamics

During year 2 of Baltic Gas, the development of the transient reactive-transport model (RTM) has been completed. The model has been applied to unravel the methane cycle in Arkona Basin (south-western Baltic Sea). The model was used to quantify the changes in production and consumption of aqueous and gaseous methane over the last 8000 yrs as a result of the marine transgression in the Baltic Sea (as shown on Figure

2). The relationships between the thickness of organic rich-muds, methanogenesis and AOM have also been investigated. A similar modelling study has been initiated in the gassy sediments of Aarhus Bay (together with Dr. A. Dale, IFM-Geomar, Germany) where high resolution profiles of concentrations and rates have recently been measured by Baltic Gas partners. Here, the focus is on how the flux and reactivity of organic matter controls the formation and depth of gassy layers, as determined by high resolution seismic images. The modelling tools will next be used to establish basin-scale and regional budgets of methane production and consumption in the Baltic Sea.

The RTM has been extended to include the oxygen and nitrogen cycles. It can simulate the effects of eutrophication on bottom-water oxygen drawdown, changes in bottom-water sulphate due to freshening of the Baltic, and changes in organic matter flux and preservation triggered by variations in productivity. Contacts have been established with other BONUS partners (at the EUTRO 2010 conference in Nyborg, Denmark (P. Regnier) and the BONUS workshop 'Uncertainties of scenario simulations' in Norrköping, Sweden (A. Dale) as we need environmental and climate change projections to force the RTM. The freshening and warming of the Bothnian Bay has also been identified as a potentially sensitive area for methane out gassing.

T 5.2: GIS- Modeling

For the spatial modeling of the potential distribution of methane in sediments of the Baltic Sea we combined geological as well as biogeochemical parameters forcing formation of methane within a geodatabase. For example, the data include sediment types, fluxes of particulate organic matter to the seafloor, concentrations of oxygen as well as sulfate etc. in bottom waters, occurrence of free gas, as well as fracture zones, along methane migrates from larger depths.

By GIS techniques like map algebra or overlay the spatial distribution of factors favorable for the formation of methane were derived. Furthermore we applied methods of Multicriteria Decision Analysis, like decision matrix.

For example, regions where muddy sediments occur, O_2 as well as SO_4^{2-} in the bottom water are low and pockmarks were observed have a high potential for enhanced CH_4 concentrations or free gas in the subsurface. Based on the derived GIS maps, gas distributions for each of the potential methane regions were calculated. According to this spatial modeling, 32% of the entire area covered by muddy sediments has a high potential for occurrence of free gas in the subsurface. The prediction by GIS modeling provided reliable results for regions like the Bay of Mecklenburg, Aarhus Bay or Eckernförde Bay where free gas is well known.

Nevertheless, additional data as obtained during the Baltic Gas cruises have to be included in order to improve the GIS-modeling. Furthermore, multi-variable statistics like CART will be applied. The model results will be cross-validated with field data from different regions of the Baltic to further improve the applied concept for spatial modeling.

Task 5.3: Integrating gas, acoustics and biogeochemistry

During the second year of Baltic Gas many new data have been obtained that will be the basis for a synthesis of the project. These data have been obtained in targeted areas that were chosen to highlight the main objectives of the project. At the present stage, a main focus is to ensure that these data are quality controlled and then entered into the data base PANGAEA. During 2010, the largest multidisciplinary research cruise of the project took place with the RV Merian throughout most of the Baltic Sea, from the Arkona Basin to the Bothnian Bay. This cruise has provided a wealth of new geochemical and geophysical data that provide an improved understanding of the controls on methane distribution and gas accumulation in the Holocene mud deposits. The general synthesis of data into GIS maps and models were discussed during the Baltic Gas Workshop on Askö in summer 2010 and the work is in progress. The GIS maps of sediment distributions, gas occurrence and methane distribution are based on a compilation of existing information, of which only a part is in the published literature, and on new results from the Baltic Gas research. The compilation and integration of new data for publishing will be discussed and coordinated during the coming Baltic Gas Workshop in Kaliningrad in February 2011. Results and conclusions from Baltic Gas will be presented during a special session on climate-active gases and gas emission at the coming Baltic Sea Conference in St. Petersburg in summer 2011.

Educational activities

BALTIC GAS educational activities during 2010 comprise a PhD-course and student participation in workshops and research cruises as outlined

- A BONUS-course on *Seismo-acoustic Imaging of Sedimentary and Gas-related Features in the Baltic Sea* took place at the University of Szczecin (Poland) and on board M/V Navigator XXI (July 15 – 27, 2010, see <http://balticgas.au.dk/balticgasaudk/workshopsandcourses/>). Altogether 20 PhD-students participated of which 6 students came from University of Szczecin (Poland) and 14 students were active in the BONUS-projects: Baltic Gas, Inflow and Hyper (for further details see *Task 1.4: Ph.D-training program*).
- Cruise planning workshop reg. RV Maria S. Merian cruise MSM 16/1 at Stockholm University and Askö Field Station Laboratory (S) (June 6 – 7, 2010). Altogether 7 PhD-students were introduced to and actively participated in planning of this major research cruise.
- BALTIC GAS workshop at Askö Field Station Laboratory (June 7 – 9, 2010) where 5 PhD-students presented their research results and were engaged in discussions and evaluations of the results.
- Three research cruises were performed during 2010 with participation of altogether 13 PhD-students. Particularly during the Maria S. Merian cruise MSM 16/1, PhD-students were trained how to handle heavy sampling gear for water and sediment sampling, seismo-acoustic imaging of the sea floor, onboard good laboratory praxis, recording a cruise logbook, and participation at onboard scientists meetings comprising research presentations, scientific discussions, general cruise logistics etc. The three cruises with PhD-participation were
 - RV Susanne A (May 4, 2010): 2 PhD-students
 - RV Maria S. Merian (July 31 – August 21, 2010): 9 PhD-students
 - RV Limada (June 10 - 14): 2 PhD-students

Stakeholder events and other related activities

The Danish Crown Prince Frederik and his wife, Crown Princess Mary, visited The Leibniz-Institute for Baltic Sea Research, Warnemünde (IOW) on September 28, 2010. The Danish Ambassador in Germany and representatives from Germany and Denmark at ministerial level participated in the visit. On this special occasion a booklet on Danish-German research collaborations in marine sciences was published by the Royal Danish Embassy, with preface written by Denmark's Minister for Science, Technology and Innovation (see <http://www.balticgas.net>). The booklet specifically mentions collaboration within the BONUS project BALTIC GAS.

The Maria S. Merian cruise MSM 16/1 (July 31 – August 21, 2010) was presented to the public through weekly reports, blogs and press releases and received significant public interest (see <http://www.io-warnemuende.de/fs-merian-2010-de.html>). Also, a small group of visitors was welcomed on board the re-

search vessel for a 12 hour cruise through the Kiel Canal (German: Nord-Ostsee-Kanal) by the end of the cruise.

BALTIC GAS research and results were presented at several meetings and conferences and were promoted through publications of peer reviewed scientific papers:

Meetings and conferences

Flury, S., H. Fossing, H. Røy, M. Lever, B. Gribsholt and B. B. Jørgensen. 2010. Enhanced methane fluxes in gassy sediments - a paradox? 10th International Conference on Gas in Marine Sediments, 5-10 August 2010, Listvyanka, Russia.

Gentz, T., M. Schlüter, R. Martinez. 2010. Identification of the regional distribution of gassy sediments in the Baltic Sea by application of Geo-Information-Systems. Bonus Annual Conference 2010, Vilnius

Jensen J.B. 2010. Major tectonic control of near bottom current sedimentation and methane distribution in the Bornholm basin, South-Western Baltic Sea. The 10th International Marine Geological Conference "The Baltic Sea Geology - 10", 24-28 August 2010, St.Petersburg, Russia

Jørgensen, B.B., S. Flury, H. Fossing, L. Holmkvist, J.B. Jensen, R.J. Parkes and the BALTIC GAS team. 2010. BALTIC GAS: Dynamic methane fluxes in the seabed. 10th International Conference on Gas in Marine Sediments, 5-10 August 2010, Listvyanka, Russia.

Jørgensen, B.B., H. Fossing and the BALTIC GAS team. 2010. BALTIC GAS: The dynamic methane fluxes in the seabed. BONUS Annual Conference, January 2010, Vilnius, Lithuania.

Mogollón, J.M., A. Dale, P. Regnier. 2010. Modeling the Holocene methane cycle in Arkona Basin sediments. 10th international conference of gas in marine sediments, September 2010, Listvyanka, Russia.

Mogollón, J.M., A. Dale, P. Regnier. 2010. Methane cycling in the Baltic Sea: Hindcast modeling at the 10 kyr timescale. Workshop on uncertainties of scenario simulations, October 14th, 2010, Norrköpping, Sweden.

Mogollón, J.M., A. Dale, P. Regnier. 2010. Methane cycling in the Baltic Sea: Hindcast modeling at the 10 kyr timescale. NSG Annual Symposium.

Regnier, P. (2010) Marine methane flux and climate change: From biosphere to geosphere. ICES workshop on models and regional climate change, January 2010. Brussels, Belgium (invited).

Regnier, P. 2010. Modeling biosphere-geosphere interactions: CO₂, CH₄ and the global seafloor carbon cycle. Introductory Lecture. Belgian Geological Society Annual Meeting, February 2010. Leuven, Belgium (invited).

Rehder, G., H. Fossing, L. Lapham, R. Endler, V. Spiess, V. Bruchert, T. Nguyen, W. Gülzow, J. Schneider von Deimling, D. Conley, B. Jørgensen. 2010. Methane fluxes and their controlling processes in the Baltic Sea, Poster presentation B41D-0328, AGU, San Francisco.

Schneider v. Deimling, J. 2010. Gas Mapping using Multibeam Mapping Sonar, Conf. Proceeding, Int. Conf. HYDRO 2010, Warnemünde.

Schneider v. Deimling, J., W. Weinrebe, D. Bürk, Z. Thot, R. Endler, H. Fossing, V. Spiess, G. Rehder. 2010. Subbottom mapping of shallow gas using medium to low frequency multibeam sounders. OS12B-03, AGU, San Francisco.

Peer reviewed scientific papers

Gülzow, W., G. Rehder, B. Schneider, J. Schneider v. Deimling, B. Sadkowiak. (submitted). A new method for continuous measurement of methane and carbon dioxide in surface waters of the Baltic Sea using off-axis integrated cavity output spectroscopy (ICOS), *Limnology Oceanography Methods*.

Regnier, P., S. Arndt, A. Dale, D.E. LaRowe, J. Mogollon, P. Van Cappellen, P. (in press). Quantitative analyses of anaerobic oxidation of methane (AOM) in marine sediments: A modelling perspective. *Earth Science Reviews*.10.1016/j.earscirev.2011.01.002, 2011.

Schmale, O, J. Schneider v. Deimling., W. Gülzow, G. Nausch, J. Waniek, G. Rehder (2010). The distribution of methane in the water column of the Baltic Sea, *Geophysical Research Letters*, 37, L12604, doi:10.1029/2010GL043115.