Bachelor Thesis

Stockholm University

Degree Project in
Marine Geology 15 hp

Investigation of the depth distribution of seafloor gas release based on single beam echosounder data collected in the Askö area in Sweden

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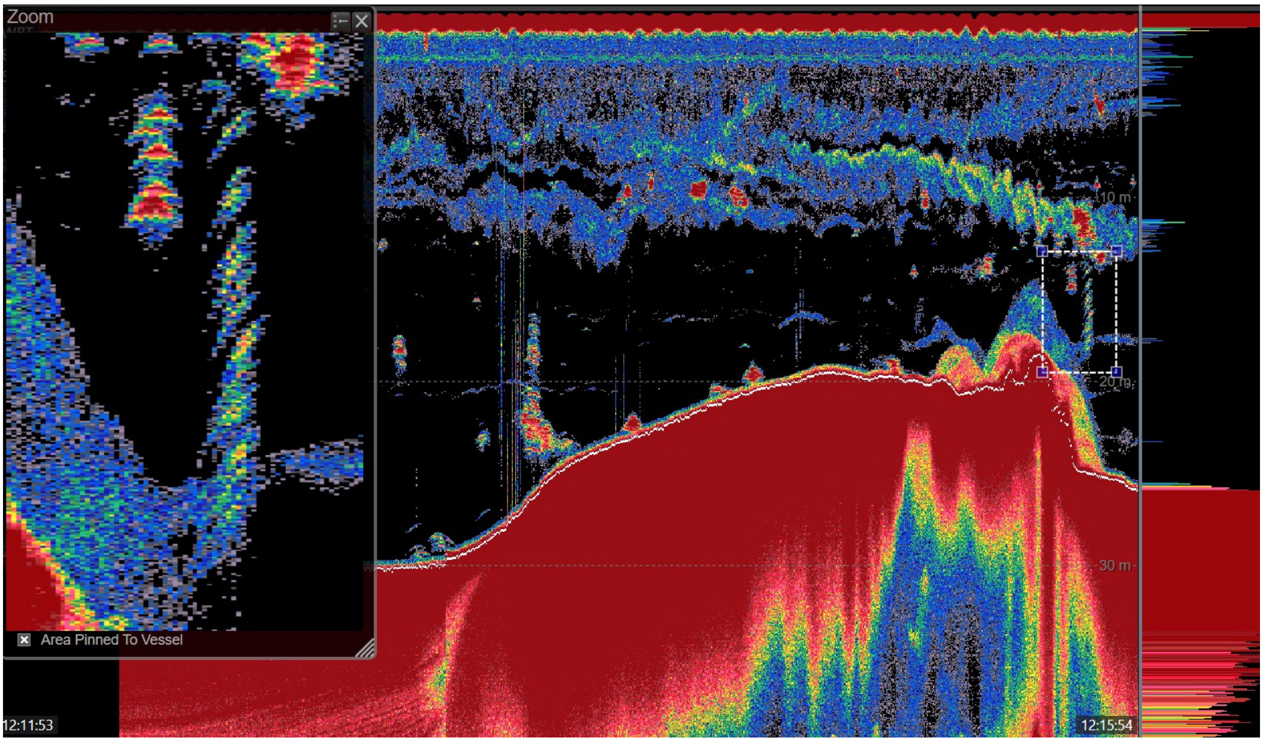

Stockholm 2024

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Abstract
Methane gas is a potent greenhouse gas that has the ability to affect global warming, and for that reason many previous studies have been done to measure and detect seafloor gas emissions. The aim of this study is to find out if there are any gas emission in the Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea and to find the position and depth distribution of such seepages. Data taken from two surveys in the Askö area are used: Survey 1 was done in September 2022 by Stockholm University and Survey 2 was done in May/June 2022 for the Swedish Radiation Safety Authority. In both surveys the data was acquired with a wideband split-beam echosounder called Simrad Ek80 with two hull-mounted transducers with center frequency at 70 kHz and at 200 kHz respectively. This echo sounder provides the ability to observe gas bubbles and seeps from the seafloor sediments. The results show that there are 76 observed gas seeps distributed in a depth interval of 7-30 m. The median of the depth of all detected gas seeps/bubbles in the Askö area is 14.67 m.

Sammanfattning

Metangas är en växthusgas som har en inverkan på den globala uppvärmningen och har av denna anledning undersökts i ett antal studier. Den tidigare forskningen har uppmärksammat mätning och detektion av gasutsläpp. Med utgångspunkt i den tidigare forskningen ämnar denna studie undersöka huruvida det finns gasutsläpp i Asköfjärden i södra Stockholms skärgård i Östersjön. Vidare syftar studien till att kartlägga djupfördelning av observerade läckage. Det samlade datamaterialet bygger på två undersökningar som är gjorda inom Askö-området. Den första undersökningen gjordes under september 2022 av Stockholms universitet och den andra undersökningen gjordes i uppdrag av Strålsäkerhetsmyndigheten under perioden maj till juni 2022. I båda undersökningarna genomfördes datainsamling genom ett bredbandsekolod för att kunna observera gasbubblor i vattenkolumnen. Ekolodet som användes är en Simrad EK80 med två skrovmonterade givare med en frekvens mellan 160-269 kHz och 45-90 kHz. Totalt var det 76 observationer av gasläckor som fördelade sig på en djupintervall mellan 7-30 meter. Däremot fanns det inga observationer utanför intervallen. Medianen för djupet för alla upptäckta gasbubblor i Askö området var därmed 14,67 meter.
Keywords: Simrad EK80, SBES, Methane gas, Seafloor gas emissions, Stockholm Archipelago, Baltic Sea, Water column, Global warming

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Introduction

The ocean is one of the most mysterious places in the world, covering more than 70% of the Earth while only approximately 20% of it has been discovered. Modern techniques provide the possibility to discover even the deep ocean with, for example, sonar systems, satellites, underwater vehicles etc. (Hayes & Pagao 2023)**.** In this study some of these modern techniques have been used to map out the methane gas emissions from Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea. Two surveys in Asköfjärden have been done in different periods, Survey 1 in September 2022 by Stockholm University and Survey 2 which was done in May/June 2022 for the Swedish Radiation Safety Authority. The acoustic water column data were analyzed with the Simrad EK80 software (v21.15) where data from both transducers (ES200 and ES70) were considered. Gas seeps or bubbles in the water column can be identified by the angle of inclination for individual bubble targets and the inclination of the whole gas seep/plume in cases where individual bubbles cannot be discerned. The understanding of gas bubble's/plume's structure is important because fish and fish aggregations can look very similar to gas bubbles and gas plumes that rise from the bottom. The measurement of the water depth beneath the survey track line is also estimated from visual inspection of the echograms.

The aim/purpose of this research is finding the answers to these questions:

1. Are there any seafloor gas emissions in the area of Askö? Where in the study area of Askö can gas seeps or bubbles be observed during the two surveys in May/June 2022 and September 2022?
2. At which seafloor depths are they most frequent?
3. What is the difference between collected data from May/June and September? What are the similarities?
4. Are gas bubbles, as observed with an EK80 single beam echosounder, limited to certain sediment type?
5. Compare the SBES result in this study with the corresponding MBES data from another study in the same area.

Theoretical background

1. Mid-water echosounders

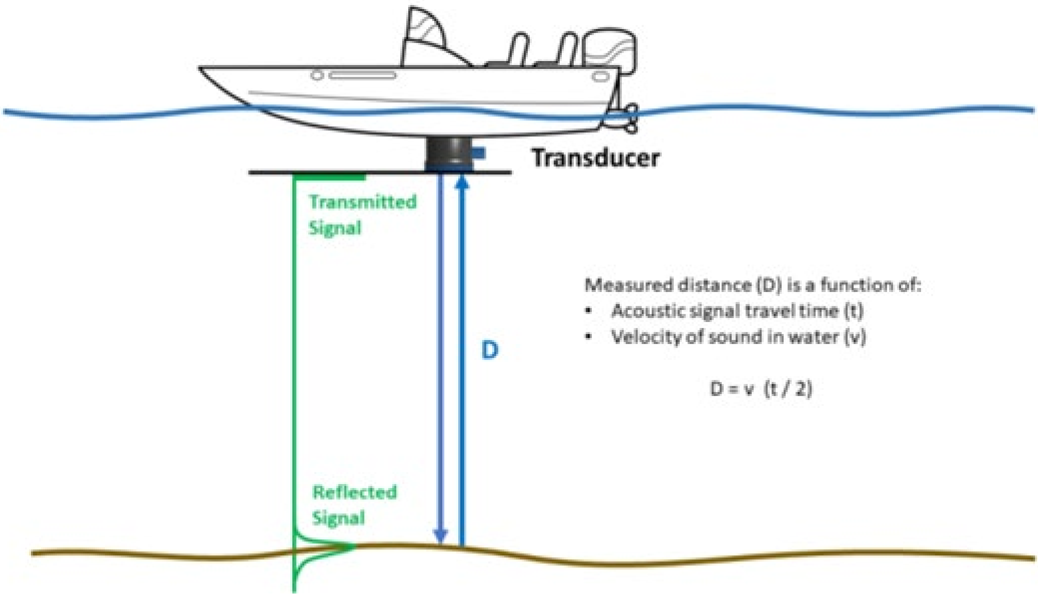

Figure 1 *Shows a vessel with a transducer, sending a sound pulse and receiving it by a receiver (Sanjeev n.d.).*

A well-established method for exploring and mapping the ocean and seafloor is the use of echosounders. Echo -sounding is based on a sound pulse that is transmitted by an acoustic source (called transmitter, Tx or projector) into the water down to the seafloor and being received by a receiver (or Rx) after reflecting from the seafloor or any target within the water column. The time it takes for the sound pulse to transmit and return after reflecting can be measured accurately (called TWT, two-way travel time), and with given sound speed (v) through the water column the depth (D) can be calculated as:

$$D = v \times (t/ 2)$$

All single-beam echo sounding (SBESs), multi-beam echo sounding (MBESs), sub-bottom profilers, seismic-reflection profiling and side-scan sonars methods share the same basic principle, although there are many differences in the errors, detailed mechanisms and interpretation possibilities between these methods (Jakobsson et al. 2016).

Echo sounding is a very important method for investigating the water column as well as determining the depth of the seafloor. Specifically, for the water column, it provides the possibility for detection of fish aggregations, biomass assessments, gas and oil leakage and target detection for military purposes. Two types of acoustic systems mainly used for acquiring information about the water column are *single beam echo sounders* (SBES) and *multibeam echo sounders* (MBES). SBES systems are designed to either record and display the backscattering from the vessel down to the seafloor or from the seafloor and down into the sediments and sub-bottom. The SBES system is considered a very useful tool for fish detection, seabed classification and for remote investigation as well as suspension matter analyses and target detection for military purposes. MBES systems are designed to determine the seafloor depth and cover a larger area (Deimling & Weinrebe 2014).

2. Geography and oceanography of the study area (The Baltic Sea)

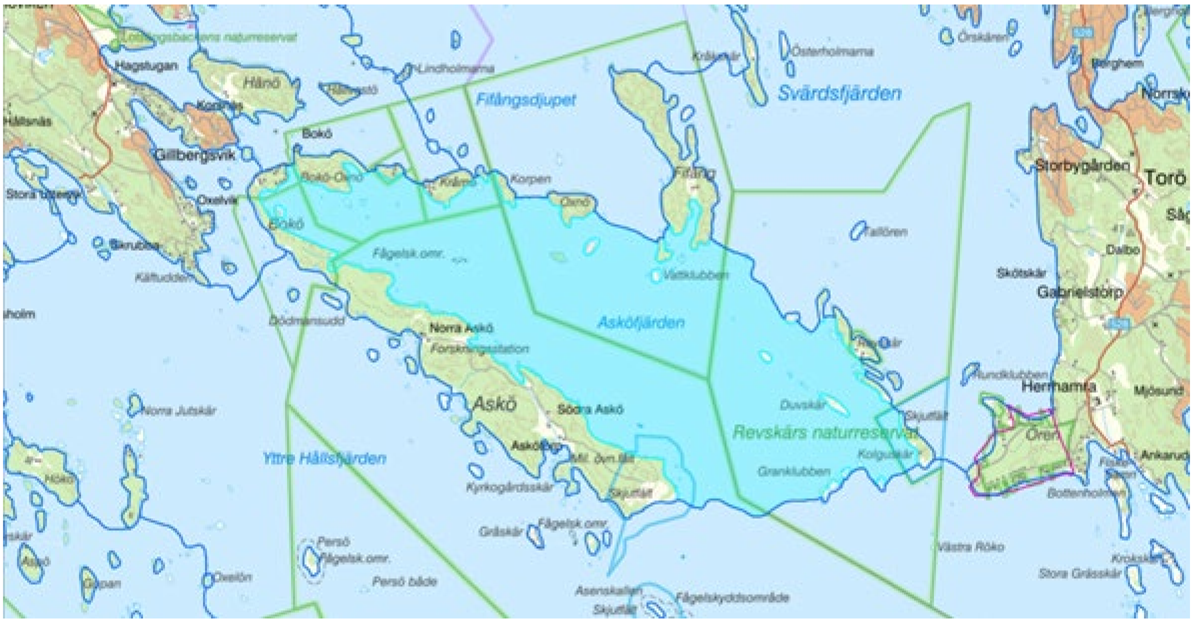

Figure 2 *A map over Asköfjärden. Taken from: (Lansstyrelsen.se)*

Both surveys were performed in Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea close to the island Askö. The Baltic Sea extends approximately from 10E to 30E longitude and 53N to 66N latitude. Tt is the largest inland sea in the world and defined as an arm of the Atlantic (Joseph 2023). The climate in the area of the Baltic Sea ranges from a humid and mild climate to subarctic climate. The currents can vary greatly, especially in the upper layers of water, because of the wind fields. Sea ice that occurs in the Baltic Sea every year covers the water and influences both wind-induced currents and sea-level variations. Baltic Sea currents can be determined by wind and thermohaline forcing which is strongly affected by ice coverage and seafloor topography. On average the surface circulation (as shown in Figure 3) of the water in the Baltic Sea is counter clockwise, where the currents induced by complex reactions happen between several things such as: wind stress at the surface, Coriolis force, water density thermohaline gradient, sea level tilt and tidal force but also the topography and friction of the bottom (Snoeijs-Leijonmalm et.al. 2017). It is not easy to measure sea currents, even in the past, due to the fishing activities and variability of wind-induced currents. In some cases the observational system of circulation pattern can be impossible in some areas of the sea. The wind field as said before is very variable with speeds reaching their maximum in December and occuring during November-March, the mean speed in December is 7-9 m/s. The minimum speed occurs during May and June and reaches 4-5 m/s. The mean direction of winds in the area of the Baltic Sea is east/northeast (Krauss 2001 p.282). The Baltic Sea is divided into several basins where each basin has a different depth, salinity and freshwater exchange, suspended and organic matter, different anoxic conditions, but also different sedimentation rate (Shahabi-Ghahfarokhi 2022 p.7). Sedimentation rate can be defined as the amount of material that is deposited over a certain time interval. Measurement of the sedimentation rate can be done by calculating the vertical accumulation or the sediment density over time (OzCoasts. Taken 01-20-2024).

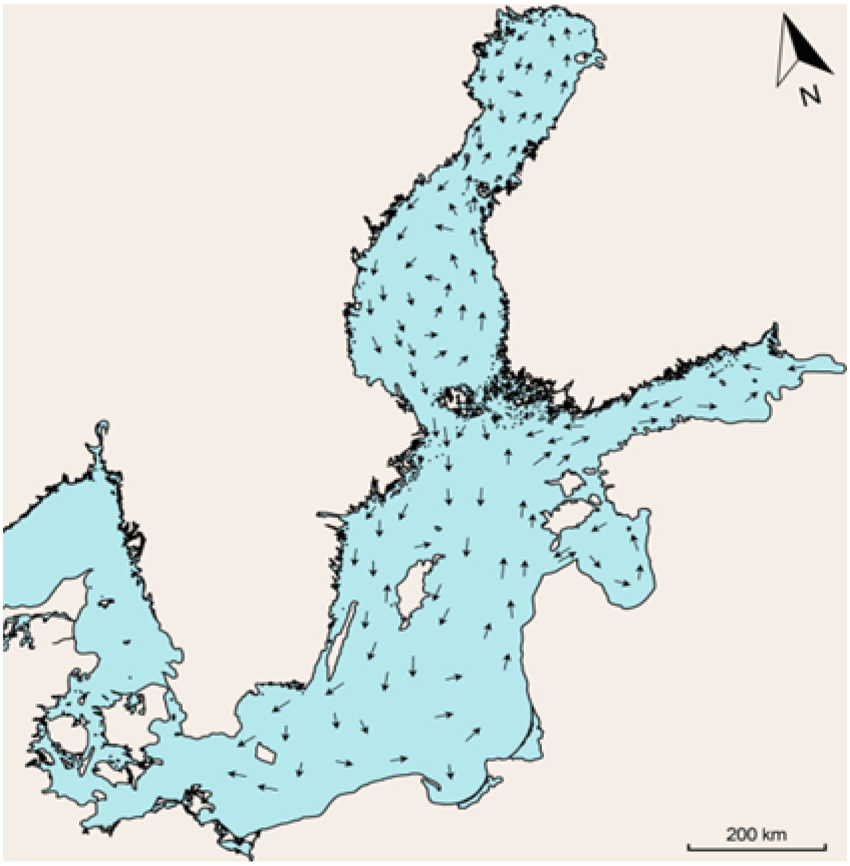

Figure 3 Shows the surface water currents in the Baltic Sea *(Snoijes-Leijonmalm et al. 2017)*

In the Baltic Sea Basin younger sediments cover the bedrock gradually. Tills which are unsorted sediments that have been deposited during the ice ages can fill up the Basins of the Sea. As well as tills, glaciofluvial deposits of gravel, sand and stones can be found on top of bedrock as remnants of systems of the glaciofluvial. Coarser glaciofluvial and tills deposits are covered by glacial clay which makes the glacial and postglacial deposits over 100 m in thickness (Snoejis-Leijonmalm et.al. 2017 p.34). The youngest sediment in the area consists of postglacial mud which is an organic rich and fine-grained material. The seabed sediments in the Baltic can be subdivided into two types: 1) depositional and 2) non-depositional. Depositional is where the sediments accumulate, while non-depositional is where transportation and erosion occur. In some parts of the Baltic Sea, especially in the north where there are on-going uplift shifts in land due to erosion, and where new areas appear above the wave base, the boundaries between the non-deposition and deposition are not constant (Snoejis-Leijonmalm et.al. 2017 p.34). Postglacial mud can accumulate in both the area with deep water and in sheltered coastal embayments. Glacial mud from the other side accumulates at the edges of these areas of deep water, while in areas with shallow water sand and coarse sediment accummulate, particularly at the coasts. Gravel (coarse sediment) is deposited by the ice sheets as till or is originally from the glaciofluvial. This gravel can be found along the rocky coasts of both Finland and Sweden. The sediment composition of the Baltic Sea can be seen in Figure 4 (Snoejis-Leijonmalm et.al. 2017 p.34).

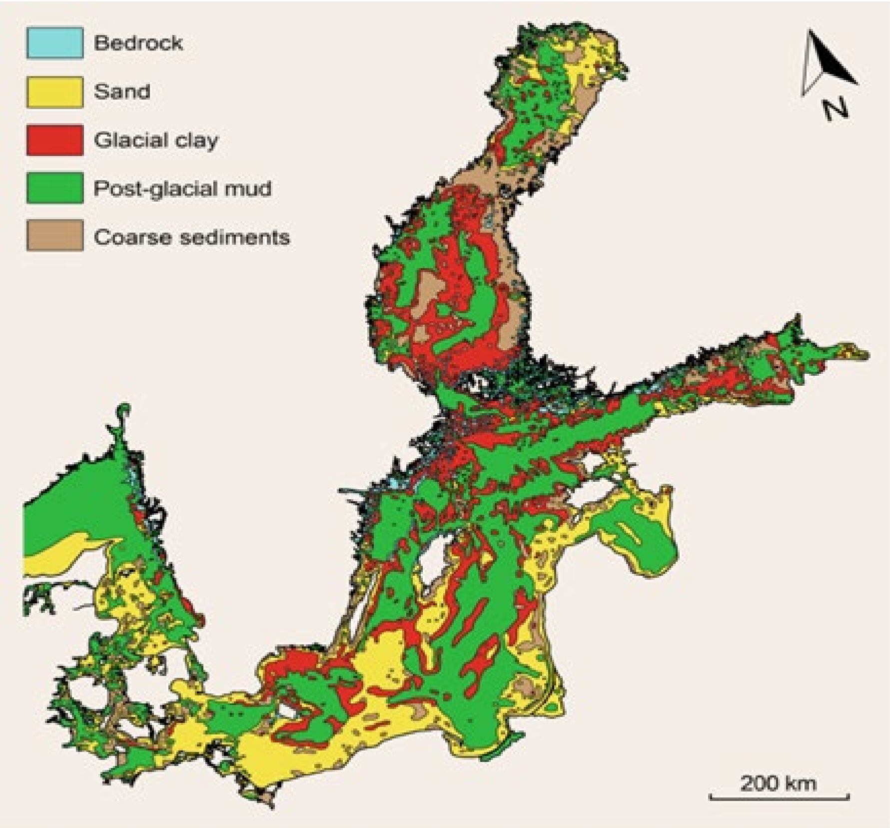

Figure 4 Shows the sub-bottom material of the Baltic Sea *(Snoijes-Leijonmalm et al. 2017)*

3. Methane gas formation in the Baltic Sea

The sedimentary (both glacial and postglacial) of the Baltic Sea can be characterized by 10 fine-grained layers, consisting of organic rich mud and clay. The major source of the methane gas in the Baltic Sea is the methanogenesis of the organic matter, mostly in the surface sediment rich in organic content. In the anoxic surface sediments methane concentrations can be controlled by production and degradation of methane by the bacterial oxidation. Both seep areas and pockmark structures can be sources for methane gas releasing into the water column. The riverine input, formation in the upper water column, and groundwater discharge can be additional methane sources that affect the concentrations of methane in the sea surface (Gülzow et al. 2013). There are three ways to transport the methane that is generated in sediment into the water column: by fluid flow, bubble transport and diffusion. Methane can be observed in the Baltic Sea with low concentrations close to the sea surface and high concentrations in the deeper layers. During the transport methane gas usually gets reduced by methane oxidation especially in the oxic and anoxic layer (Gülzow et al. 2013). In the Baltic Sea severe eutrophication has been undergone, eutrophication being the process where the nutrients increase in the water body and sediments. Microorganisms on the sediment surface degrade the organic matter and the sediment becomes hypoxic (low oxygen condition) and some areas become anoxic (oxygen free). These areas are called dead zones (Broman el al. 2017). In the Stockholm archipelago many deep bottom parts turned to be anoxic because of the eutrophication. The increased input of nutrients caused anoxic conditions in the deep soft sediments (Schiewer 2008 p. 324-325).

4. The exploring of methane gas emission by using marine geophysical methods

Because methane gas is a greenhouse gas and has the ability to affect the climate and lead to global warming, many studies in different ways have been done to detect, observe and measure the methane gas emission from the marine sediments. A study has been done since 1992 (Söderberg & Flodén 1992) in the Stockholm Archipelago in Baltic Sea to explore the gas eruption and gas seepages at the seabed. This study gave evidence of releasing gas seeps in crystalline bedrock along the tectonic lineament. The methods used in this study are acoustic echo sounders, continuous seismic reflection with a frequency between 450-900 Hz, side scan sonar with frequency at 100 kHz and 500 kHz and echo sounding at 30 and 4 kHz. Further measurements and observations were done by using sonobuoy refraction shooting and diving. 60 gas seeps had been found in that area by using acoustic mapping methods and many of these seeps had been inspected in detail by diving (Söderberg & Flodén 1992).

Another study was done in 2018 to determine the size of an individual bubble and the number of bubbles by using acoustic geophysical methods and remote sensing. In the vessel a Simrad EK80 wideband transceiver was utilized with a vertical resolution of 7.5 cm and operation between 16 and 26 kHz. The study was done in the East Siberian Arctic Sea (ESAS). It is an important area for studies of climate changes due to the massive methane reservoir in the area (Weidner et al. 2019 p.104-115). The same year the study was performed, in the summer of 2018, a study was done in the Baltic Sea when the water temperature reached the highest temperature since 1926 due to the heat wave. Measurements of CO2 and NH4 concentrations in surface water have been done by cavity ringdown spectrometers. The data of the water column has been collected by acoustic geophysical methods by RV-Electra, which belongs to

Stockholm university. The results of this study showed that the heat wave led to fluxes in the emissions of CO_2 and CH_4 in the coastal zones of the sea (Humborg et al. 2019).

Methods

1. Data collecting

1.1 RV-Electra

Data has been collected by RV- Electra, a 24.3 meter long and 7.2 meter wide research vessel with a 31 m^2 lab which has a dedicated area where the CTD and other mapping systems launch from. The vessel has dynamic positioning allowing station keeping and many acoustic echo-sounders, such as a midwater sonar, sub-bottom profiler and multibeam echo-sounder, but also an ADCP. Acoustic mapping systems in RV-Electra are operated from a control room in the ship. By using core launching arrangements and dedicated winches from the aft deck, coring and sampling can be carried (Jakobsson et al. 2021).

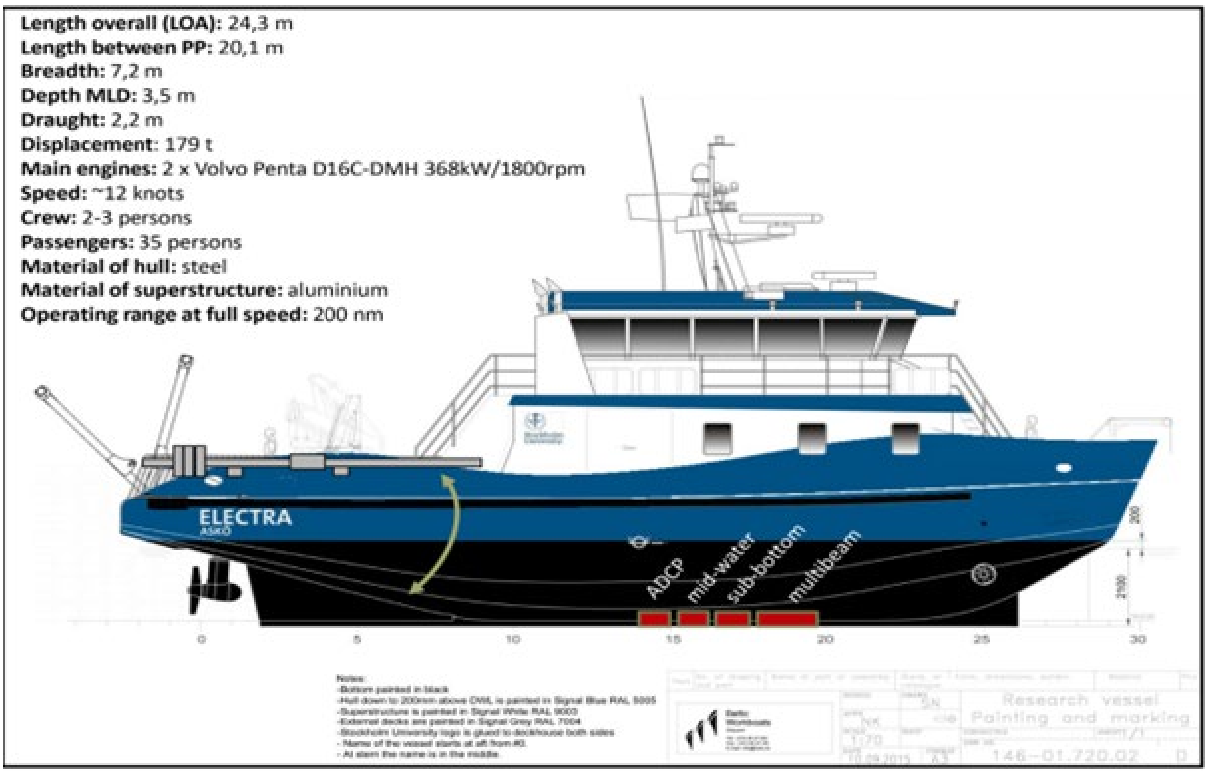

Figure 5 The figure above shows the vessel RV-Electra and information about it (Jakobsson et al. 2021).

The table below in Figure 6 shows a summary of the technical specifications of mapping equipment, navigation system and motion sensor in RV-Electra vessel. It also shows the individual systems and further description (Jakobsson et al. 2021).

Multibeam: Kongsberg EM2040, 0.4°x0.7°, 200–400 kHz (max depth 600 m)
RTK GPS: Kongsberg/Seatex Seapath 330+ (Position accuracy xy ±1 cm + 1 ppm RMS, z ±2 cm + 1 ppm RMS, heading accuracy 0.05°)
Motion sensor: Kongsberg/Seatex MRU5+ (heave/pitch/roll)
Sub-bottom profiler: Kongsberg Topas PS40, 24ch, parametric (35–45 kHz/1–10 kHz)
Midwater split-beam sonar: Kongsberg EK80, 70 kHz/200 kHz
Side-scan: Klein 5000 V2, 455 kHz
Acoustic Doppler Current Profiler (ADCP): Teledyne Workhorse Mariner, 600 kHz
SVP (Sound velocity/pressure): Valeport (mounted in the hull)
SVS (Sound velocity sensor): Valeport MiniSVS
CTD: Seabird 911+, including conductivity, temperature, pressure, dissolved oxygen, turbidity, fluorescence (Chlorophyll A) and PAR sensors
GoPro Camera mounted on CTD and in a water proof casing with two separate light sources
Piston corer, 6 m long loaded with 473 kg led weights
Grab sampler

Figure 6 Mapping equipment, navigation system and motion sensor in RV-electra vessel (Jakobsson et al. 2021).

1.2 Water column mapping with acoustic methods

1.2.1 Position, heading and attitude:

Water column and all other echo-sounders mapping systems in RV-Electra receive positions, attitude and heading from a system called Kongsberg Seapath 330+. This system includes a reference unit, MRU5+ motion and two antennas, GPS (global positioning system) and GLONASS (global Navigation Satellite System). Kongsberg Seapath 330+ system is dual frequency and has the ability of using RTK (Real Time Kinematic) corrections (Jakobsson et al. 2021).

1.2.2 Midwater sonar:

In the RV-Electra vessel wide-band system "Simrad EK80 " is installed. The data of water column broadband can be collected by two split-beam transducers with a 7°circular beam, the first one is Simrad ES200-7C and the other one is Simrad ES70C-7C. Both transducers pinging at the same time and their frequencies ranging between 160-269 kHz and 45-90 kHz. The transmit power for the transducers differs depending on the transducer, for the ES200-7C it sets to 150W while for ES70C it is set to 750W. The pulse length is not the same either, for the ES200-7C it sets to 8ms, while for ES70C it sets to 4ms. By using Kongsberg's software version 1.8.3, the EK80 system can be operated. All the data of EK80 can be processed by using a series of Matlab scripts provided by Kongsberg Maritime (Jakobsson et al. 2021).

EK80 system is a wideband system with a wide selection of high-quality transducers and transceivers and has an operational range (between 10 - 500 kHz). The system also has the ability for storage of raw data for analysis and replay (Kronsberg. Taken 09-13-2023).

1.2.3 ADCP (Acoustic Doppler Current Profiler):

In the water column it is important to measure both the vertical and horizontal ocean current components, this type of measurement can be done by a hydroacoustic instrument called an ADCP. It is mounted furthest aft of all acoustic mapping systems in the vessel and installed with a transducer set at 600kHz (Jakobsson et al. 2021).

2. Data processing

The collected data of the water column echosounders in both surveys is raw data and needs a series of operations to analyze, organize and transform it into usable information. In this study the raw data has been analyzed by using a software called Simrad EK80 (v.2.0.0).

EK80

EK80 files include data about fish, fish aggregations and gas bubbles that rise from the bottom and in the water, it also includes the thermohaline stratification that can be identified in the data. The EK80 files (.raw format) used in this study are taken from two surveys. The aim is to detect gas bubbles, gas trains or gas plumes that can be found in the water column of both surveys. In the profile of the water column gas bubbles and gas seeps can be found between the fish and fish aggregations and other features which may make the detection of gas difficult. For this reason, it is important to have understanding about the bubbles and gas seeps/plumes structure in the water column profile. Gas seeps or bubbles in the water column profile can be identified by the angle of inclination for each individual bubble and the inclination of the whole gas seep/plume. The structure of gas bubbles appears like three or more thin, horizontal lines above each other as a vertical grouping (as shown in Figure 7 and 8). They can be straight lines, bent like bows or even straight with a positive slope. The bubbles are tilted because they rise continuously in the water, the tilt occurs when the bubble rise slightly in between each ping of a series of pings on the same bubble. Water column features can be identified in the ES200 echogram or ES70 echogram, depending on the clarity of features.

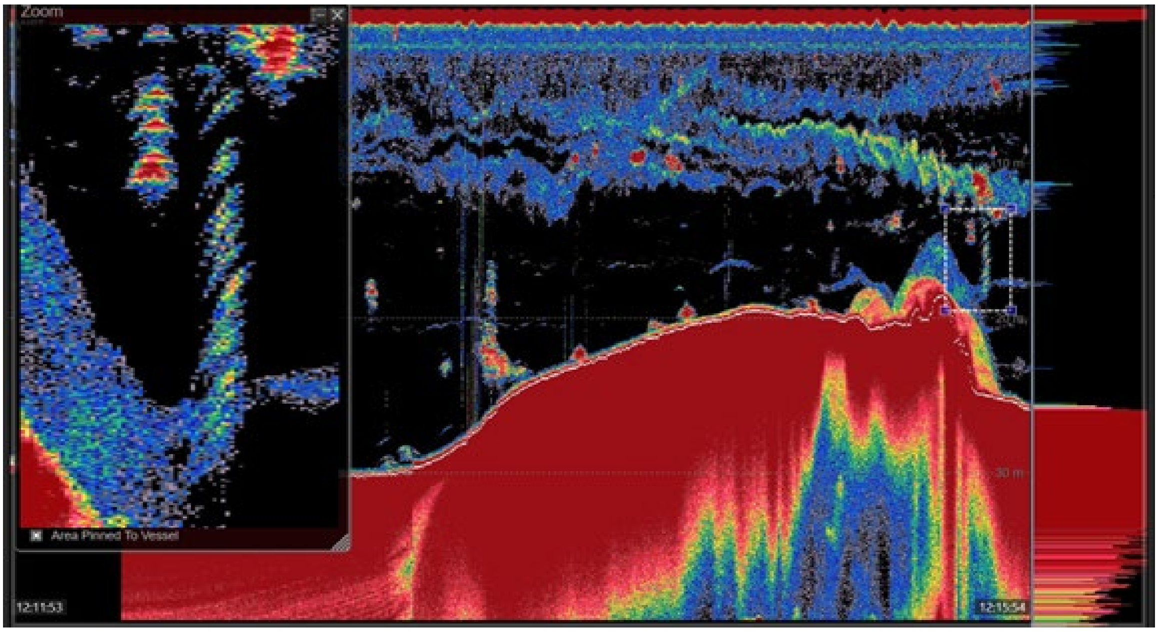

Figure 7 ES70 echogram from EK80, shows a methane gas plume.

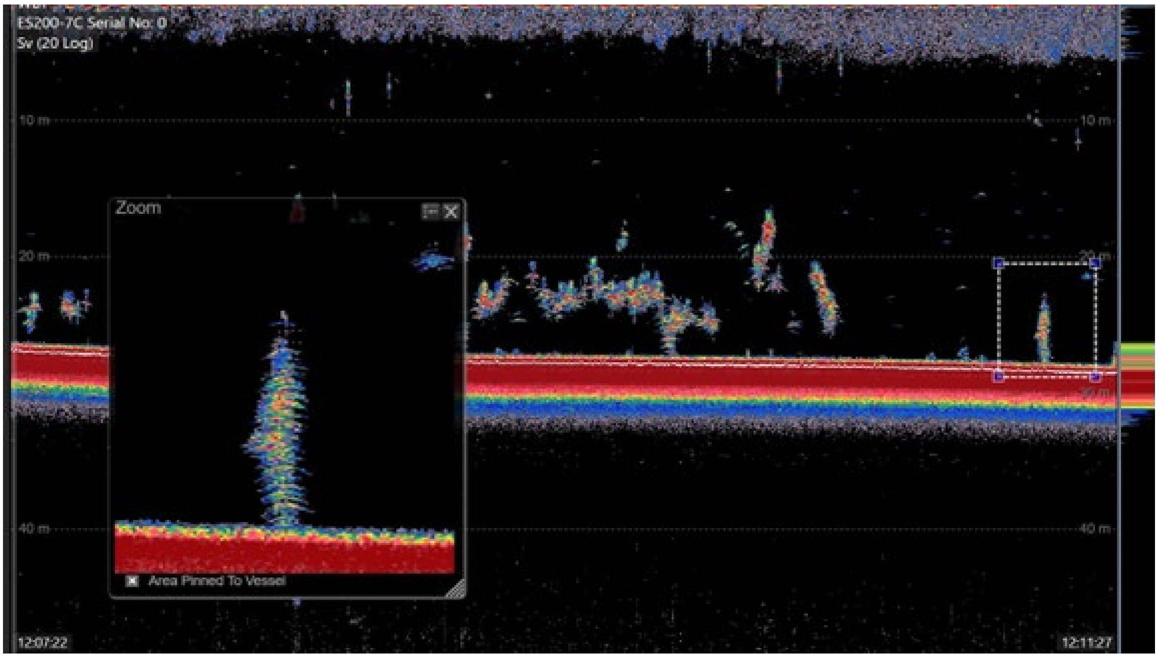

Figure 8 ES70 echogram from EK80, shows a methane gas plume.

The structure of gas bubbles or seeps can be easy to see or otherwise observe, as the example in Figure 7 and 8, because of the size and clarity. In other cases, it is not that easy to identify, because there are many fish groups and targets that look very similar to gas seeps. In Figure 9 there are fish groups that look very similar to the gas seeps, but the angle of inclination is bent to the right instead. Observing gas bubbles is more difficult than observing gas seeps, because gas bubbles consist of only a few lines above each other and can be mixed with the fishes around as in Figure 10.

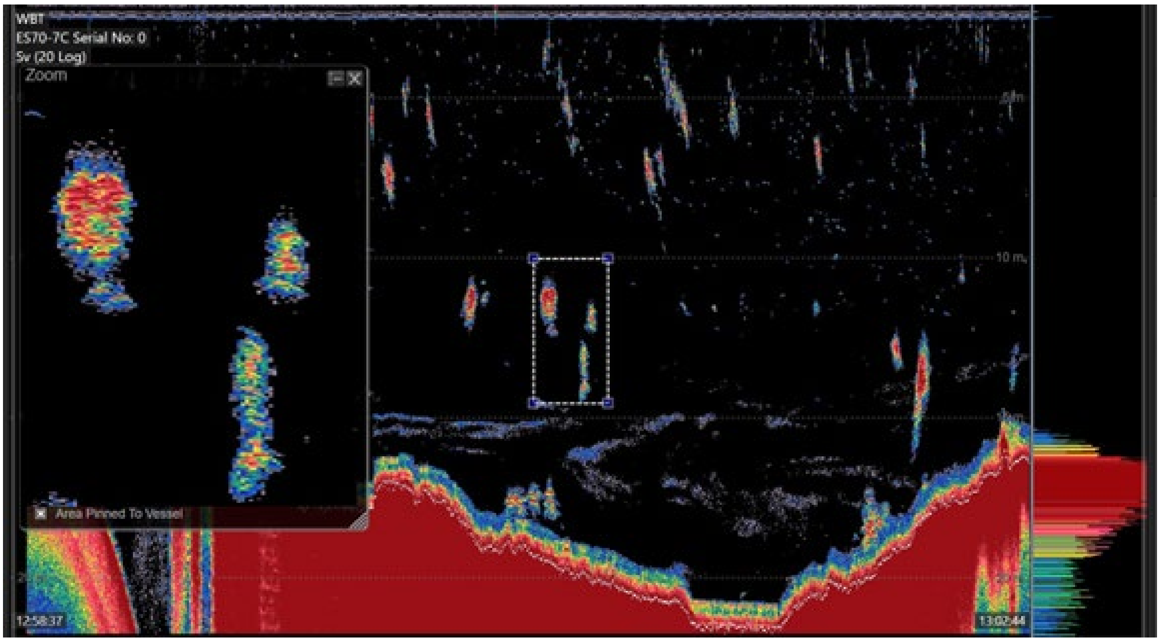

Figure 9 ES70 echogram from EK80, shows fish aggregations in different ways.

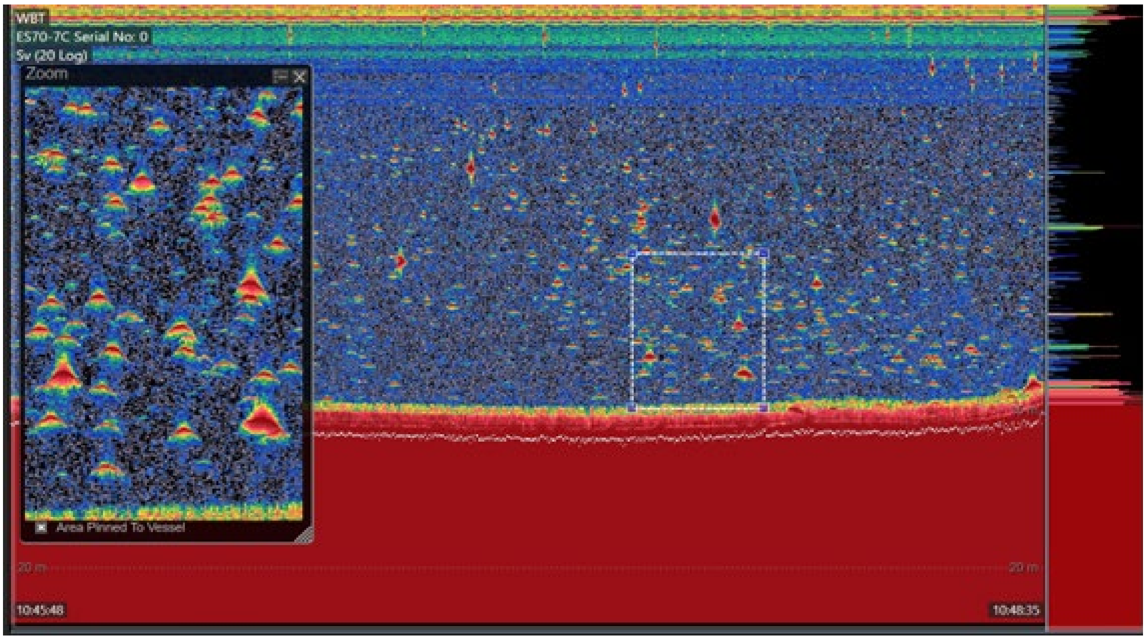

Figure 10 ES70 echogram from EK80, shows fishes and fish aggregations.

For several reasons the data can be very unclear as shown in Figure 11, in which case it is very difficult to analyse the water column data. Not only are structures difficult to see but also the seafloor depth.

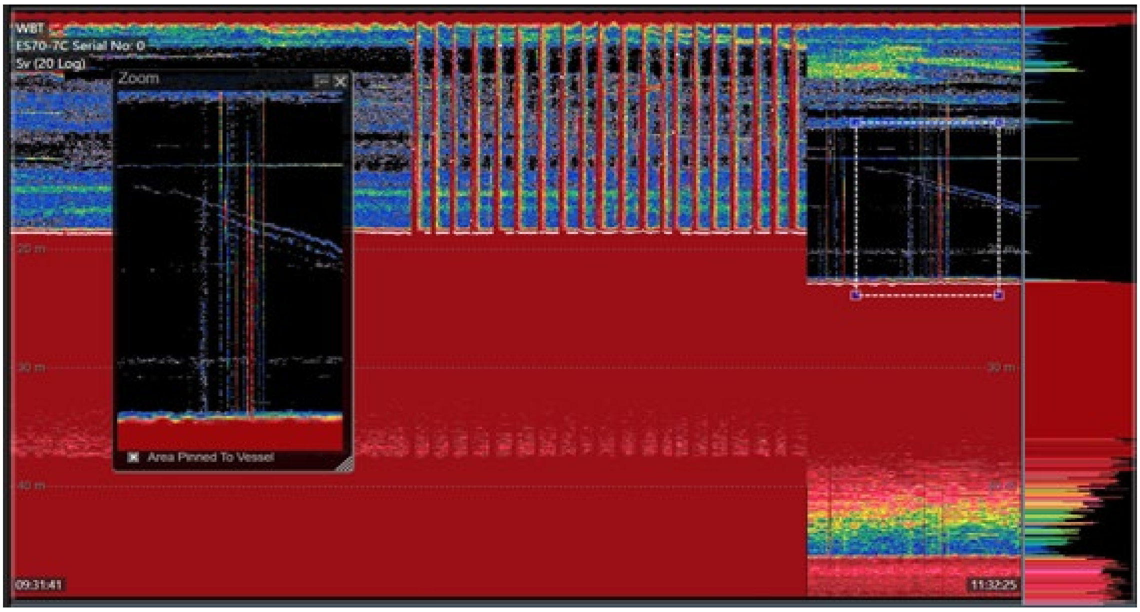

Figure 11 ES70 echogram from EK80, contains unclear data of the water column.

The most important part of detecting the gas bubbles or seeps is to note the position and depth for every gas seep. Depth that has been noted is the deepest point of the gas seep (in water column) and the depth of the seafloor below that seepage. The position was noted for both latitude and longitude positions. The longitude- and latitude lines are defined as measuring lines of the Earth surface positions and can be expressed as degrees of a full circle (which contains 360°) because they are angular measurements. Each degree of the full circle is divided into 60 minutes and one degree of the latitude is about 69 miles, one minute is divided into 60 seconds and is about one mile while one second is just about 100 feet. There are several ways to write the longitude and latitude measurements, it can be written as (degrees° minutes′ seconds") or (degrees°. minutes′ seconds") or even as (degrees° minutes′. seconds") (nwcg.gov). In the Simrad EK80 the position of the latitude and longitude is in the DMM (degrees, decimal minutes) format which must be converted to DD (decimal degrees) format. The DD format makes it possible for the QGIS to read the position. To convert the position from DMM to DD, the decimal minutes must be divided by 60.

Results

The results review the observed gas seeps in both surveys in the Asköfjärden: Survey 1, which was done in September 2022 by Stockholm University, and Survey 2, which was done in May/June 2022 for the Swedish Radiation Safety Authority. The histograms below show the number and the depth of observed gas seeps in both surveyed areas in Askö. It also shows the water depth along the cruise track of both surveys. Gas seeps that were detected in EK80 echograms in Survey 1 were mostly a few gas bubbles in vertical grouping (mostly consisting of only three or four samples (sample: horizontal line in the echogram)) in the water column. While gas seeps from Survey 2 were easier to observe because the structure was more like a seep or a plume, big, and the angle of inclination was clearer to see. The positions of each detected gas seep and cruise track has been shown in the maps below. Sub-bottom material in the study area of Askö is also reviewed in a map below. All maps are done in QGIS (version 3.28.5) in the UTM (Universal Transverse Mercator) projection zone 33 with the coordinate reference system SWEREF99 TM.

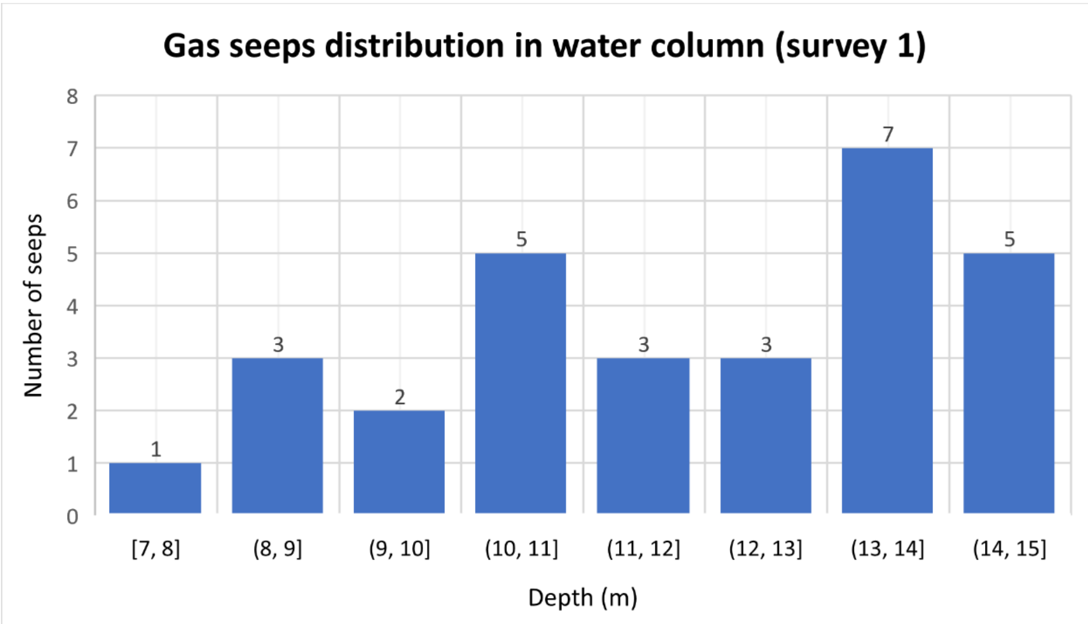

Figure 12 Histogram shows observed gas seeps emissions in the water column from Survey 1 in the Asköfjärden. X-axis = depth of observed gas seeps, y-axis = amount of the observed gas seeps.

The histogram in Figure 12 shows 29 gas seeps found in different depth intervals between 7 m and 15 m. As the histogram shows, gas seeps are mostly found in the depth interval 13-14 m (there are 7 gas seeps observed there) and between 10-11 m (5 gas seeps) and between 14-15 m (5 gas seeps). Of gas seeps in depth between 7-8 m there is only one. There are fewer gas seeps at shallower depths. The median of the depth where the gas seeps are found is about 12.56 m.

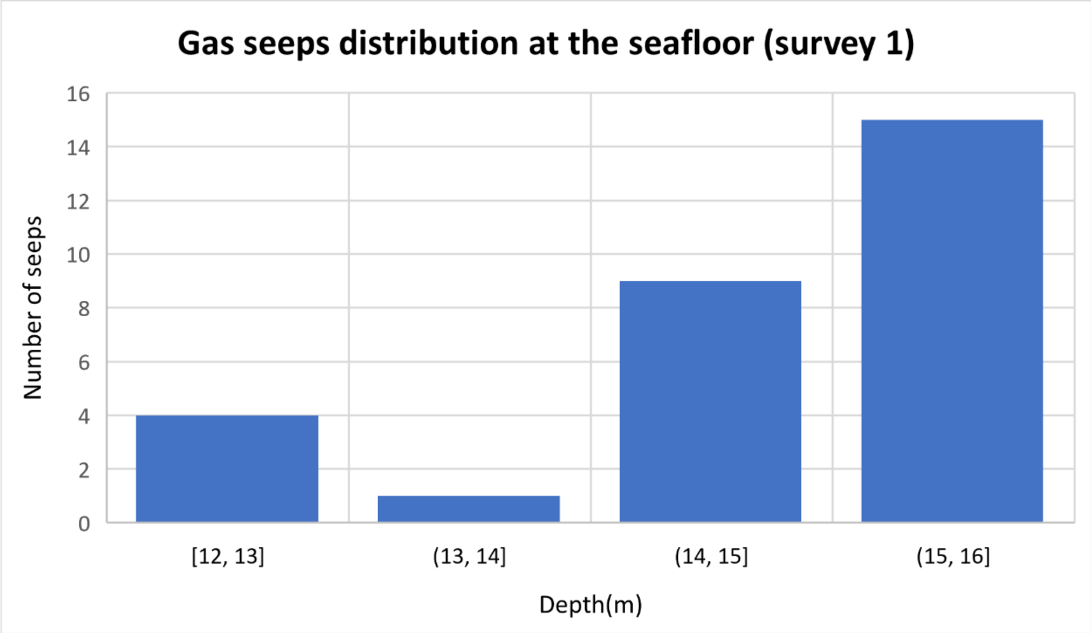

Figure 13 Histogram shows the depth of seafloor where observed gas seeps were releasing from Survey 1 in the Asköfjärden. X-axis = seafloor depth below the observed gas seeps, y-axis = amount of the observed gas seeps.

The histogram in Figure 13 shows the depth of the seafloor where observed gas seeps been released from in Survey 1 (29 gas seeps). The depth of the gas seeps at the seafloor ranging between 12-16 m, mostly observed between 15-16 m (15 seepages). The median of the depth of the gas seeps close to the seafloor is about 14.71 m.

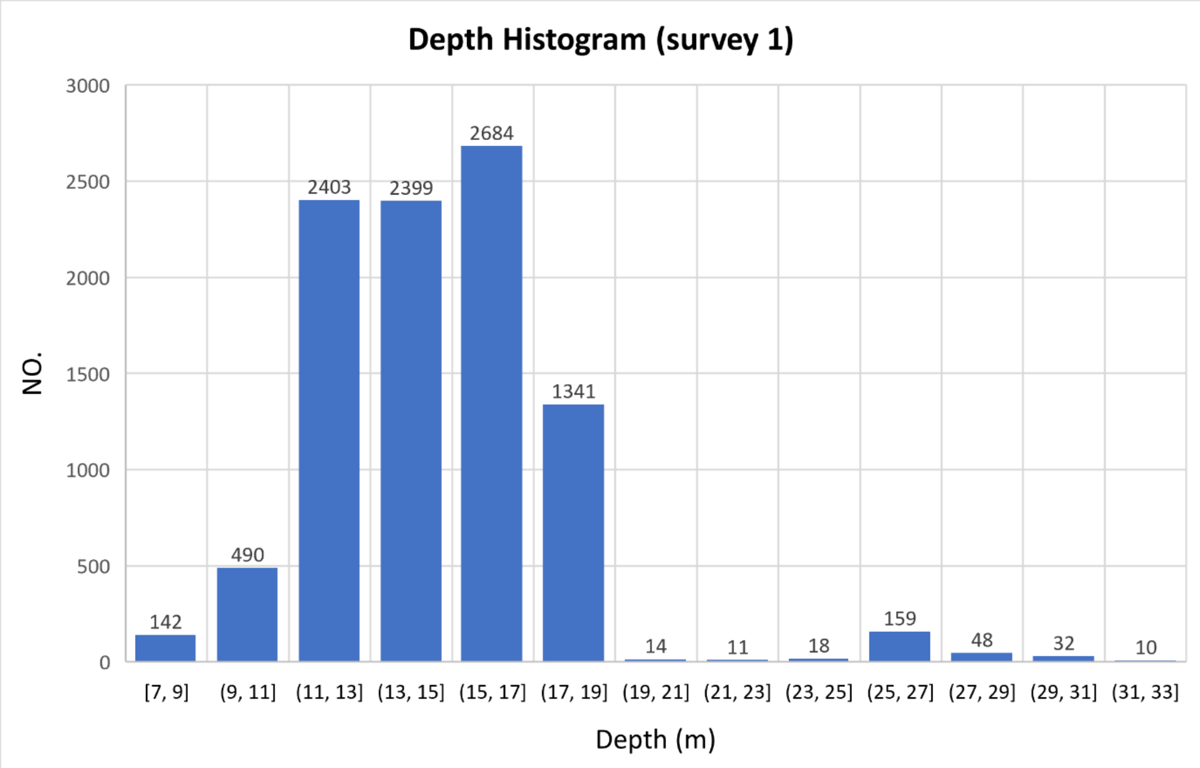

Figure 14 Histogram shows water depth from Survey 1 in the Asköfjärden in the southern Stockholm Archipelago. X-axis = water depth of areas determined with SBES, y-axis = amount of the determined areas.

The histogram in the Figure 14 shows all the water depth areas that have been measured by SBES along the cruise track of the Survey 1. There were about 9751 noted water depths ranging between 7-33 m. As the histogram shows water depth is mostly between 15-17 m in the study area of Survey 1. The median of the water depth in Survey 1 is 14.33 m.

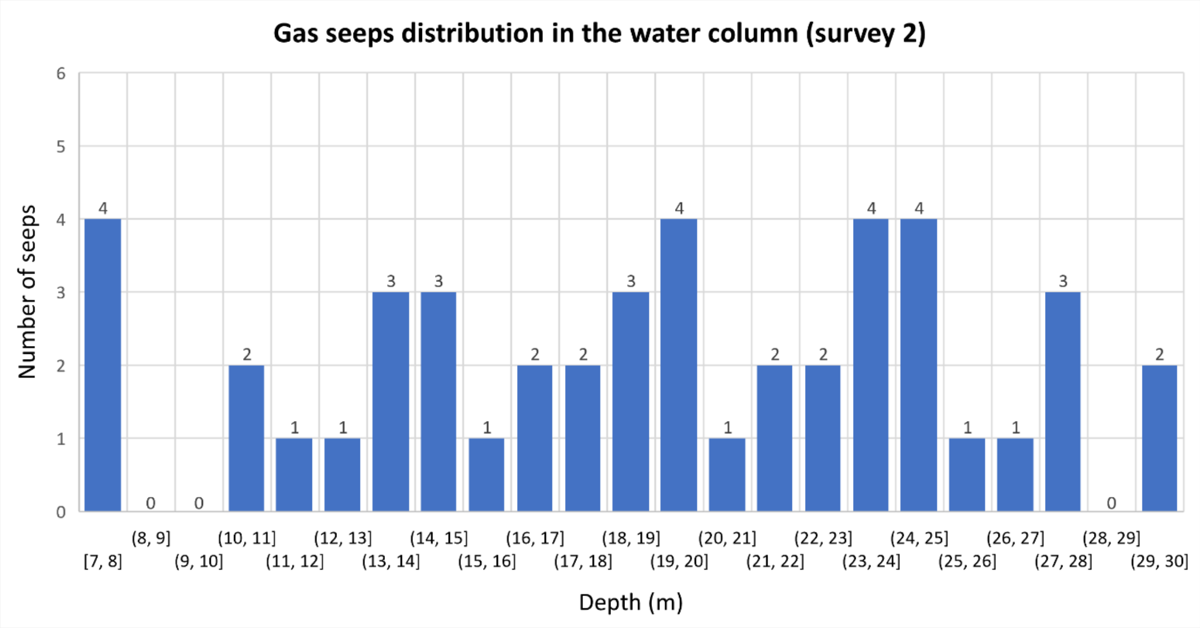

Figure 15 Histogram shows gas seeps emissions from Survey 2 in the Asköfjärden in the southern Stockholm Archipelago. X-axis = depth of observed gas seeps, y-axis = amount of the observed gas seeps.

The histogram in Figure 15 showing the gas seeps detected in a study area in Askö by Survey 2. It shows 47 observed gas seeps in depths ranging between 7-30 m. The detected gas seeps are mostly found in depths between 19-20 m (there are 5 observed gas seeps) while there is no detected gas in depths between 8-10 m. The median of the depth where the gas seeps are found is about 19.56 m.

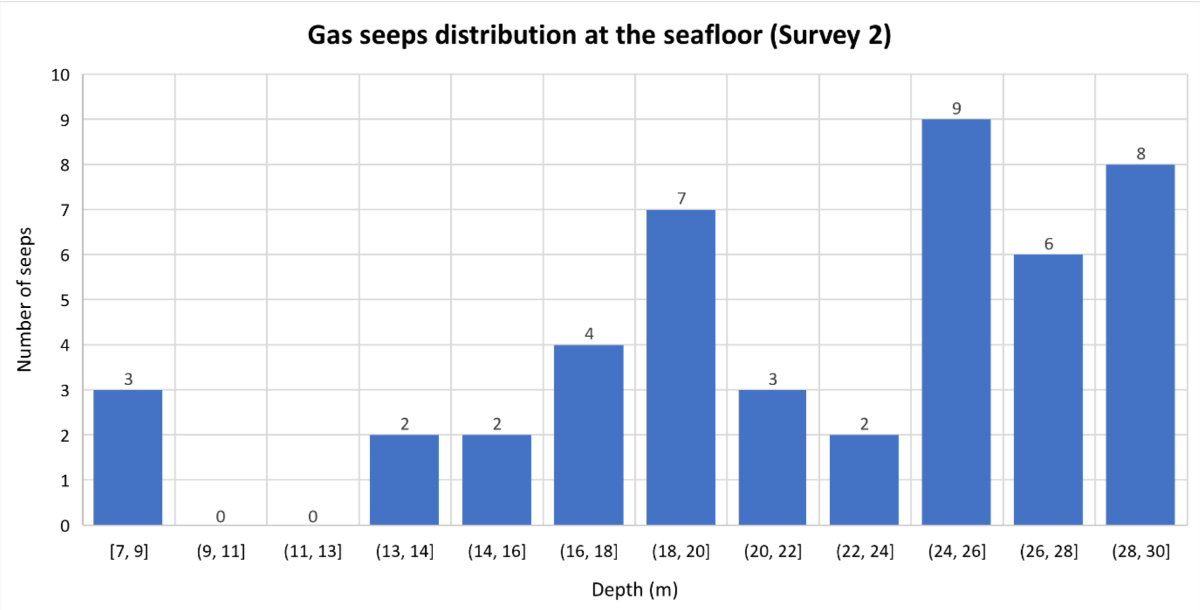

Figure 16 Histogram shows gas seeps emissions from Survey 2 in the Asköfjärden in the southern Stockholm Archipelago. X-axis = depth of observed gas seeps at the seafloor, y-axis = amount of the observed gas seeps.

The histogram in Figure 16 shows the depth of the observed gas seeps of Survey 2 at the seafloor. There are 47 observed gas seeps releases from the seafloor at the depth between 7-30 m, mostly at the depth between 24-26 m (about 9 gas seeps). The median depth of the gas seeps at the seafloor is about 23.88 m.

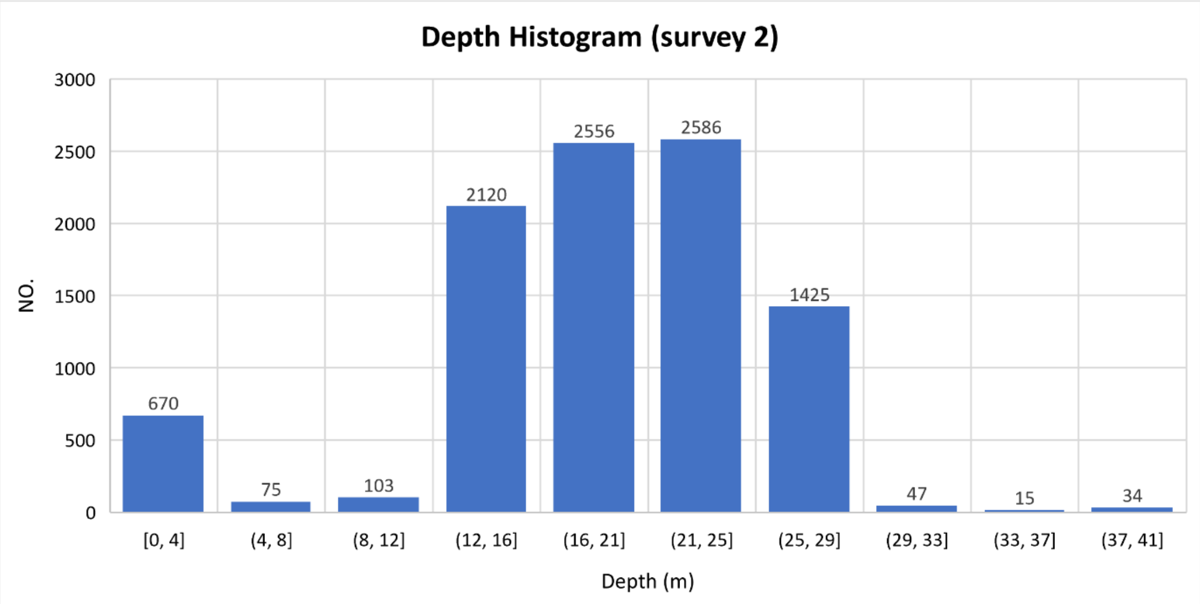

Figure 17 Histogram shows water depth from Survey 2 in the Asköfjärden in the southern Stockholm Archipelago. X-axis = water depth of areas determined with SBES, y-axis = amount of the determined areas.

The histogram in Figure 17 shows all the water depth areas that have been measured by SBES along the cruise track of the Survey 2 between the depths 0-41 m. The water depth in this area is mostly between 21-25 m. The median of the water depth in Survey 2 is about 19.5 m.

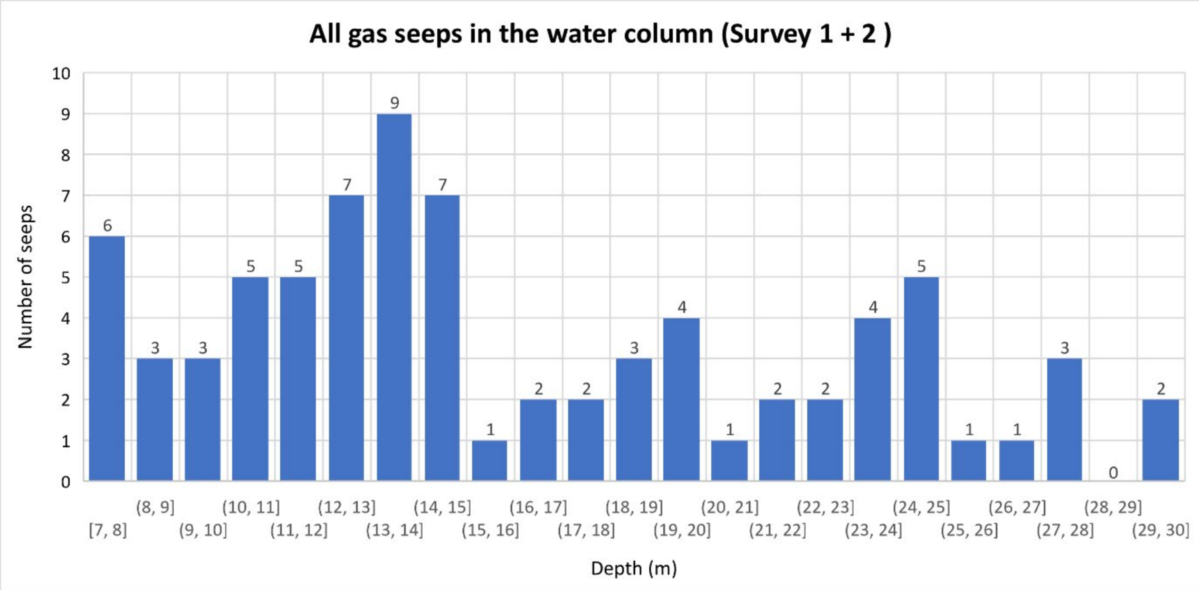

Figure 18 Histogram shows gas seeps emissions from Survey 1 and Survey 2 in the Asköfjärden in the southern Stockholm Archipelago. X-axis = depth of observed gas seeps, y-axis = amount of the observed gas seeps.

The histogram in Figure 18 shows all detected gas seeps of both Survey 1 and 2 over the study area. all observed gas seeps (76 gas seeps) as histogram shows can be found in the depth between 7-30 m. The highest number of seeps can be found at the depth between 13-14 m (9 gas seeps). The median of the depth of all detected gas seeps in the Askö area is 14.67 m.

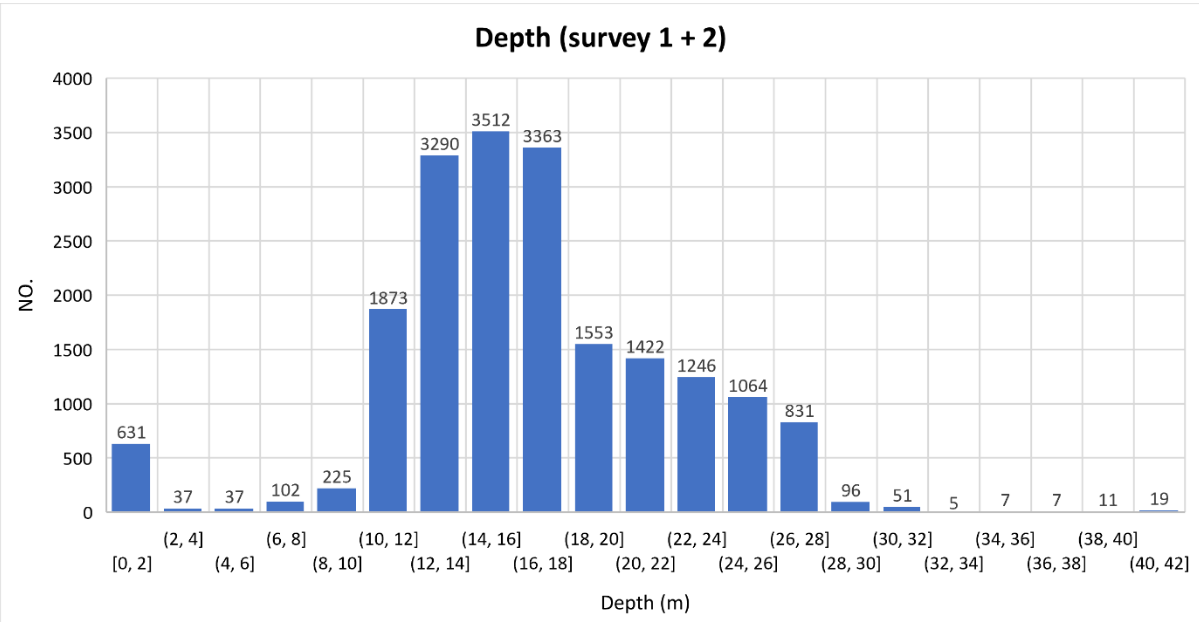

Figure 19 Histogram shows water depth from Survey 1 and Survey 2 in the Asköfjärden in the southern Stockholm Archipelago. X-axis = water depth of areas determined with SBES, y-axis = amount of the determined areas.

The histogram in Figure 19 shows all the water depth along the cruise track of both Survey 1 and 2 between the depth 0 m and 42 m. The water depth in the study area is mostly at the depth between 14 m and 16 m. The median of the water depth is about 16 m.

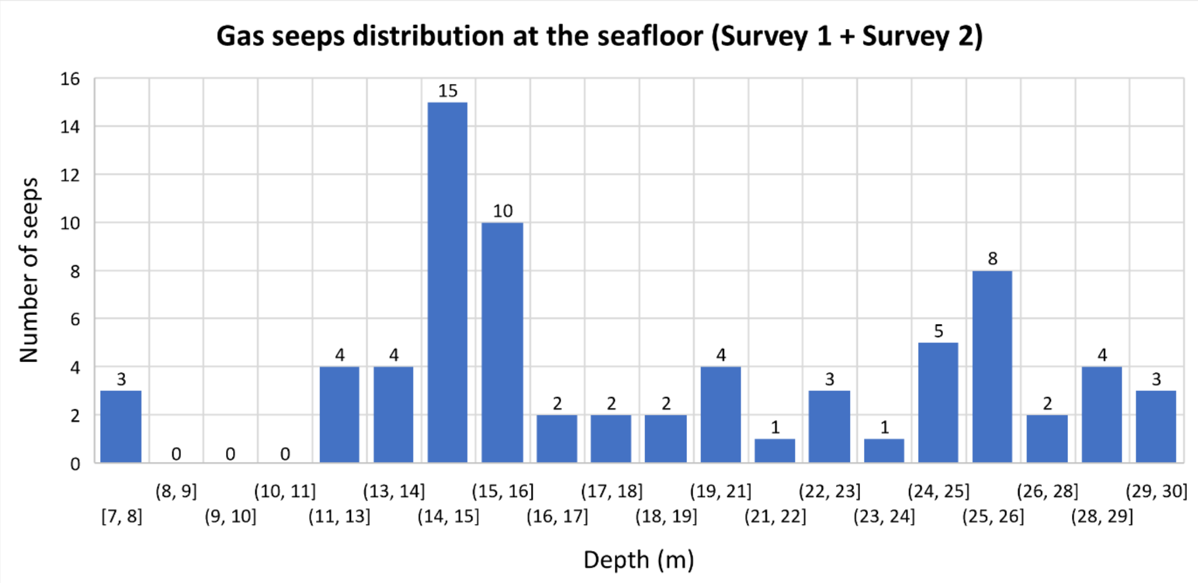

Figure 20 Histogram above shows the gas distribution of observed seepages at the seafloor in the Asköfjärden in the southern Stockholm Archipelago. X-axis = depth of observed gas seeps at the seafloor, y-axis = amount of the observed gas seeps.

The last histogram in Figure 20 shows 76 observed gas seeps in the Askö arean, divided into 20 bins set to the depth interval 7-30 m. No gas seeps/bubbles been observed in a deeper or shallower depths. Gas seeps releases mostly at depths between 14 m and 16 m. The median depth of the gas seeps at the seafloor is 17.13 m.

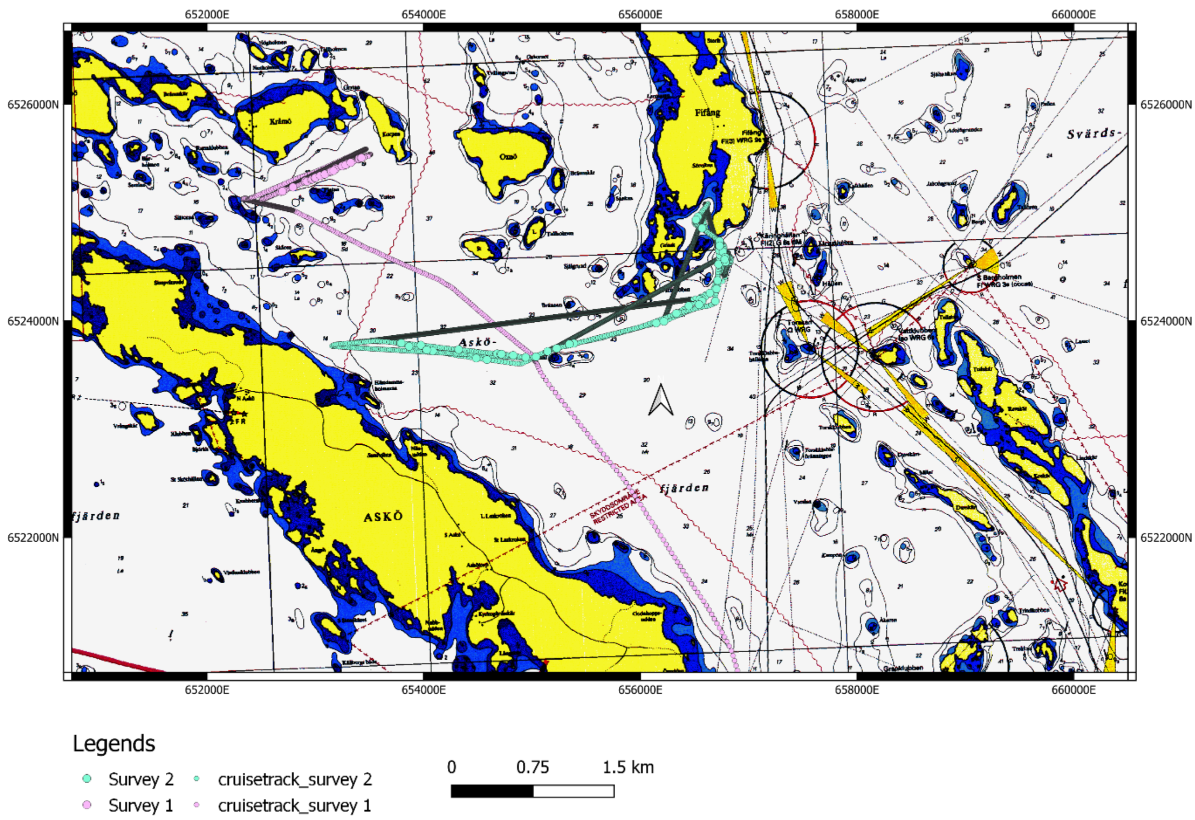

Figure 21 Map over the Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea. Cruise track of Survey 1 = light purple small circles, cruise track of Survey 2 = light green small circles. Observed gas seeps from Survey 1 = light purple big circles, observed gas seeps from Survey 2 = light green big circles.

Figure 21 shows a map over the Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea close to the island Askö. The white color on the map marks areas of water, while the yellow color marks areas of land and the blue color marks areas immediately surrounding the land. As shown in the map there are two different colors each one represents a survey and the emission of gas in that area. The information about position of Survey 1 (close to Kråmö) is shown by the light purple circles, the bigger light purple circles represent the gas seeps emission, and the smaller light purple circles (which look like a line on the map) represent the cruise track. The reason why the cruise track is much longer than observed gas seeps in that area is because only a part of the whole data was processed. The cruise track and gas seeps emission of Survey 2 (done in May/June 2022 for the Swedish Radiation Safety Authority) extends from Fifång to Askö island, represented by a light green color on the map. The bigger circles represent gas seeps emission in the area, while smaller ones represent the cruise track.

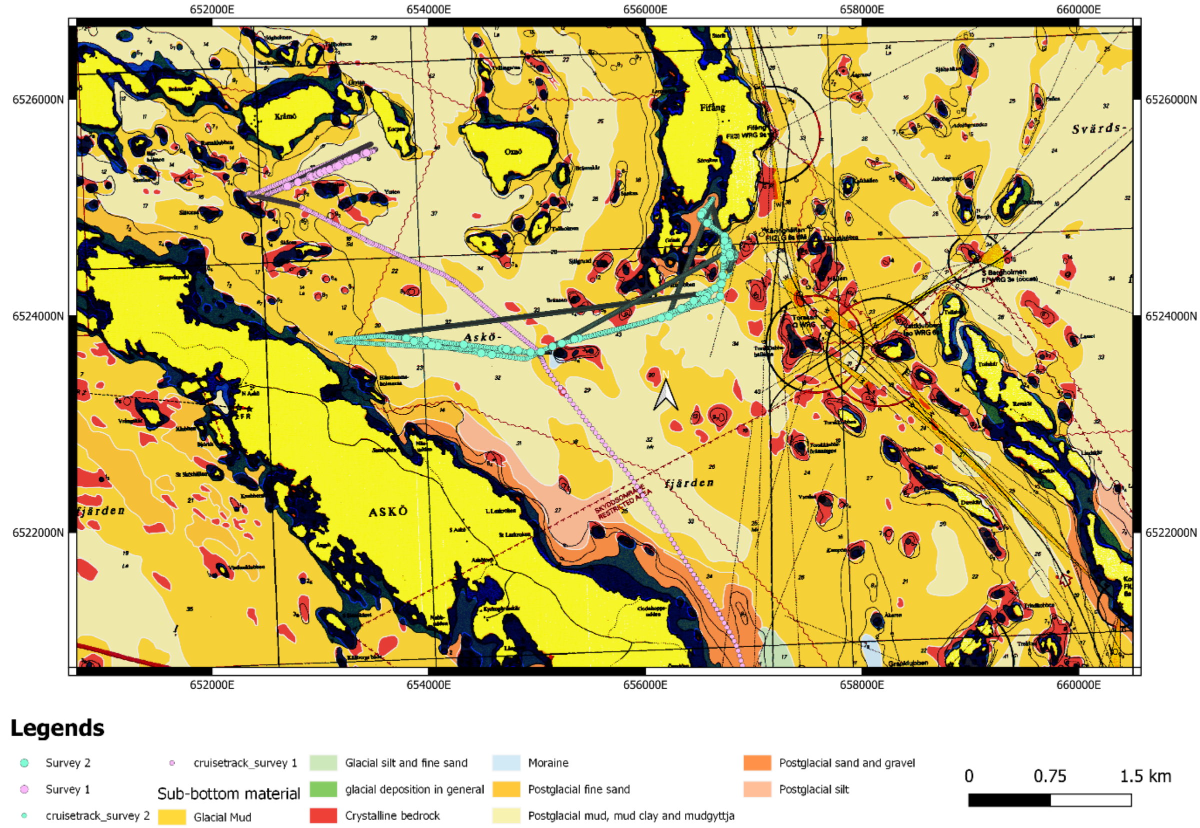

Figure 22 Map over the Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea. Cruise track of Survey 1 = light purple small circles, cruise track of Survey 2 = light green small circles. Observed gas seeps from Survey 1 = light purple big circles, observed gas seeps from Survey 2 = light green big circles. Sub-bottom materials data is taken from SGU (Sveriges Geologiska Undersökning).

The geological map in Figure 22 represents the sedimentary composition that covers the seafloor in Asköfjärden in the southern Stockholm Archipelago. The sub-bottom material of the study area shown in the map mostly consists of glacial mud and postglacial mud, mud clay and mud gyttja. The sub-bottom material of the area along the gas seeps emission from the Survey 1 consists of glacial mud and postglacial mud, mud clay and mud gyttja. While the seafloor sediment along the seep's emission of the other survey (Survey 2) consists of postglacial sand and gravel, glacial mud; postglacial mud, mud clay and mud gyttja and crystalline bedrock.

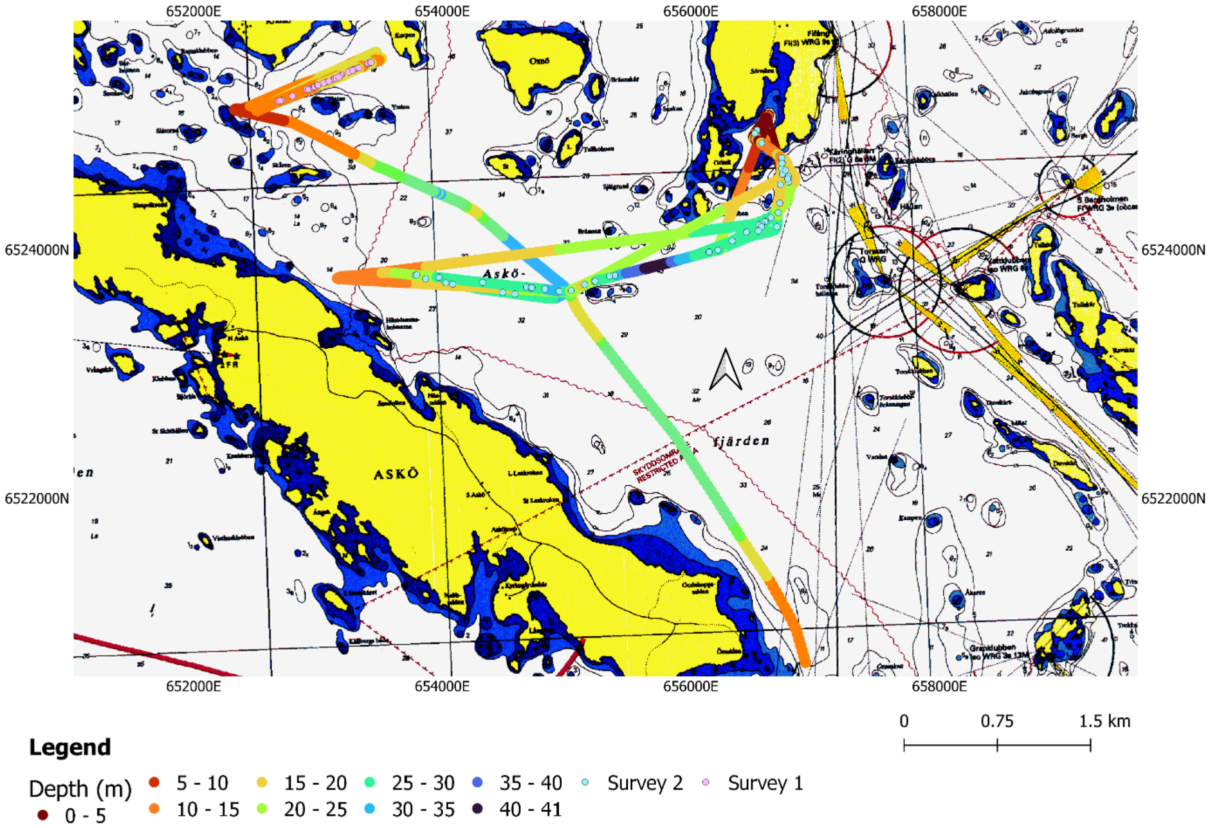

Figure 23 Map over the Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea. Observed gas seeps from Survey 1 = light purple big circles, observed gas seeps from Survey 2 = light green big circles.

The last map in Figure 23 describes the cruise track water depth in colors with depth intervals in meters and position of gas seeps emissions over the Asköfjärden in the southern Stockholm Archipelago. As shown in the legend of the map the depth intervals start with dark brown color at 0 m and gets deeper where the colors change, up to the dark blue which shows the deepest point at 41 m.

Interpretation and Discussion

The water column SBES with two split-beam transducers pinging at the same time and their frequencies ranging between 160-269 kHz and 45-90 kHz gave the ability to observe gas bubbles and seeps in the Asköfjärden Southern of Stockholm Archipelago. Both surveys were done in the Asköfjärden but in different areas with water depth shallower than 41 m. By using the SBES (that measures the travel time of a pulse from vessel to the seafloor and back to determine the water depth), the depth of many areas along the cruise track of both Survey 1 and Survey 2 have been observed (19382 measured areas). The water depth of about 52% of the measured area is between 12-18 m as shown in Figure 19. The water depth along cruise track of Survey 1 was in a depth interval between 7 m and 33 m, which means no seepage can be found at a depth greater than 33 m or lesser than 7 m. The histogram in Figure 14 shows 9751 measured areas with water depths divided into 13 bins (the blue columns in histogram) set to a certain depth interval. It also shows that the water depth in the area along Survey 1 is mostly between 15 m and 17 m. Because not all the data from Survey 1 was available, and only a part of it was processed as shown in the map in Figure 21, gas seeps may also occur in other places along the cruise track as well as in the observed ones. In particular, there are some observed gas emissions from Survey 2, where the cruise tracks of both surveys cross at one point. From the other side there are 9631 measured areas from Survey 2, with water depths divided into 10 bins. Every bin is set for a certain depth in meters, and as the histogram in Figure 17 shows, the water depth in that area is mostly between 21 m and 25 m.

As the results show, gas seep emissions are common in Askö area. Since there are 76 observed gas seeps, whereof 29 were observed along the cruise track of Survey 1, and 47 in the other one. The distribution of gas seeps in the water column of both Surveys is in the depth interval of 7-30 m, mostly between 13-14 m (where 9 gas seeps were observed). The distribution of gas seeps in water column from Survey 1 is in the depth interval of 7-15 m (Figure 12), and most of them are observed in the depth interval of 13-14 m. Seven (7) gas seeps were observed at that depth interval. The data from Survey 2 showed 47 observed gas seeps distributed in a depth interval of 7-30 m, mostly at the depth 19-20 m.

Figure 20 shows where gas seeps were releasing from the depth of the seafloor, because all the gas seeps in the water column releases from the seafloor and emission into the water column at different depths. As the histogram in Figure 20 shows, the distribution of gas seeps on the seafloor is in the depth interval 7-30 m and releases mostly from depths between 14-15 m. The distribution of gas seeps at the seafloor from Survey 1 is shown in Figure 13 where seepages can only be found between 12 m and 16 m. Along the cruise track of Survey 1, gas seeps been observed mostly at a depth interval of 15-16 m. To compare the results with gas seeps on the seafloor from Survey 2, as shown in Figure 16, it has been found at depths between 7 m and 30 m which is a much wider depth interval than in Survey 1. The reason can be that the water in area of Survey 2 is deeper and there are more observed gas seeps than Survey 1. As mentioned before the cruise track of Survey 1 shows the water depth of the whole survey while observed gas seeps are not for the whole cruise line but a part of it, which makes it difficult to see whether there are more gas seeps in deeper water than in shallower water. But it would be possible to limit the depth under the processed part to approximately 20 m by using the map in Figure 23. Then the observed gas seeps are releasing from water depths ranging at 7-20 m.

One similar thing in the depth distribution of the gas seeps of both surveys is that no gas seeps could be observed at water depth shallower than 7 m. The reason could be that at shallower depths it can become tricky to detect or observe bubbles and identify it from other targets like fish or noise, because at shallower depths the beam gets smaller. The data for this study was collected by two split-beam transducers with a 7° circular beam, the footprint of which increases diameter and beam width with increasing depth, as shown in Figure 24. (Michaels et al. 2019 p.47-48)

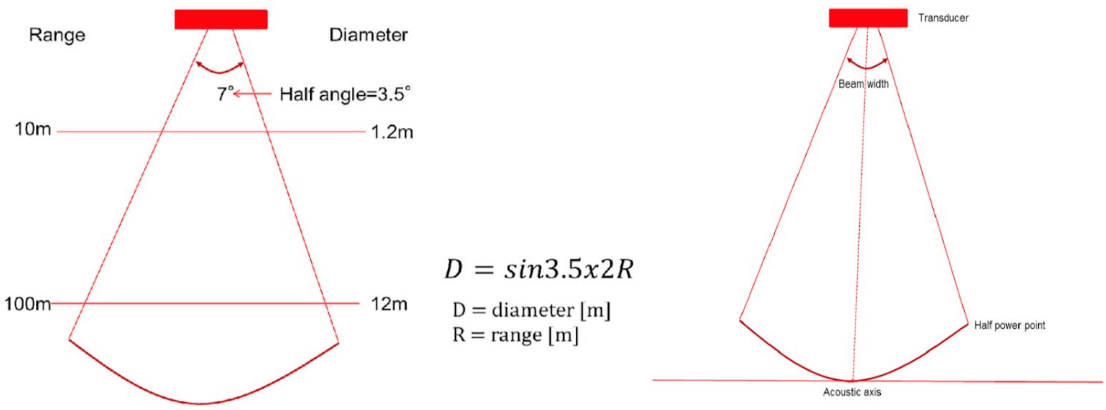

Figure 24 Range = Depth, 7° = beam angle. The figure above shows how the beam width and diameter changes with increased depth/range. *Taken from: (Michaels et al. 2019)*

As the beam gets wider with increasing depth, the target can be pinged many times, which makes the identification easier, while when the beam gets smaller a target can not be pinged as many times. Close to the transducer, a target may only get one ping and in that case, it is difficult to differentiate a rising bubble from a fish or other noise.

Why were gas seeps in Survey 1 not observed in a water deeper than 15m, even though the water depth as determined by SBES in that area can achieve a depth of 33m? It is likely because, as mentioned before, the processed data does not cover the whole surveyed area, but only a part of it, where the depth of processed area is limited between 7 m and 20 m.

Similarly, why does the distribution of gas seep in the area of Survey 2 only appear in depths between 7-30 m, when the water depth in that area can reach up to 41 m? There is as of yet no clear answer for this. It could be because of many reasons such as oxygen conditions, sedimentary rate, the sub-bottom material of that area, or that the specific area in question simply does not release gases. With more research the answer could surely be found.

What does the transport of methane gas from the seabed into the water column up to the atmosphere depend on? The transport of gas bubbles depends mostly on the size of the bubble. If it is smaller than 2.5 mm, then no transport to the atmosphere occurs and it can be deducted from the estimation of methane gas. But when the size of the bubble is greater than 3.0 mm, then the bubbles transport an amount of methane gas to the atmosphere (Weidner et al. 2019 p.104-115). The bubbles smaller than 2.5 mm will, at any depth interval, either be dissolved in the water or mass transported. The dissolved methane is prone to oxidation which makes it impossible for the methane to reach the atmosphere, and vertical density gradients also obstruct the methane in reaching the atmosphere. But this obstacle does not work in the shallow coastal system, because of the ebullition that reaches the atmosphere directly from the seafloor. In water depths shallower than 45 m, intensive bubble transport has been investigated between the seafloor and the atmosphere (Humborg et al. 2019).

Since in both surveys, Figure 21 SBES have been used instead of MBES, not the whole area of Askö has been covered, and the information and data show only what happened during the cruise track. When it comes to the coverage of the water column and seafloor the MBESs outperform the SBESs, because the SBESs beam width is about 7°, while the MBESs have a swath opening angle about 120° (Urban et al. 2023). One advantage to using multibeam is that it secures a good resolution of targets both close to the bottom and in the water column, as well as a large sampling volume (Michaels et al. 2019).

How could the results change if a MBES has been used instead? By comparing this study with *"Potential links between Baltic Sea submarine terraces and groundwater seeping"* by Jakobsson (2020), performed in the same area, we can see the differences in the amount of detected gas seeps and the depth distribution of observed gas seeps. The Jakobsson (2020) study was performed in an area east of Askö and the information was analyzed and logged by using MBES. The results showed an abundance of gas seeps with a mean and median water depth of 21 m and 20 m respectively. The shallowest observed gas seeps were found at a water depth of 3 m and the deepest at a water depth of 40 m (Jakobsson et al. 2020). Compared to the results in this study, Jakobsson et al. (2020) observed a higher number of gas seeps and bubbles due to the larger area, and the gas seeps could be observed in water depth of 3 m at their shallowest, while in this study, where SBES has been used, gas seeps/bubbles could be observed at a water depth of 7 m at their shallowest, and of 30 m at their deepest. Although the depth of the surveyed area (Jakobsson et al. 2020) is up to more than 50 m, no seepages could be observed at deeper water than 40 m. The reason as to why no gas emissions were observed in the deepest parts was not discussed in the Jakobsson et al. (2020) study, but may be relevant to investigate in future studies.

The map in Figure 21 shows the position of every observed gas seep and the cruise track of both surveys. Finding the position of every gas seep is simple, and done by using the coordinates on the map. The map also shows whether the gas seeps are close to each other or not. The distribution of gas seeps in Survey 1 is almost evenly divided along the cruise track (gas seeps/bubbles are not very close to each other, nor very far away). By taking a closer look at the gas seeps distribution in Survey 2 in Figure 25, the observed gas seeps/bubbles are not even close to be evenly divided, but can rather be found very close to each other in some areas, and far away in others.

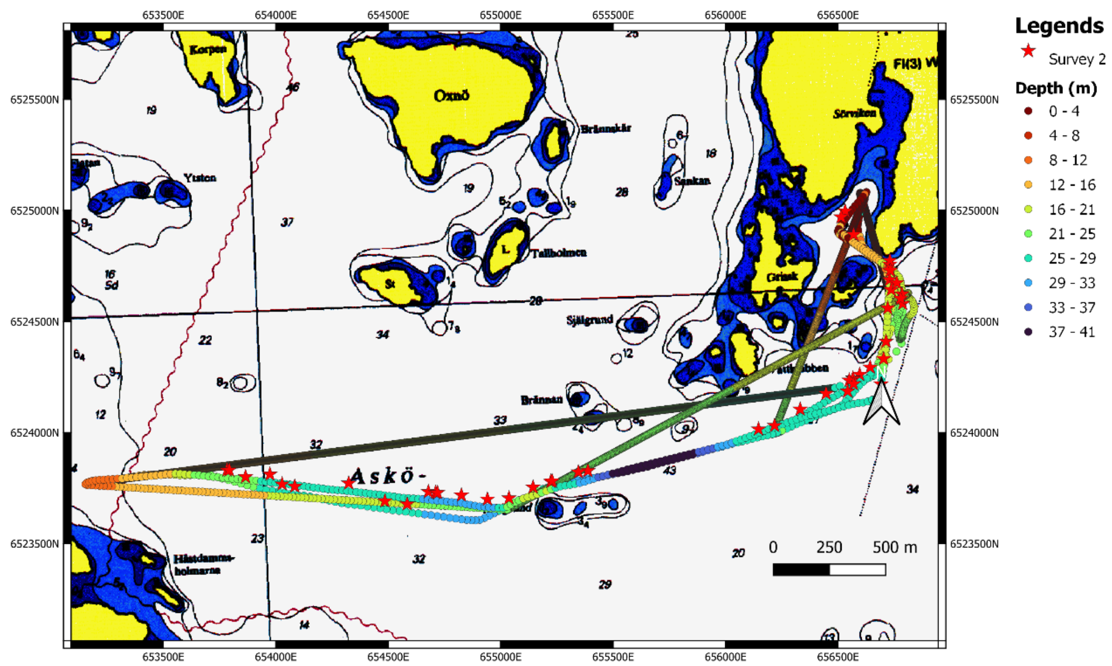

Figure 25 Map over the Asköfjärden in the southern Stockholm Archipelago in the Baltic Sea. Observed gas seeps from Survey 2 = red stars.

The sediment type where every gas seep releases from is shown in the map in Figure 22. The whole area of Askö in the map is mostly covered by glacial mud and postglacial mud, mud clay and mud gyttja. The sub-bottom material covered in the study area of Survey 1 shows four gas seeps have been released from glacial mud and 25 gas seeps released from postglacial mud, mud clay and mud gyttja. While in the area of Survey 2, most gas seeps released from postglacial mud, mud clay and mud gyttja (25 seepages), 16 gas seeps from glacial mud, 3 sees from postglacial sand and gravel and finally 3 seeps release from crystalline bedrock. The total number of gas seeps released from the sub-bottom covered by postglacial mud, mud clay and mud gyttja is 48, while the total gas seeps released from the area covered by glacial mud is 20, in addition to 3 from postglacial sand and gravel, and finally 3 from crystalline bedrock. Which means that gas seems to release the most from areas covered by postglacial mud, mud clay and mud gyttja, although the distribution of sediment types in Asköfjärden is not equal, and so it would be easier to draw conclusions about how much gas is released from each sediment type, using data that covers the entire area of Asköfjärden. Although the methane emission occurs in the sediments by methanogenesis of the organic matter, in this study 3 gas seeps could be observed releasing from hard crystalline bedrock. The data about the seafloor's material was taken from SGU, but it could be represented in many different maps, so a possible explanation could be that the map is not perfect. But on the other hand, there is an ongoing study/project "Production and consumption of the greenhouse gas methane in the crystalline bedrock" from Linnaeus University showing that the formation and consumption of methane gas not only occurs in the soft sediments but also in the crystalline bedrock. Because of the lack of information, it is difficult to say whether these gas bubbles/seeps truly released from crystalline bedrock or from sediments, but the possibility that these seepages released from crystalline bedrock does exist (Linneas university 2024-02-29).

The total methane gas seeps observed in the Asköfjärden from both surveys are about 76 total, in an area with water depth ranging from 0-42 m. The seeps' distribution, as the result showed in Figure 18, ranges between 7-30 m, which means there was no observed gas seep or bubbles above 7 m or below 30 m. Because the methane gas is a greenhouse gas that can affect the climate if it reaches the atmosphere, it is important to measure its concentration at the seafloor. As mentioned, many studies have been done to detect and measure the methane gas emission in many places around the world, and in different environments. Many studies have also been done in Asköfjärden because it is an area where gas emissions are a fairly common occurrence. Because the aim in this study is only to observe the gas seeps with depth distribution and note the position of them, it has not yielded much information about the size of the bubbles or seeps, and/or the concentration of observed seepages. It is also difficult to say whether the emissions reached the atmosphere or not, because no gas bubbles or seeps have been observed at or close to the water surface. For this reason, it would be interesting for further research to measure the methane gas concentration at the surface, as well as the size of the bubbles in areas of observed gas seeps, especially when it comes to the deeper parts of the area, as even in other studies, gas seeps could not be found in the deepest areas, and the explanation as to why remains undeclared. The investigation of the sediments where every gas seep releasing from is also a potentially interesting object for further research.

Conclusion

The investigation of the methane gas emissions in Asköfjärden in the Baltic Sea shows 76 observed gas seeps distributed in a water depth between 7 m and 30 m. The data from Survey 1 demonstrates that the water depth along the cruise track is between 7 m and 33 m and the observed 29 seepages are in the water column at a depth range of 7-15 m. The depth of methane gas seeps at the seafloor of Survey 1 is between 12 m and 16 m. The data from Survey 2 from the other hand showed 47 observed seepages along the cruise track along a water depth ranging between 0-41 m. Observed gas seeps from Survey 2 are distributed in the water column at depths from 7 m to 30 m, and the seafloor gas seeps are also distributed in a depth interval of 7-30 m. No gas seeps could be observed at a depth greater than 30 m or at a depth lesser than 7 m. The maps in Figures 21, 22 and 23 show that gas emissions are common in the area of Asköfjärden, as gas seeps are observed along the cruise track in both surveys. The accumulation of the sediment also showed that the study area is mostly covered by glacial mud and postglacial mud, mud clay and mud gyttja. Since 48 of 76 gas seeps seem to release from areas covered by postglacial mud, mud clay and mud gyttja, that makes those the primary methane gas emitting sediment types in the explored area.

Acknowledgments

I would like to thank my supervisors Professor Christian Stranne and Professor Martin Jakobsson for all their valuable help and guidance throughout the project. Furthermore, I would like to extend my gratitude to everyone who showed interest in my work. Thank you all for your support.

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Appendices