CHAPTER 1

Introduction

This chapter gives a general overview of the background and importance of bubble-releasing methane seeps and thus the relevance of this thesis. Furthermore the aim of this thesis, the geological setting of the three study areas, the used methods, the project framework as well as the outline of the thesis are briefly discussed. More detailed information about the items dealt with in the introduction is provided in the 'introduction', 'study area', 'data and methods' sections of the subsequent chapters. Whereas the introduction is intended as a brief overview more detailed background information is given and integrated with the results in the 'final discussion' chapter.

1.1. Background

Bubble-releasing seeps, often referred to as gas seeps or cold seeps, are locations at the sea or lake floor where gas, mainly methane (CH_4), is transferred as a free gas phase (bubbles) from the sediments into the overlying water column. Over the last decades, methane release has become a very important scientific, economic and even political issue. The release of methane, a major component of the global carbon cycle, strongly affects the atmosphere, the biosphere, the hydrosphere and the geosphere (Fig. 1.1.) (Judd, 2003; Judd and Hovland, 2007). Furthermore methane is becoming an increasingly important energy resource.

Methane is a very important greenhouse gas with 21-23 times the global warming potential as the same mass of carbon dioxide and it accounts for 20% of the greenhouse forcing since the mid 1700's (Lelieveld et al., 1998; IPCC, 2001b). Strong changes in atmospheric methane concentrations and coupling with changes in atmospheric temperatures are well-known from ice cores for the last 650 kyr (Petit et al., 1999; Spahni et al., 2005; IPCC, 2007b). Since pre-industrial times, atmospheric methane concentration has more than doubled to

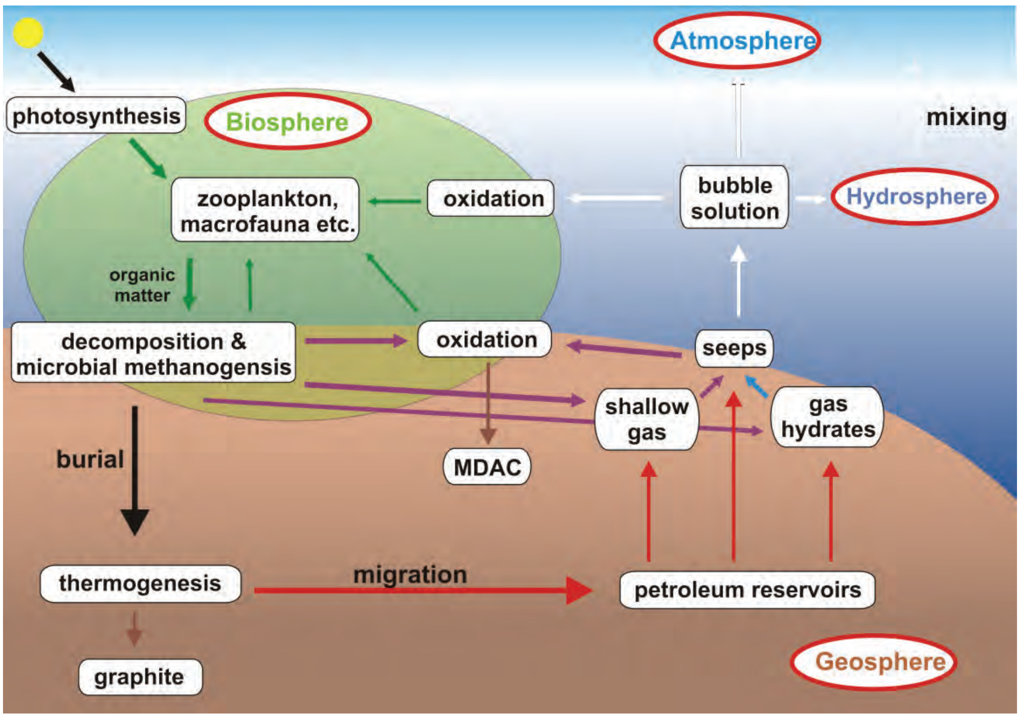

Figure 1.1. Schematic diagram indicating the role of methane and methane release in the carbon cycle (after Judd and Hovland, 2007).

unprecedented high values, due to increasing emissions from anthropogenic sources (livestock, rice paddies, etc.) (Fig. 1.2.A.) (Wuebbles and Hayhoe, 2002; IPCC, 2007b). The total global methane budget is well-known but the strength of each source and sink and their trends are not (IPCC, 2007a). Therefore a correct assessment of natural methane sources (wetlands, oceans, etc.) and sinks is essential to better evaluate the human impact on global atmospheric methane concentration and consequently on global climate change (Fig. 1.2.A.)(IPCC, 2001a; IPCC, 2007a).

Until recently only gas hydrates were considered as a major geological source for atmospheric methane. Destabilizing these ice-like compounds of gas and water present in the ocean sediments could be one of the explanations for the rapid warming episodes during the Earth's history (Dickens et al., 1997; Dickens, 2001; IPCC, 2001b; Etiope, 2009). It is only very recently that other geological methane sources, mainly offshore seeps, have been regarded as possible important contributors to atmospheric methane (IPCC, 2007b) (Fig. 1.2.B.). Before, these sources were regarded negligible, as indicated by their absence in Fig. 1.2.A. (IPCC, 2001b). Current estimates of global methane emissions into the atmosphere from marine bubble-releasing seeps vary between 0.4 and 48 Tg yr^{-1}, with 20 Tg yr^{-1} being a conservative estimate (Judd, 2004; Judd and Hovland, 2007; Etiope, 2009). A comparison with other geological methane sources shows that bubble-releasing methane seeps should be regarded as one of the major natural sources of atmospheric methane (Figs. 1.2.A. and 1.2.B.). However until now the amount of methane released at seeps is still largely unknown. There is a need to obtain correct estimates about the actual area of active seepage and the temporal variability of the seepage intensity and activity. Until the distribution and activity of methane seeps is better understood, seeps should not be neglected as an atmospheric methane source. Judd and Hovland (2007) give a very good overview of and references to this topic. They also indicate the reluctance of atmospheric

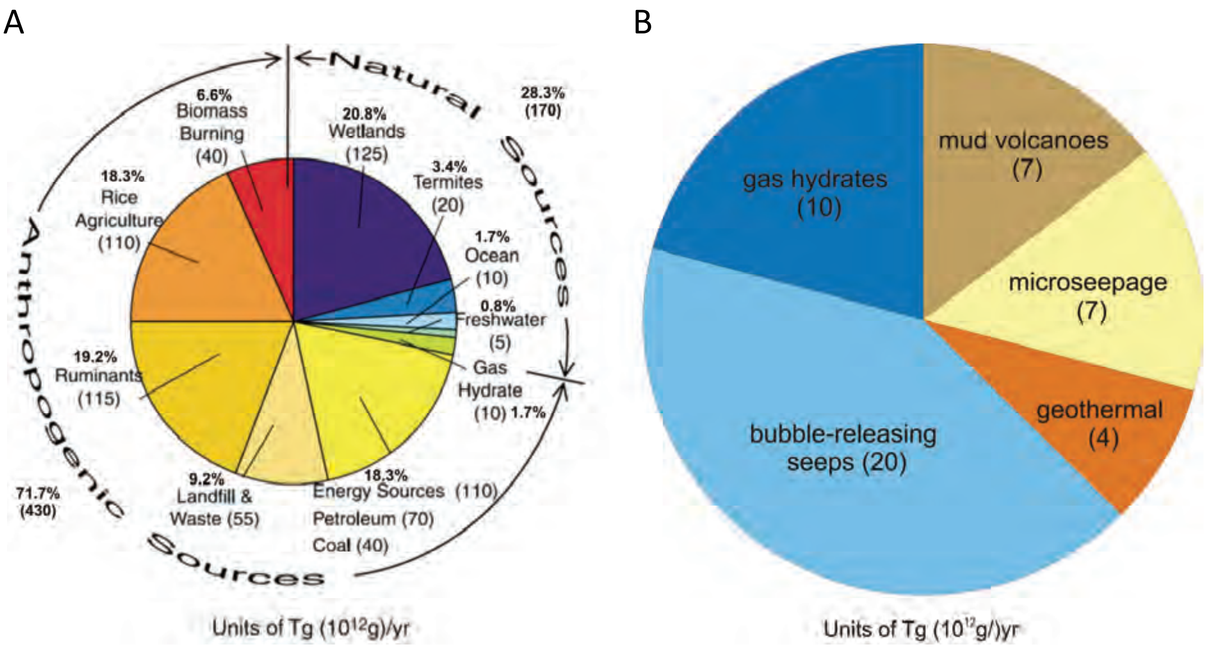

Figure 1.2. A. Diagram showing the relative contributions from various sources of methane to the global atmospheric methane budget. The total atmospheric methane budget is estimated to be 600 Tg of CH_4 yr^{-1} of which 71.7% has an anthropogenic source and 28.3% a natural source Note the absence of methane seeps as a possible source (IPCC, 2001b; Kvenvolden and Rogers, 2005). **B.** Diagram showing the relative contributions from various geological methane sources (Etiope and Klusman, 2002; Etiope and Milkov, 2004; Judd and Hovland, 2007; Etiope, 2009).

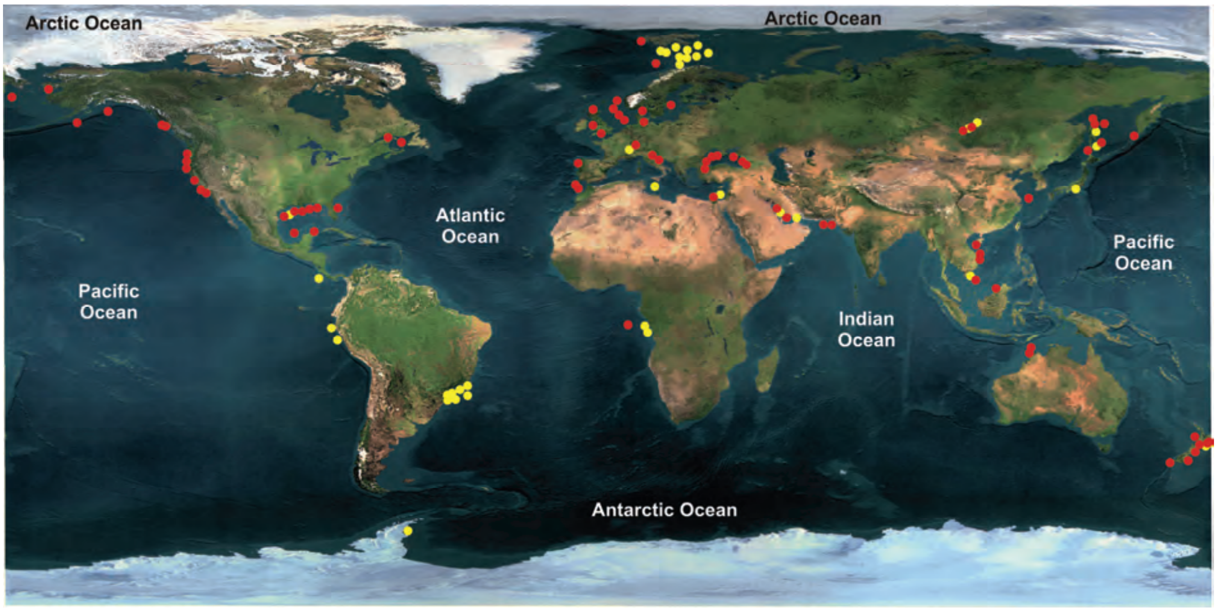

Figure 1.3. Worldwide distribution of bubble-releasing seeps (red dots) and gas seepage indicators (bacterial mats, authigenic carbonates, ice streamthroughs, etc.) (yellow dots). Where seeps as well as the seep indicators are present; they are indicated by red dots (after Judd and Hovland, 2007).

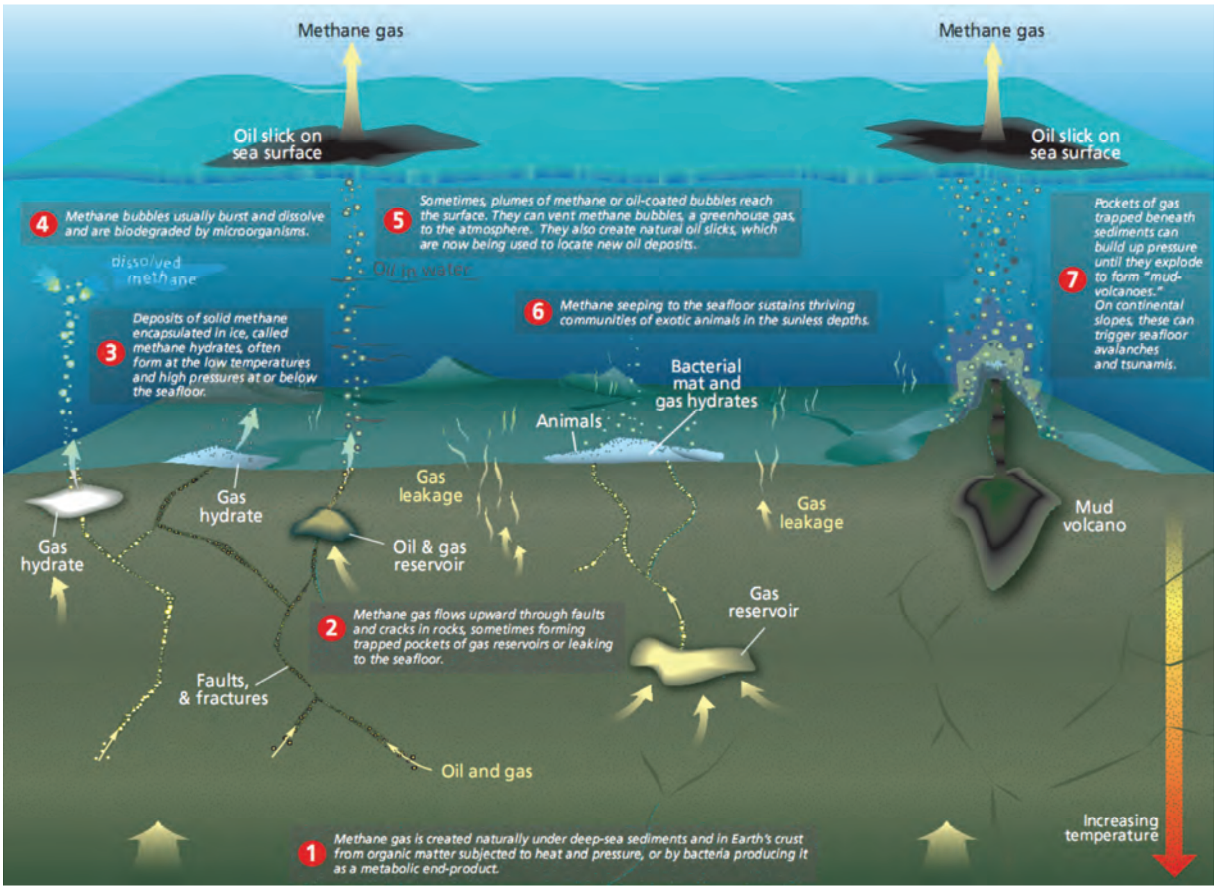

Figure 1.4. A general overview of the subsurface- and water-column features associated with gas-bubble release as witnessed in the Gulf of Mexico where gas-bubble release is associated with oil leakage (Jean Whelan, WHOI).

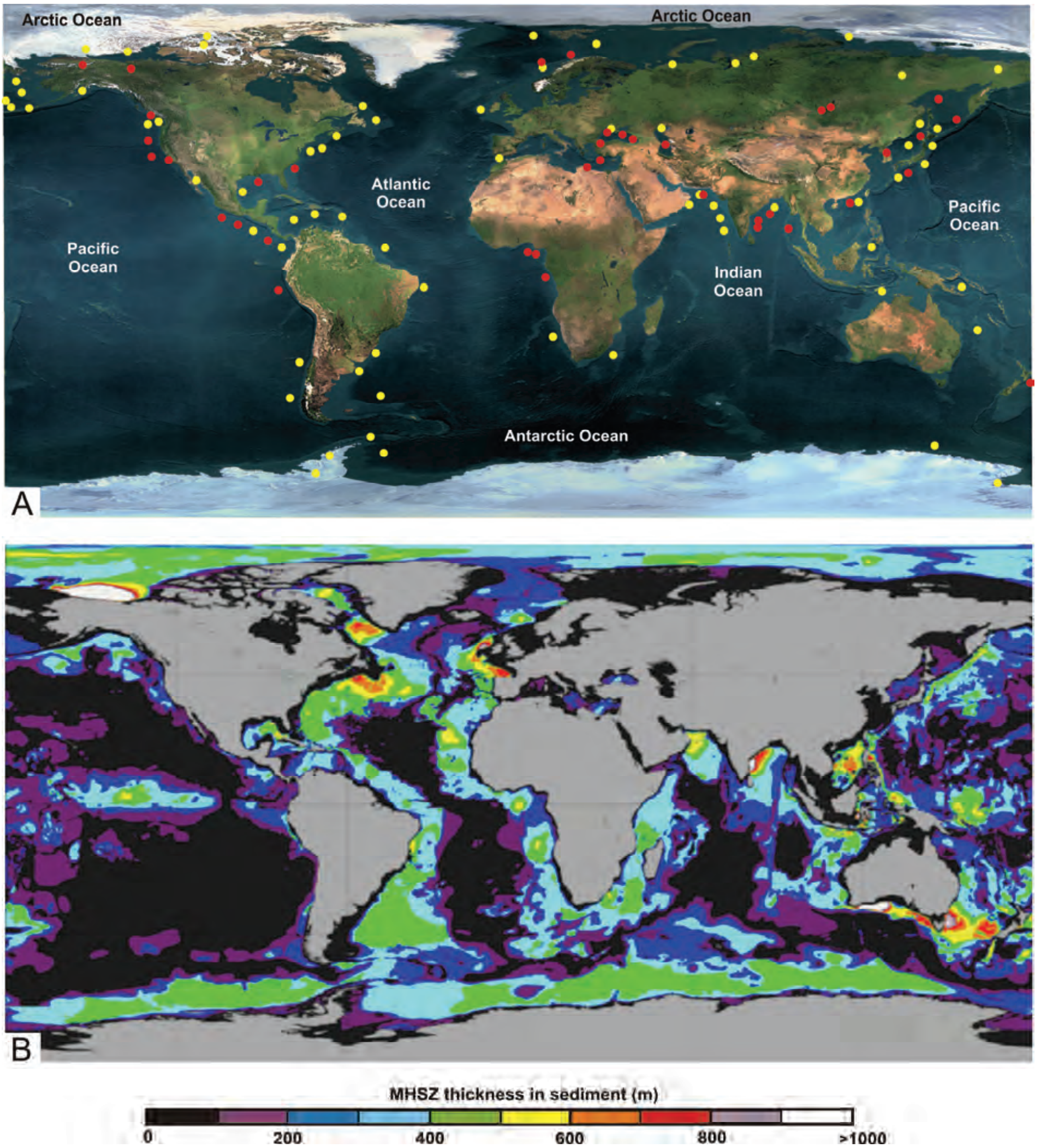

Figure 1.5. A. An overview map of all locations on Earth with recovered gas hydrates (red circles) and inferred gas hydrates (yellow circles). B. Estimated thickness of the gas-hydrate stability zone in the world's oceans (Krey et al., 2009).

modelers to take into account the existence of these geological sources and processes. This alone is already an indication that there is a strong need to study and understand this natural release of methane and the processes involved.

Recent literatures shows that methane seeps and related features occur worldwide from coastal areas to the deep ocean trenches at all possible oceanographic and plate tectonic settings (Fig. 1.3.) (Judd, 2003; Judd and Hovland, 2007). However most seep sites occur at continental margins where organic-rich sediments accumulate and methane is formed. microbially from methanogenesis of organic material or thermogenically resulting from catagenesis of organic material at depth and at higher temperatures (Figs. 1.1. and 1.4.)

(Whiticar, 1999; Judd and Hovland, 2007). The migration of methane and other fluids through the sediments towards the seabed is related to the buoyancy of methane and/or to overpressure generated at depth. During the migration towards the seabed, dissolved and/or free methane gas can be stored in the sediments due to structural or stratigraphic traps (Fig. 1.4.). The largest methane reservoirs present in the ocean's sediments are solid methane hydrates (Fig. 1.5.). These crystalline structures consisting of gas and water can only form and be stable under high-pressure and low-temperature conditions with substantial amounts of gas and water. It is believed that there is more carbon stored in methane hydrates than in all other fossil fuels combined (Fig. 1.5.) (Henriet and Mienert, 1998; Paull and Dillon, 2001; Max et al., 2006; Sloan and Koh, 2007). If pressure and temperature conditions change, gas hydrates can dissociate and hereby support gas seeps at the seafloor and enhance sediment destabilization (Bouriak et al., 2000; Bünz et al., 2005). When methane and other

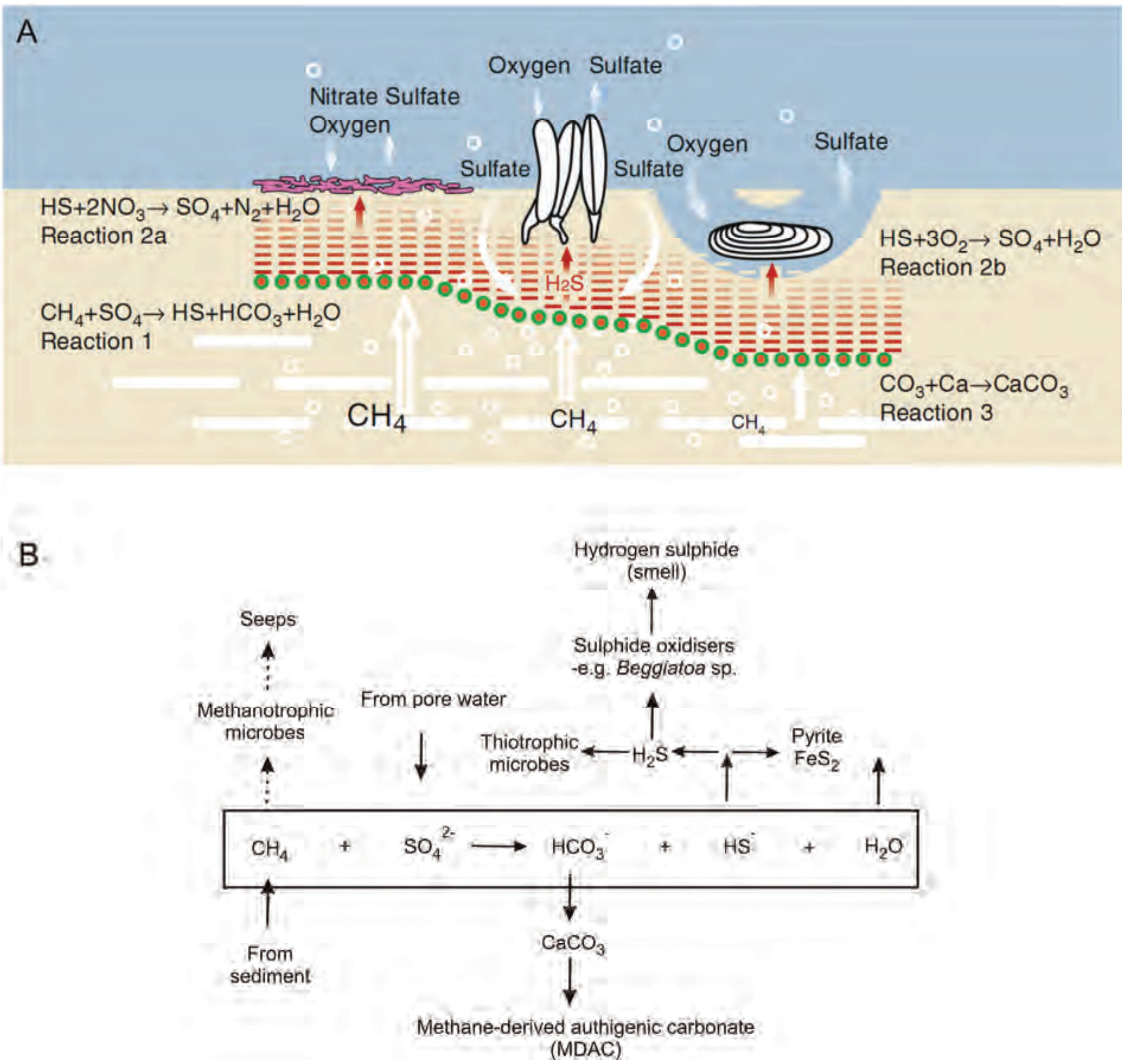

Figure 1.6. A. An overview of the chemical reactions that take place at the seabed-water column transition zone as a result of the anaerobic oxidation of methane (AOM). Note that a difference in methane flux leads to different chemosynthetic fauna's and that AOM is strongly associated with authigenic carbonate formation (Suess, 2010). **B.** A schematic overview of the anaerobic oxidation of methane and its resulting chemical species and methane-related products (Judd and Hovland, 2007).

fluids are released at the seabed after migration through the sediments, their origin as well as their formation depth and the possible followed migration pathways can be deducted from the carbon isotopes ($\delta^{13}C_{CH_4}$) and hydrogen isotopes (δD_{CH_4}) of the released methane (Whiticar, 1999; Judd and Hovland, 2007). Other isotope ratios, e.g. from Sr, B, Li, I, etc., or geothermometers like the lithium-magnesium ratio can also help to indicate the source depth and the followed migration pathway of the fluids released at the seafloor (Aloisi et al., 2004).

Generally, dissolved methane present in pore waters of the near-surface sediments gets completely oxidized by consortia of methane-oxidizing archaea and sulfate-reducing bacteria in anaerobic environments or by the aerobic activity of bacteria (Figs. 1.4. and 1.6.) (Reeburgh et al., 1993; Boetius et al., 2000; Boetius and Suess, 2004; Sommer et al., 2006). As a result of the bacterial activity, seeps can support unique endemic ecosystems of marine organisms (bacteria, tubeworms, clams, etc.) which are strongly related to the flux of dissolved methane, as shown in Fig. 1.6. (see chapters 4, 5 and 7) (Boetius, 2000; Suess, 2010).

Another strong seabed manifestation of high methane fluxes and the associated anaerobic oxidation of methane (AOM) is the precipitation of methane-derived authigenic carbonates (MDACs) or authigenic barites (Boetius, 2000; Greinert et al., 2001; Michaelis et al., 2002; Greinert et al., 2002; Suess, 2010). As shown in Fig. 1.6., MDACs are formed as the product of Ca (and/or Mg) and the bicarbonate resulting from AOM present in the pore waters or bottom waters. Since these carbonates result from AOM, MDACs also have typical carbon isotopes ($\delta^{13}C_{CH_4}$) (see chapters 4, 5 and 7) (von Rad et al., 1996; Judd and Hovland, 2007). Based on their typical geochemistry, fossil MDACs can even provide evidence of fluid flow and AOM in areas where fluid flow only occurred in geological times and has ceased a long time ago (Campbell et al., 2008; De Boever et al., 2009). By the formations of carbonate hardgrounds, seeps can also support non-chemosynthetic organisms.

It is only where fluid flow is focused, mainly at bubble-releasing seeps, that methane can pass the benthic AOM filter and can be released into the water column (Figs. 1.4. and 1.6.) (Judd, 2003). Besides the chemosynthetic fauna and the authigenic carbonates, focused fluid flow leads in some cases to peculiar seabed features like mud volcanoes, pockmarks, etc. These features are all related to seabed fluid flow and possibly with bubble release, nevertheless their genesis can be completely different (Judd and Hovland, 2007).

Methane seepage and the associated features are clearly widespread and diverse, but the activity of seepage is also very variable and transient. Seepage activity changes over short (minutes to days) related to e.g. tides or currents or even over long time scales (years to glacial/interglacial) related to e.g. eustatic sealevel changes (Leifer et al., 2004; Greinert, 2008). The activity and the amount of methane released at the seafloor are also strongly related to the methane sources and the fluid flow pathways and vice versa (see chapters 5 and 7).

Besides the wide variety of scientific interests, the release of methane at the seafloor and the associated features can be economically valuable as potential indicators of deeper hydrocarbon reservoirs. Furthermore the presence of seeps and shallow gas reservoirs pose a threat to offshore constructions, affecting seafloor stability and possibly destroying drilling rigs, pipelines etc (Judd and Hovland, 2007).

It is clear that bubble-releasing seeps and seabed fluid flow are very interesting in various ways and attracted the attention of a variety of scientists and people from industry. Notwithstanding the large amount of studies focusing on gas seeps, their distribution, activity and controls are still largely unknown. A better understanding of these controls, activity and the distribution of seeps, especially bubble-releasing seeps which are the pinnacle of focused fluid flow, would allow more correct assessments of atmospheric methane input from seeps, the fauna associated with seeps and could help to find new energy resources.

1.2. Study objectives

The major objective of this study is to determine the main geological controls on gas-bubble release to better evaluate the distribution of seeps and their associated features. This study should form a solid base for methane flux calculations and for exploration of new hydrocarbon resources. Therefore several seep areas around the world, occurring in different geological settings, have been studied and are compared based on the integration of hydro-acoustic investigations (single- and multibeam echosounding, side scan sonar, seismics), seafloor observations (ROV, submersible, TV-sled) and grainsize-, geochemical- and thermal analyses. Seeps were studied in the NW Black Sea (a passive continental Margin), in the SW Pacific Ocean (an active continental margin) and in Lake Baikal (a rift lake) to see if there are clear differences in control on seepage related to these distinct geological environments. Besides the overall geological and structural setting the main focus was on the role gas hydrates, methane-derived authigenic carbonates, faults and sediment type play in controlling seep distribution.

The main questions posed are:

1) What are the different geological controls on seep distribution, on a basin-wide scale, on kilometer scale and on meter scale?
2) Do seeps occur at certain seafloor morphologies or at certain water depths? Which are these morphologies and how do they relate to the seep distribution, seep activity and to the associated fauna's?
3) Do gas hydrates act as a buffer, a source or a sink for methane and how do hydrates relate to the distribution of bubble-releasing seeps?
4) Can faults be regarded as the main geological features controlling seeps on a kilometer to meter scale? Or is the type of sediment and/or the stratigraphic build up and geometry more important in focusing subsurface fluid migration and the release of gas bubbles at the seafloor?
5) What is the spatial relation between bubble release and other seep-related manifestations at the seafloor and shallow subsurface, e.g. chemosynthetic fauna, authigenic methane-derived carbonates, etc.)?

1.3. Geological setting

1.3.1. Black Sea – Dnepr paleo-delta

The Black Sea is a large semi-enclosed marginal basin surrounded by alpine mountain chains (the Greater Caucasus, Pontides, Southern Crimea, and Balkanides) (Fig. 1.7.). The only connection it has with the world oceans is via the Bosporus Strait through the Marmara Sea, the Dardanelles and the Mediterranean Sea. The Black Sea was formed via back-arc spreading during the Early, Cretaceous-Early Paleogene associated with the subduction of the Neo-Tethys below the Balcanides-Pontides volcanic Arc. (Robinson et al., 1996; Dinu et al., 2005). The Black Sea consists of two large basins, the Western Black Sea Basin and the Eastern Black Sea Basinseparated by the Andrusov Ridge. Sediment thickness in the Black Sea varies from 19 km in the Western Black Sea, 5-6 km on the Andrusov Ridge and 12 km in the Eastern Black Sea (Tugolesov et al., 1985). Since the Eocene, the Black Sea region has changed to a dominantly compressional environment (Nishishin et al., 2003). The study area, the Dnepr paleo-delta, is located on the continental margin of the northwestern Black Sea, above the Kalamit Ridge where the top of the Cretaceous lies at depths of less than 1 km (Fig. 1.7.) (Robinson et al., 1996).
There is no direct evidence for large petroleum reservoirs below the study area; however several oil and gas fields are being produced in the vicinity of the Dnepr paleo-delta (Fig. 2.1.) (Dinu et al., 2005; Popescu et al., 2007). In the Black Sea, the Maykop formation of Middle to Upper Eocene age is the chief hydrocarbon source that feeds numerous mud volcanoes in

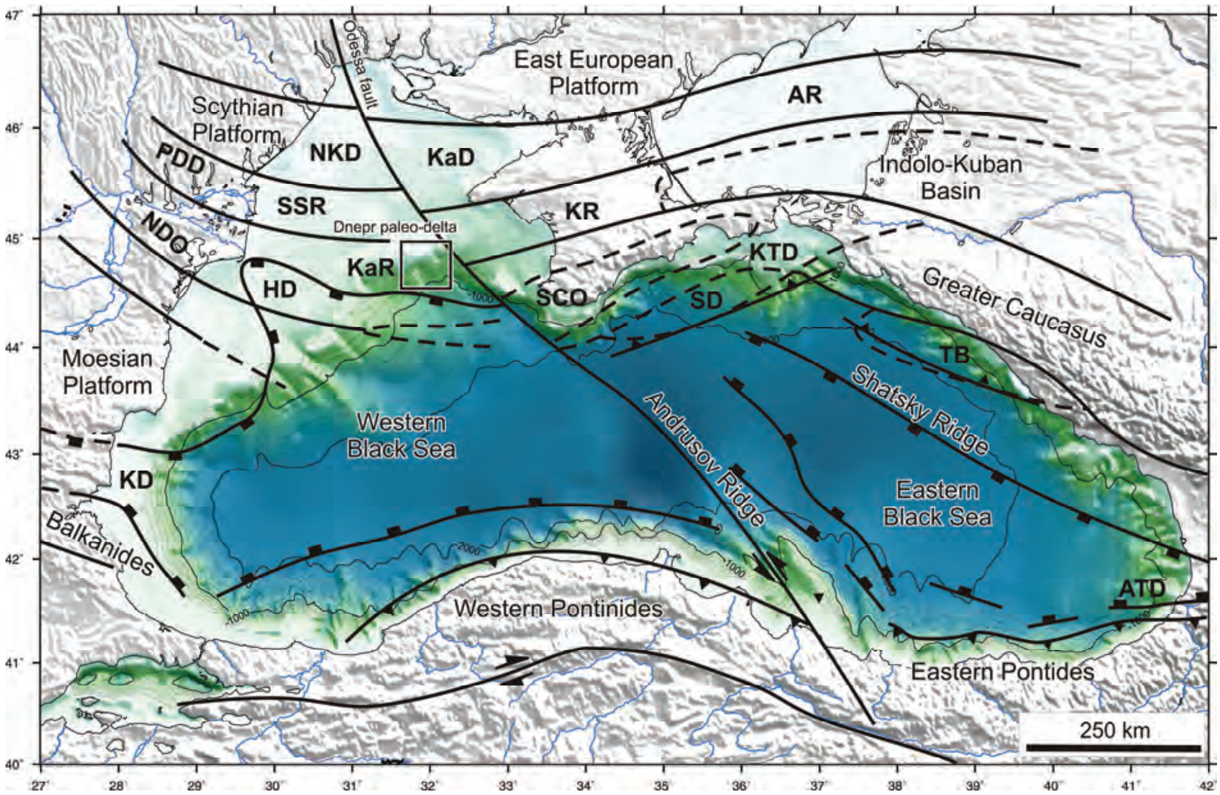

Figure 1.7. Tectonic map of the Black Sea region with indication of the Dnepr paleo-delta study area. (Abbreviations: NDO—North Dobrogea Orogen, SCO—South Crimea Orogen, PDD—Pre-Dobrogea Depression, NKD—North Kilia Depression, KaD—Karkinit Depression, KaR—Kalamit Ridge, HD—Histria Depression, SD—Sorokin Depresion, KTD—Kerci-Taman Depression, KD—Nijna-Kamciisk Depression, ATD—Adjaro-Trialet Depression, TB—Taupse Basin, SSR—Suvorov–Snake Island Ridge, KR—Kramski Ridge, AR—Azov Ridge, BR—Bubkin Ridge (after Dinu et al., 2005).

the deeper basins (Fig. 1.8.) (Robinson et al., 1996; Bohrmann et al., 2003; Kruglyakova et al., 2004). In the Dnepr paleo-delta however, the methane seeps are probably sourced by Holocene organic-rich sediments deposited during successive sea-level lowstands when the main inflowing rivers, Dnepr and Dnestr, deposited organic-rich material hundreds of kilometers beyond their present mouths forming shelf-edge deltas at the present-day shelf break. After the last sea-level lowstand water level rose, leading to fresh-water outflow from and salt-water inflow into the Black Sea through the Bosporus. As a result of density differences and the absence of complete water-column mixing, the Black Sea became the biggest anoxic basin in the world, covering an area of 423,000 km^2, with favorable conditions for preserving organic material and generating hydrocarbons. Microbial degradation of the organic-rich sediments present in the paleo-deltas has led to the formation of shallow gas associated with prolific gas seepage at the seabed at various shelf-break locations in the Black Sea (Fig. 1.8.). The seeps in the Dnepr paleo-delta are associated with a variety of authigenic carbonate build-ups formed by the anaerobic oxidation of microbial methane (Luth et al., 1999; Peckmann et al., 2001; Thiel et al., 2001; Amouroux et al., 2002; Michaelis et al., 2002). The presence of gas hydrates in the study area is indicated by bottom-simulating reflections (BSRs) on seismic data from -700 m water depth (Lüdmann et al., 2004; Zillmer et al., 2005).

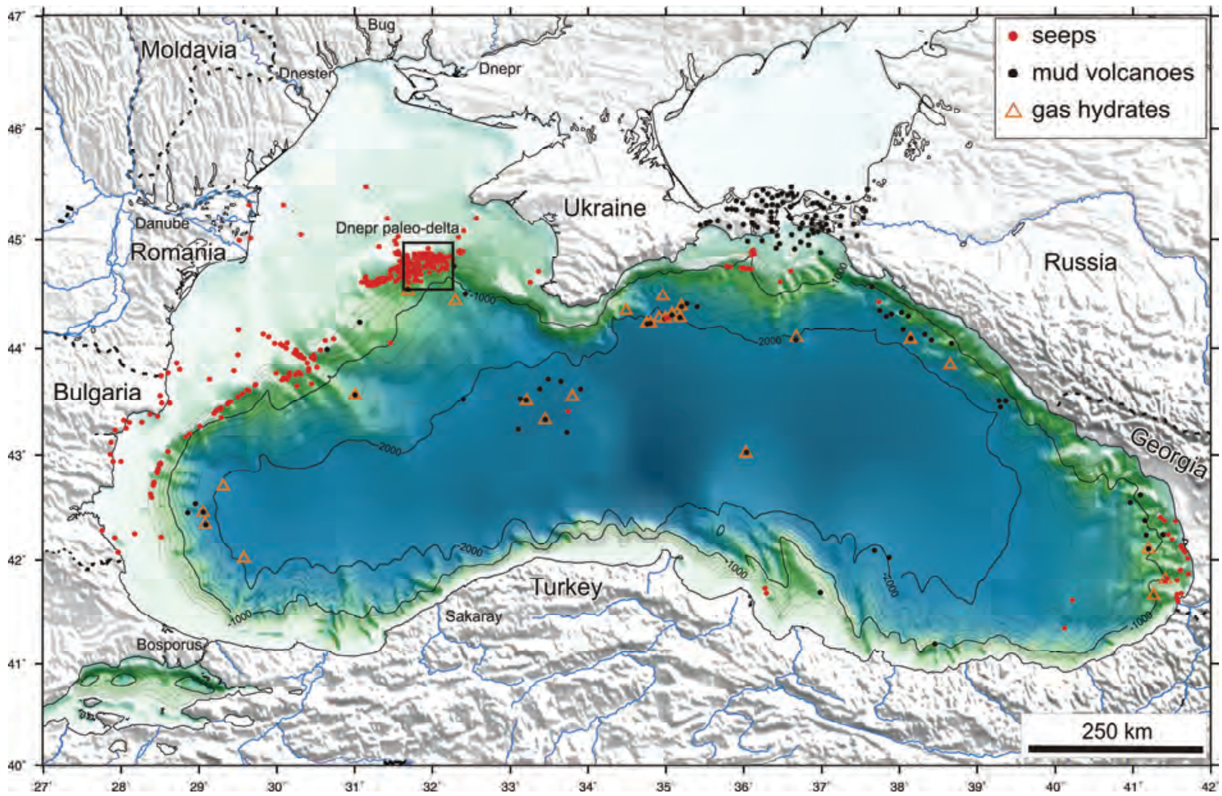

Figure 1.8. Overview map of the Black Sea with indications of seep locations, mud volcanoes and sampled gas hydrates (after Egorov et al., 1998; Naudts et al., 2006; Judd and Hovland, 2007; Popescu et al., 2007).

1.3.2. SW Pacific Ocean – Hikurangi Margin

The Hikurangi Margin in the SW Pacific Ocean on the eastside of the New Zealand's North Island is an active accretionary margin formed by the westward oblique subduction of the Pacific Plate underneath the Australian Plate at a convergence rate of about 40-50 mm/yr (Fig. 1.8.) (Barnes et al., 2010). The 25 Myr old Hikurangi Margins forms the southern end of the Tonga-Kermadec-Hikurangi subduction zone. The Rock Garden study area is positioned above a 3 km high subducted seamount which has strongly deformed and uplifted this part of the Hikurangi Margin (Pecher et al., 2005; Barnes et al., 2010). This area can be regarded as the transition zone between the classic frontal accretionary system in the south and the steeper margin associated with tectonic erosion and subducting seamounts in the north (Barnes et al., 2010). Laterally the Hikurangi Margin can be divided in a western part with an imbricated foundation of pre-subduction accretionary wedge of mainly scraped off Pliocene – Pleistocene trench-fill turbidites. The boundary between these two units may be significant for the distribution of the different seeps sites at the Hikurangi Margin (Fig. 1.10.) (Lewis and Marshall, 1996; Barnes et al., 2010). The Hikurangi Margin comprises six seep areas with a total of 32 seep sites detected by visual or acoustic observations or by sampling of seep fauna or authigenic carbonates (Fig. 1.10.) (Lewis and Marshall, 1996; Greinert et al., 2010). Almost all discovered seeps on the Hikurangi Margins occur within or on the edge of the gas-hydrate stability zone. The presence of gas hydrates on the Hikurangi Margin is indicated by the widespread occurrence of BSRs on seismic data from -650 m water depth (Henrys et al., 2003; Pecher et al., 2010). Notwithstanding the widespread occurrence, gas hydrates have only been sampled at three seep sites (Fig. 1.10.) (Greinert et al., 2010). Hydrates have not yet been retrieved in the Rock Garden study area, although BSRs occur at shallow subsurface depth and even pinch out near the ridge crest. Some of these sites, e.g. the studied Faure Site,

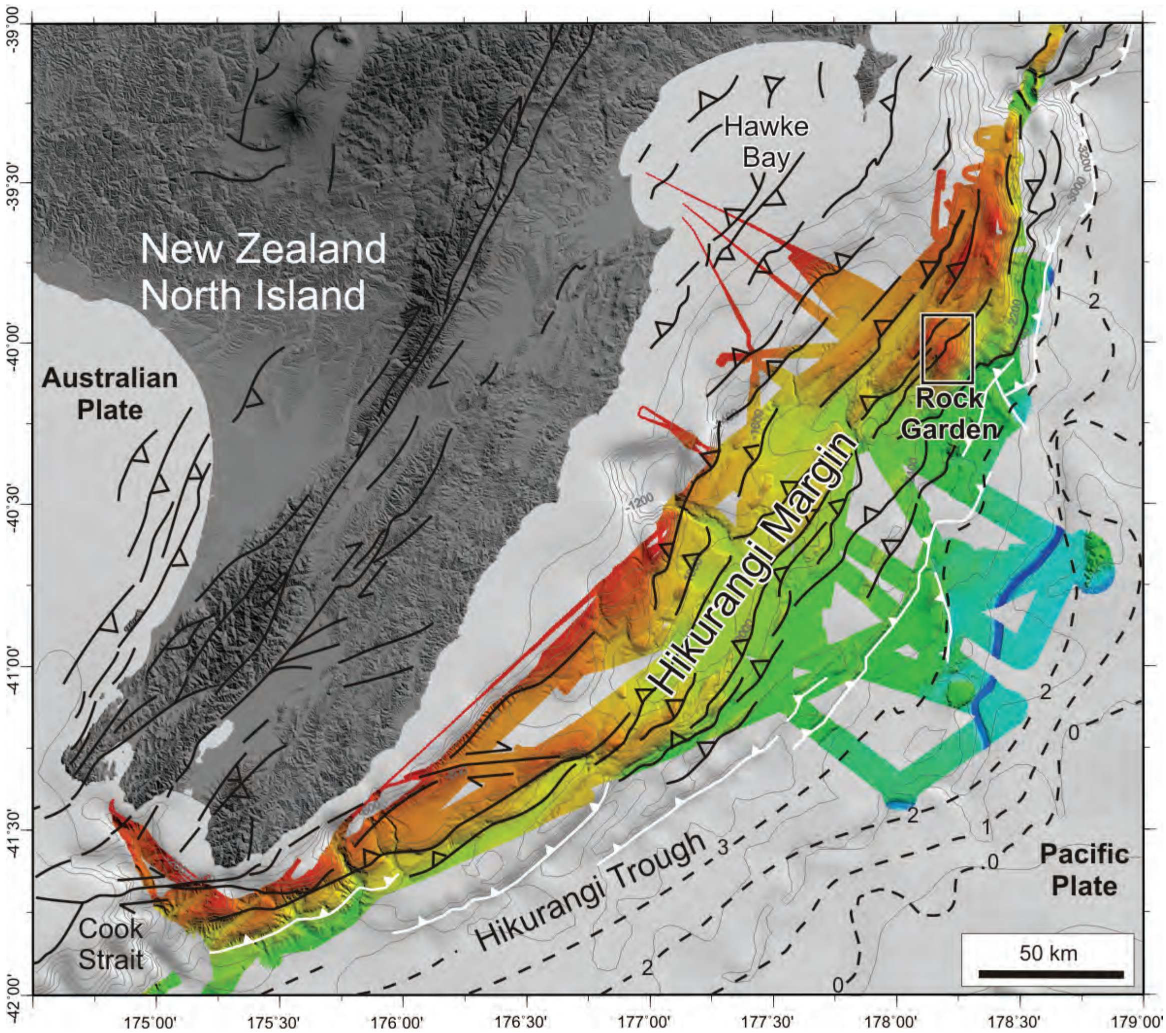

Figure 1.9. Tectonic map of the Hikurangi Margin with indication of the Rock Garden study area. The white trusts represent the principle deformation front, the major active faults are shown in black and the thickness (km) of the trench-fill turbidites is also indicated (after Lewis et al., 1998; Barnes et al., 2010).

are associated with seepage and/or submarine landslides (Pecher et al., 2005; Faure et al., 2006). As for other seep sites in the Hikurangi Margin, deep reaching fractures play an important role in the distribution of seeps in the Rock Garden area (Crutchley et al., this issue).

1.3.3. Lake Baikal – Posolsky Bank

Lake Baikal is a rift lake in Southern Siberia which occupies the three central depressions of the Baikal Rift Zone (BRZ); the Southern, the Central and the Northern Baikal Basins (SBB, CBB & NBB) (Fig. 1.11.). The lake has a maximum depth of -1637 m and it holds 20% of the world's liquid surface fresh water which makes it the deepest lake and the largest lake with regard to volume in the world. The rifting of the BRZ started ca. 30-35 Ma ago as a result of the India-Eurasia collision and is still active at an extension rate of about 4-5 mm/yr (Tapponnier and Molnar, 1979; Petit et al., 1997; Calais et al., 1998; Petit et al., 1998). The three basins are separated by two structural highs; the Selenga Delta Accommodation Zone (SDAZ) between the SBB and the CBB, and the Academician Ridge Accommodation Zone (ARAZ) between the CBB and NBB. The three Baikal Basins have a clear asymmetric geometry with large displacement faults at their western borders and small normal faults at their eastern borders (Fig. 1.1.)

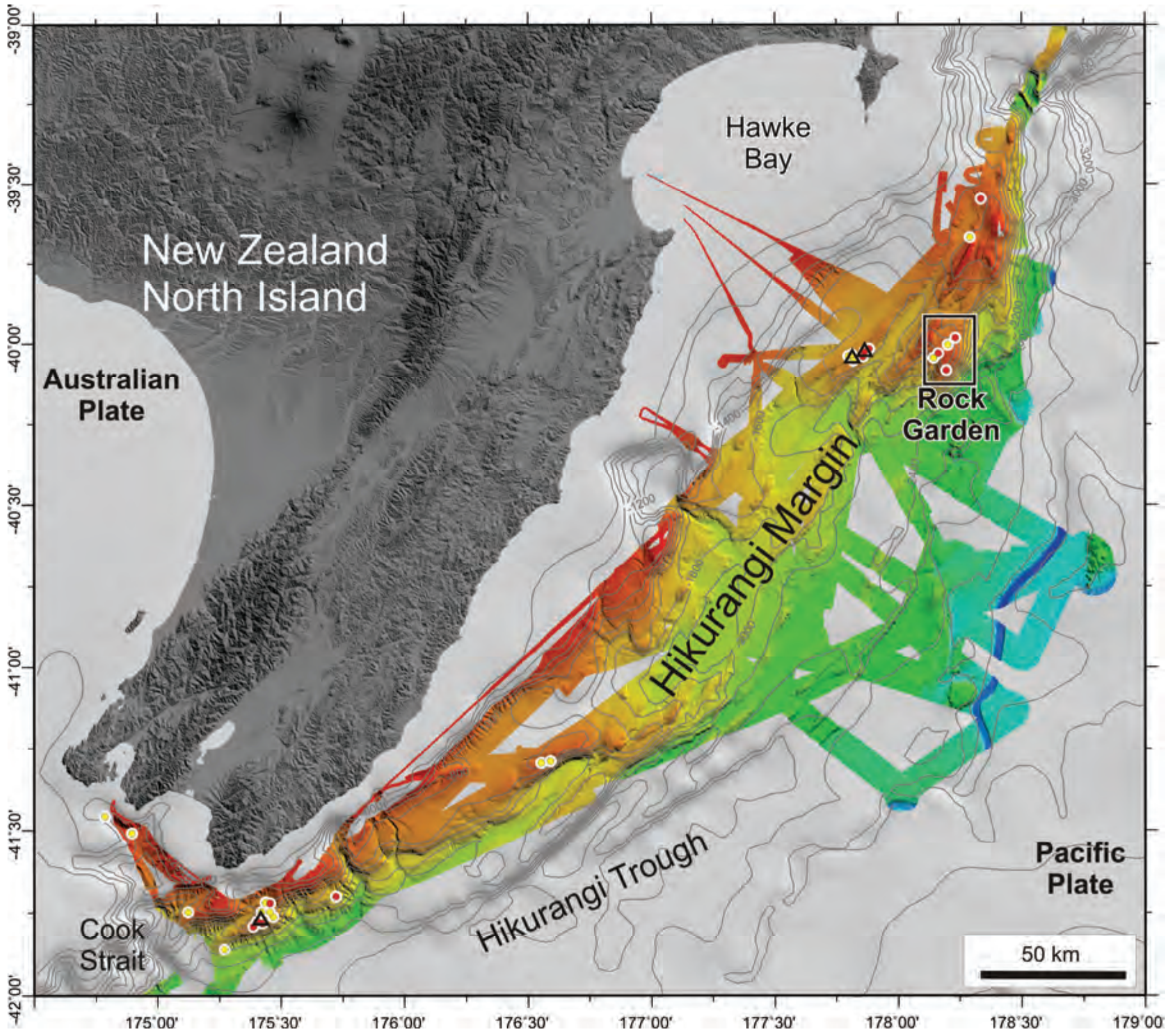

Figure 1.10. Overview map of the Hikurangi Margin with indications of seep locations (red dots), gas seepage indicators (yellow dots) and sampled gas hydrates (black triangles) (Greinert et al., 2010).

(Hutchinson et al., 1992; Mats, 1993; Scholz et al., 1993). Sediment thickness in the basins varies between 4.4 km in NBB, over 7 km in SBB to 7.5 km in the CCB (Kontorovich et al., 2007). The study area, the Posolsky Bank fault block, is located near the Posolsky Fault which is an eastern segment of the Obruchevsky Fault that marks the western margin of the SBB (Fig. 1.11.). The Posolsky Bank structurally belongs to the SDAZ (Scholz and Hutchinson, 2000; Bezrukova et al., 2005; Charlet et al., 2005).

The presence of seeps in Lake Baikal was already described in ancient records reporting on areas with absent ice cover in winter ('ice streamthroughs'), abundant fish deaths and observation of bubbles at the lake surface (Fig.1.12.) (Granin and Granina, 2002). Since the observation of BSRs on seismic recordings and the subsequent sampling of deep hydrates during the Baikal Drilling Project (BDP-97), methane seeps, oil seeps and gas-hydrate-bearing mud volcanoes have been discovered on many locations in the SBB and the CBB (Fig. 1.12.) (e.g. Hutchinson et al., 1991; Golmshtok et al., 1997; Vanneste et al., 2001; Williams et al., 2001; Klerkx et al., 2003; Matveeva et al., 2003; Khlystov, 2006; Klerkx et al., 2006). All mud volcanoes occur at locations with an anomalous shallow BSR near major faults. Geothermal fluid pulses along these large faults are believed to have led to hydrate destabilization and source the mud volcanoes (Vanneste et al., 2001; De Batist et al., 2002; Van Rensbergen et al., 2002; Vanneste et al., 2002; Klerkx et al., 2006). Notwithstanding the occurrence of gas-bubble release at some of the

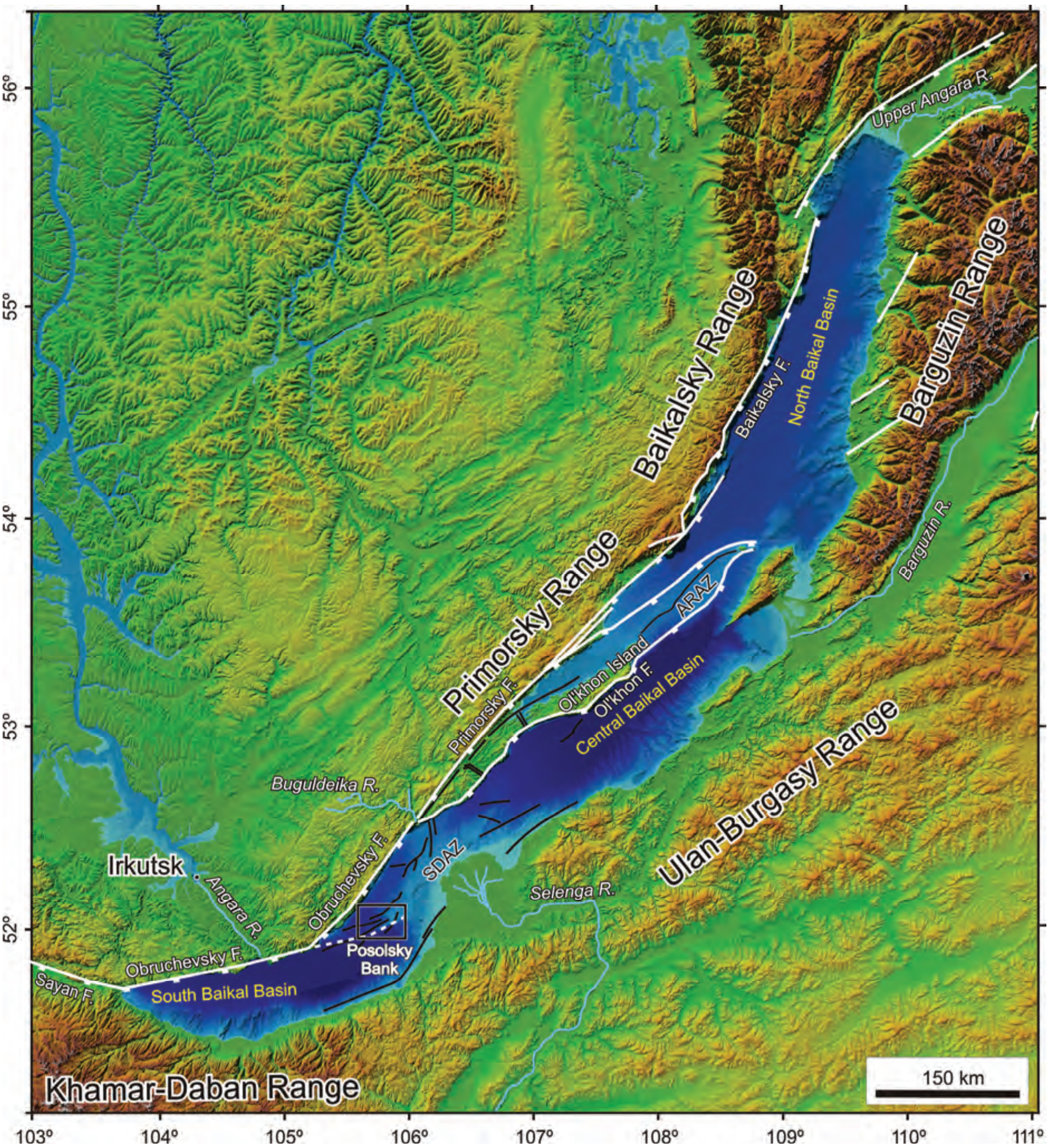

Figure 1.11. Tectonic map of Lake Baikal with indication of the Posolsky Bank study area (Klerkx et al., 2006). (Abbreviations: SDAZ—Selenga Delta Accommodation Zone; ARAZ—Academician Ridge Accommodation Zone).

mud volcanoes, a majority of the methane seeps occur outside of the gas-hydrate stability zone near deltas or canyons (Granin and Granina, 2002). The seeps on the Posolsky Bank are unique since they occur on the scarp of a tilted fault block, outside of the GHSZ. Furthermore, the released methane has a mixed microbial-thermogenic origin with a small ethane admixture (Kalmychkov et al., 2006).

1.4. Methods

Since the release of gas bubbles and its associated features are often associated with disturbances of the natural environment they cause different anomalies in a variety of datasets. To better understand the distribution of and the controls on gas-bubble releasing seeps different datasets have been integrated. This includes water-column data, seafloor data

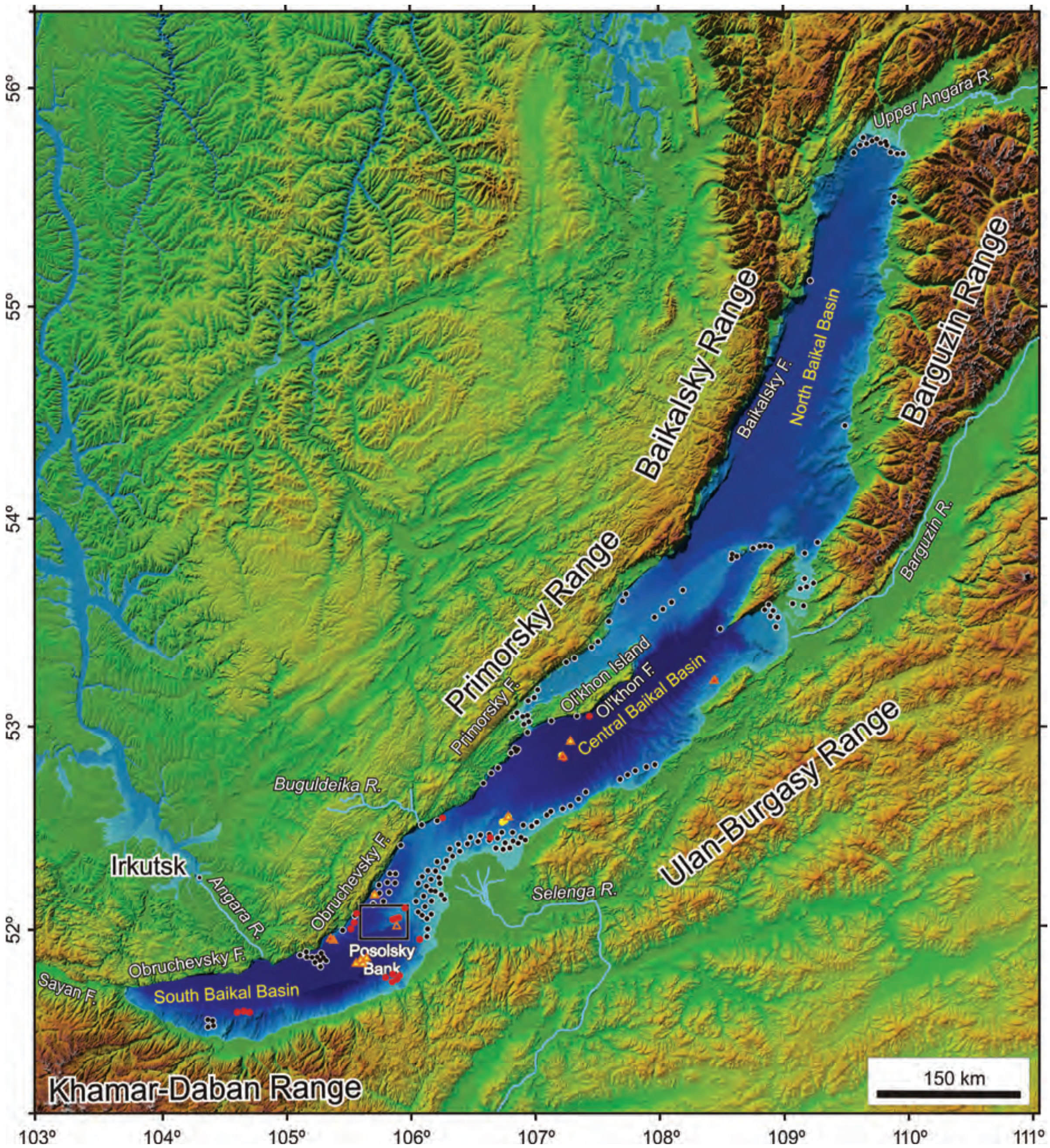

Figure 1.12. Overview map of Lake Baikal with indications of seep locations (red dots), gas seepage indicators (black dots), mud volcanoes (yellow dots) and sampled gas hydrates (orange triangles) (Granin and Granina, 2002; Klerkx et al., 2006; Schmid et al., 2007).

and subsurface data. This study mainly used acoustic methods since they are strongly affected by the occurrence of free gas in different media.

1.4.1. Water-column data

The hydro-acoustic water-column data is the essential dataset for this study, since the high impedance contrast between free gas and water allows the detection and positioning of gas-bubble release from the seafloor into the water column over vast areas in a limited time span (Greinert et al., 2006; Artemov et al., 2007). Bubbles in the water column have been detected with single-beam echosounders in all three study areas (Fig. 1.13.). On such echosounder records the rising bubbles form acoustic anomalies that are commonly referred to as "flares".

On the Black Sea a hull-mounted SIMRAD EK500 dual-frequency (38-120 kHz) split-beam echosounder was used which operates with a total beam width of 7°. Bubble detection on the Hikurangi Margin was performed with two echosounder systems a SIMRAD EK500 using 12 and 27 kHz and a SIMRAD ES60 using 38 kHz. On Lake Baikal also two different echosounder systems were used; a FURUNO-1000 and a FURUNO-1100, both operating at 28 kHz. All these systems are able to detect rising bubbles with sizes ranging from mm to cm scale (see chapters 2-6).

Flares were even observed on high-resolution seismic data (5 kHz). Visual observation of seeps in the Black Sea was also performed with a submersible and video sled (Fig. 1.13.). On the Hikurangi Margin gas bubbles were detected with the forward-looking sonar (325-675 kHz) installed on the ROV and by visual ROV observations (Fig. 1.13.) (see chapters 2-6).

From all the used methods, seep detection by the use of echosounders is the most effective since a large area can be covered even during deployment of other gear. Furthermore, very small bubbles can be detected, which are visually sometimes hard to indentify. Visual observations have the advantage of being able to pinpoint the bubble-releasing location on the seafloor with a higher accuracy than what can be achieved by echosounders. They also allow monitoring of the seep activity, accurate flux determinations and observations of seep-related seafloor manifestations. But deployments of ROVs or submersibles are much more cumbersome and the area covered on the seafloor is much smaller.

1.4.2. Seafloor data

Since active seep sites are often associated with typical seafloor morphologies, with chemosynthetic faunal communities or with authigenic methane-derived carbonates, they are relatively easy to be observed by a wide range of seafloor observations, even at instances without active release of bubbles. For this study two different types of seafloor data were used: acoustic seafloor data from multibeam and side-scan sonar measurements and visual seafloor observations done with a ROV, with a submersible, with a video sled or with other TV-guided equipment (Fig. 1.13.).

On the Black Sea and on Lake Baikal a 50 kHz SeaBeam 1050 swath system was used that was operated with 120° swath, transmitting and receiving 108 beams of 3° by 3° beam angle. At the Hikurangi Margin different, lower frequency systems were used adapted to the larger water depth. The used multibeam systems were the SIMRAD EM120 which operates at 20 kHz with 191 beams of 2° by 2° beam angle and the SIMRAD EM 300 which operates at 30 kHz with 135 beams of 2° by 2° beam angle. Besides obtaining the water depth, all used multibeam systems were able to record the raw backscatter data which gave extra information about the nature of the seafloor near the seep sites (e.g. presence of MDACs, etc.). In the Black Sea, backscatter seafloor data was also obtained by side-scan sonar measurement with the SONIC-3 sonar system (30 kHz). In case of the Black Sea, the results from the multibeam system was more useful than the data obtained from the side-scan sonar, since the multibeam backscatter data is correctly positioned at the seafloor, which is not the case for the side-scan sonar data, even with the side-scan data having a larger theoretic horizontal resolution than the multibeam backscatter data (0.5 m by 0.5 m versus 5 m by 5 m) (see chapters 2-6).

The visual observation techniques discussed in section 1.4.1. have also been used for seafloor observations. From all used visual observations techniques it is clear that the ROV and submersible are most suited for detailed long-term (minutes to hours) observation of seeps and the surrounding seafloor. Video sleds and other TV-guided equipment have the advantage of being less complicated and are ideal for making transects but they normally don’t have the capability of sampling gas or rocks (see chapters 2-6).

As for the water-column observations, large seafloor observations are best done with acoustic methods which are able to cover a lot of ground in rather small time spans. Possible interesting areas indicated by the acoustic observations can then be inspected by visual

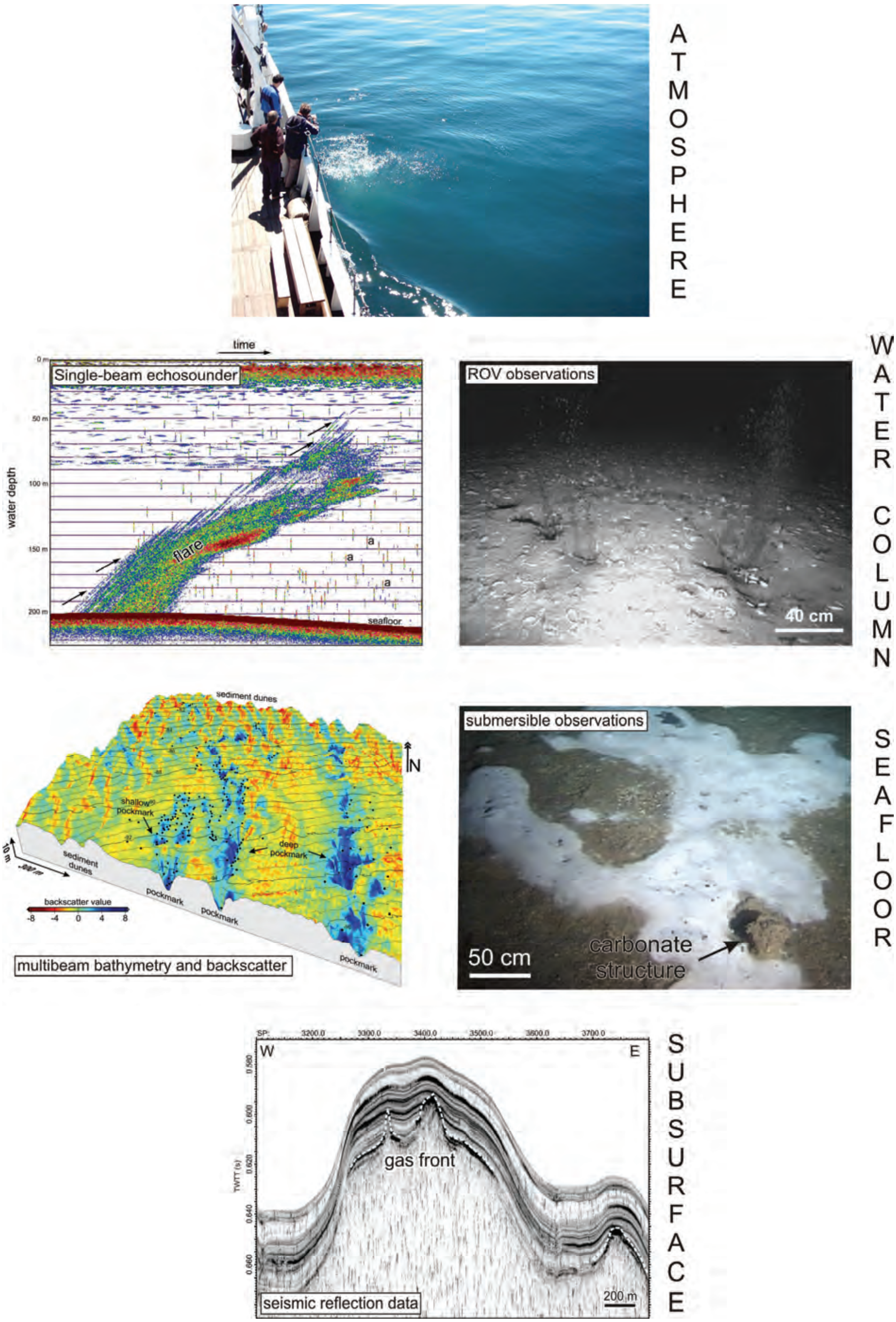

Figure 1.13. Overview of the main datasets used in this study.

seafloor observations which allow very detailed seafloor characterization.

1.4.3. Subsurface data

The presence of seep sites on the seafloor is often indicated by shallow gas in the subsurface. Different kinds of seismic reflection data has been used to image the presence, the behavior and the kind (i.e. free gas versus hydrate) of shallow gas in the subsurface (Fig. 1.13.). In the Black Sea, sediment coring was undertaken to investigate possible correlations between high-backscatter patches on multibeam data, seep occurrences and shallow gas. For the Lake Baikal study, seismic reflection data was used to make calculations for heat flow and hydrate stability.

Four types of seismic reflection data were acquired using four different sources (5 kHz pinger, SIG-sparker, CENTIPEDE sparker and GI-gun) each within a different frequency range showing different aspects of the subsurface geology and shallow gas distribution. The very shallow was investigated using a deeptow 5 kHz pinger with a theoretical resolution of 30 cm, for a maximum penetration of 35 ms two-way travel time (TWTT). To achieve a bit more penetration, single-channel reflection data were collected with a SIG and with a CENTIPEDE sparker source with a passive surface streamer with 10 hydrophones. The SIG has a central frequency of 500-700 Hz and a theoretical resolution of 1 m, for a maximum penetration of 200-300 ms TWTT. Whereas the CENTIPEDE has a central frequency of 1100-1200 Hz and a theoretical resolution of 70 cm, for a maximum penetration of 100 ms TWTT. Possible hydrate reservoirs in the Black Sea were visualized with multi-channel seismic data acquired with a GI-gun source (central frequency of 150 Hz) and a passive surface streamer with 16 hydrophone groups. The theoretical vertical resolution of the GI-gun data is 6 m and the maximum penetrations is 600 ms TWTT.

As indicated in the previous paragraph each seismic source has its own characteristics, sources with higher frequency have higher resolutions and are more affected by shallow gas, whereas sources with a lower frequency have lower resolutions but are able to visualize the deeper subsurface even with the presence of near surface shallow gas. A nice comparison of the different seismic reflection techniques and its application for shallow gas detection is given in chapter 2, as well as in chapter 3, 4 and 6.

1.5. Project framework

The datasets obtained for this study came from the EC-FP5 project CRIMEA (Black Sea), the New Vents SO191 cruise (New Zealand), several BELSPO and INTAS projects and an FWO "Krediet aan Navorsers" project (Lake Baikal).

<u>Dnepr paleo-delta (Black Sea)</u>
The EC-FP5 project CRIMEA ("Contribution of high-intensity gas seeps in the Black Sea to methane emission to the atmosphere") (2003-2006) studied and quantified the transfer of methane emitted at bubble-releasing seeps at the seafloor through the water column and into the atmosphere. This RCMG-UGENT coordinated project focused on the Dnepr paleo-delta area and the Dvurechenskiy mud volcano area in the Ukrainian Part of the Black Sea. As RCMG-UGENT, we were responsible for the geological characterization of the seep areas; e.g. subsurface methane sources, the migration pathways and controls on seep distribution. The results obtained in the Dnepr paleo-delta are described in CHAPTER 2-4 (Naudts et al., 2006; Naudts et al., 2008; Naudts et al., 2009)

<u>Hikurangi Margin (SW Pacific Ocean)</u>
The SO191 expedition to the Hikurangi Margin (2007) was funded by the Federal Ministry of Education and Research (Germany) in the framework of the COMET project within the R&D program GEOTECHNOLOGIEN (grant 03G0600D and 03G0191A). The ROV work during the SO191 cruise was co-funded by FWO Flanders. The purchase of the ROV was possible thanks to an Impulsfinanciering of the Special Research Fund of Universiteit Gent. The SO191 expedition focused on seeps and associated gas hydrates at the Hikurangi Margin to better understand the role of methane in the global biogeochemical cycle. The results obtained with the ROV and other TV-guided gear in the Rock

Garden area of the Hikurangi Margin are described in CHAPTER 5 (Naudts et al., 2010).

Posolsky Bank (Lake Baikal)
The data studied from Lake Baikal were obtained within the framework of the BELSPO-project "Gas hydrates and gas seeps in Lake Baikal" (1998-2001), the BELSPO-project "Gas hydrates and gas seeps in Lake Baikal (Phase 2)" (2001-2003), the INTAS-project "Assessment and evaluation of gas hydrates in Lake Baikal" (1998-2000), the INTAS-project "A new bathymetric computer map of Lake Baikal" (2000-2002), the INTAS-project "MULTISGAS - Multidisciplinary study of natural gas seeps in Lake Baikal" (2002-2004) and the FWO project Krediet aan Navorsers L. Naudts "Detailkartering van actieve methaanbronnen, moddervulkanen en gashydraten in het Baikalmeer door middel van multibeam-bathymetrie" (2009). All of these projects had mainly the goal to assess the distribution of gas hydrates, mud volcanoes and seeps in Lake Baikal. For this study all available data within the Posolsky Bank area was combined to understand the present seep sites, as described in CHAPTER 7 (Naudts et al., submitted).

1.6. Thesis outline

The thesis consists of a general introduction chapter, followed by a result part consisting of five chapters which are followed by a discussion/conclusion part consisting of two chapters. The first four chapters of the result part (CHAPTER 2 - CHAPTER 5) have been published in international peer-reviewed journals; the remaining CHAPTER 6 is submitted. Since each of these chapters has been published individually an overlap regarding introductions and methodologies is unavoidable; this however allows the separate reading of each chapter. A number of other relevant papers published during the time of this study can be found in the publication list added in appendix A. Since a large time of this study has been spend on research expeditions, an overview is given in appendix B.

CHAPTER 2 gives an overview of shallow gas, gas-hydrate occurrence and bubble-releasing seeps and their detection by geophysical methods. Taking into account the used methods and datasets this chapter can be seen as an introduction chapter to CHAPTER 3-6. This chapter has been published as: *Naudts, L., De Batist, M., Greinert, J., Artemov, Y., 2009. Geo- and hydro-acoustic manifestations of shallow gas and gas seeps in the Dnepr paleo-delta, northwestern Black Sea. The Leading Edge 28, 1030-1040.*

CHAPTER 3 reports on the large scale geological controls on seep distribution in the Dnepr paleo-delta, northwestern Black Sea. This chapter gives also an overview of different seafloor morphologies that are associated with bubble-releasing seeps in the Black Sea and other seep areas. The almost 3000 detected seeps in this area, makes the Dnepr paleo-delta one of the largest known seep areas in the world. This chapter is published as: *Naudts, L., Greinert, J., Artemov, Y., Staelens, P., Poort, J., Van Rensbergen, P., De Batist, M., 2006. Geological and morphological setting of 2778 methane seeps in the Dnepr paleo-delta, northwestern Black Sea. Mar. Geol. 227, 177-199.*

CHAPTER 4 focuses on the shelf area of the Dnepr paleo-delta seep area discussed in CHAPTER 3, more precisely on the relation between high acoustic seafloor backscatter and the associated local distribution of seeps. Analyses of geophysical, geochemical and seafloor observations identified methane-derived authigenic carbonates as the being the main cause for the enhanced backscatter and associated seeps distribution. This chapter is published as: *Naudts, L., Greinert, J., Artemov, Y., Beaubien, S.E., Borowski, C., De Batist, M., 2008. Anomalous seafloor backscatter patterns in methane venting areas, Dnepr paleo-delta, NW Black Sea. Mar. Geol. 251, 253-267.*

CHAPTER 5 looks at two different seafloor manifestations of bubble-releasing seeps on the Hikurangi Accretionary Margin, east of New Zealand's North Island. Seafloor observations made by a ROV and other TV-guided gear integrated with seismic and geochemical data allowed explaining the differences between the two seeps sites in regard to the depth of the gas-hydrate stability zone and the tectonic history. This chapter is published as: *Naudts, L., Greinert, J., Poort, J., Belza, J., Vangampelaere, E., Boone, D., Linke, P., Henriet, J.P., De Batist, M., 2010. Active venting sites on the gas-hydrate-bearing Hikurangi Margin, Off New Zealand: Diffusive- versus bubble-released methane. Mar. Geol.272, 233-250.*

CHAPTER 6 deals with bubble-releasing seeps in the rift-lake environment of Lake Baikal. The seeps on the Posolsky Fault Scarp near the crest of the Posolsky Fault Block are fed by gas coming from below the gas-hydrate stability zone. The fault associated with the seepage rather cuts off the gas-bearing layers than acts as a fluid conduit. This chapter is submitted as: Naudts, L., Khlystov, O., Granin, N., Chensky, A., Poort, J., De Batist, M., submitted. *Stratigraphic and structural controls on the location of active methane seep on Posolsky Bank, Lake Baikal.* Mar. Pet. Geol.

CHAPTER 7 integrates all findings discussed in the previous chapters with published data from other bubble-releasing seep site in the world to come up with the similarities and differences in geological controls on the distribution of seeps. This chapter also discusses if these similarities or differences are related to the specific geological setting.

CHAPTER 8 gives an overview of the final conclusions and raises some questions which have originated from this study.

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