UNIVERSITY OF TROMSØ UIT

THE FACULTY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF GEOLOGY

# A multidisciplinary subsurface analysis of mud volcanoes and salt diapirs in European Seas

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A dissertation for the degree of
Philosophiae Doctor

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‘I demolish my bridges behind me - then there is no choice but forward’

*Fridtjof Nansen*

# Preface

My PhD thesis was carried out at the Department of Geology of the Faculty of Science and Technology at the University of Tromsø (UiTø), from November 2005 to October 2008. A sick leave caused a delay but I was able to continue my thesis while working at Bellona Foundation (Oslo), which allowed me to finish and submit my PhD thesis in July 2012. Financing for this project was provided by the European funded Hotspots Ecosystem Research at the Margins of the European Seas (HERMES) project (75%) and the University of Tromsø (25%). During that twenty five percent of my time financed by the University of Tromsø I assisted in teaching and preparation of field courses onboard R/V Jan Mayen (renamed to RV Helmer Hanssen in 2012). At the end of 2006, I had a three weeks stay at IFREMER (Brest, France) for processing high-resolution sediment profiler and very-high resolution 2D acoustic data. Results of this work are part of Paper I presented in my thesis. A six months stay at the National Oceanography Center in Southampton (UK) was dedicated to the interpretation and discussion of high resolution 3D seismic data with my co-supervisor Prof. Dr. Christian Berndt (now at IFM-GEOMAR, Kiel, Germany).

Additional three weeks at IFM-GEOMAR were used for Multi-Sensor Core Logger (MSCL) data interpretations. National and international cruises allowed me collecting data from the Barents Sea and the Western Moroccan margins. Indeed, my offshore field work allowed me to benefit from close collaboration with different research groups and disciplines from geophysics, sedimentology and geochemistry.

My dissertation consists of an introduction and a total four papers (two published and two submitted). The introduction aims to explain the overall objectives integrating the different research topics dealt by the individual papers. The main topic, fluid flow in continental margins of the European seas, focus on the morpho-structural analysis of seabed features linked to sediment mobilisation processes (mainly submarine mud volcanoes and salt diapirs) and how are they influenced by their source areas. Trigger mechanisms for the targeted seabed structures are here related to mass wasting events in Paper I, salt diapirism (Papers II-IV) and clay mineral dehydratation in Paper II and III and a diffuse flow at Paper IV related to salt diapirism. The results of this research have been presented at various international conferences and led to the following four scientific articles:

Paper I:

Perez-Garcia C., Feseker T., Mienert J., Berndt C., 2009. The Håkon Mosby Mud Volcano: 330 000 years of focused fluid flow activity at the SW Barents Sea slope. Marine Geology 262, 105-115, doi: 10.1016/j.margeo.2009.03.022.

Paper II:

Perez-Garcia, C., C. Berndt, D. Klaeschen, J. Mienert, L. Haffert, D. Depreiter, and M. Haeckel, 2011. Linked halokinesis and mud volcanism at the Mercator mud volcano, Gulf of Cadiz. Journal of Geophysical Research. 116, B05101, doi:10.1029/2010JB008061.

Paper III:

Haffert L., Haeckel M., V. Liebetrau, C. Berndt, M. Nuzzo, A. Reitz, F. Scholz, J. Schönfeld, C. Perez-Garcia, S.M. Weise, Fluid evolution and authigenic mineral paragenesis related to salt diapirism – the Mercator mud volcano in the Gulf of Cadiz. *Paper submitted to Geochimia et Cosmochimia Acta, 2012.*

Paper IV:

Perez-Garcia, C., Safronova, P., Mienert, J., Berndt, C. and Andreassen, K. Extensional rise and fall of a salt diapir in the Sørvestsnaget Basin, SW Barents Sea. *Paper submitted to Marine and Petroleum Geology, 2012.*

# Table of contents

## Papers I-IV

## Scope of the Thesis

Understanding how mud volcanoes and cold seep sites on continental margins function and how they are distributed (Figure 1) is important for quantifying their contribution to the global biogeochemical carbon cycle and for assessing their role in climate change (e.g. Dimitrov, 2002; Kvenvolden and Rogers, 2005).

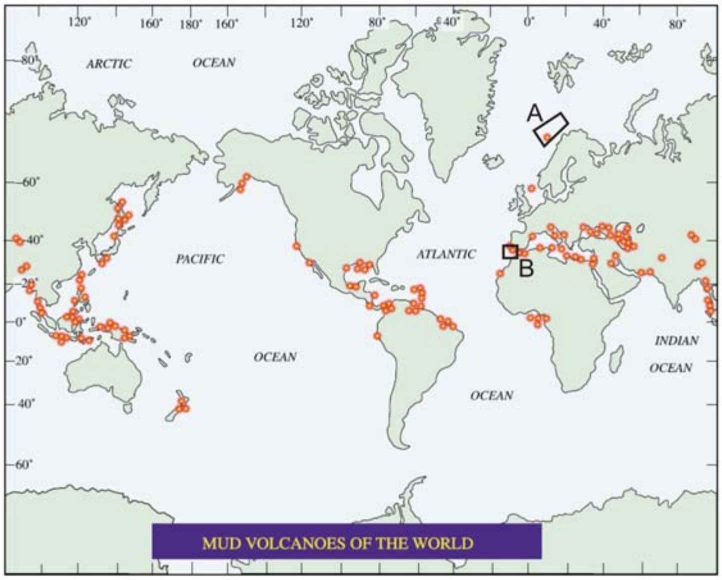

Figure 1. Map showing the global distribution of onshore and offshore mud volcanoes (red dots). Black boxes mark the study areas of this PhD thesis: a) the SW Barents Sea and b) the western Moroccan Margin in the Gulf of Cadiz. Figure modified from Kvenvolden and Rogers (2005).

Mud volcanoes and cold seeps have been an important target for the Hot spots Ecosystem Research on the Margins of European Seas (HERMES) project due to their control on deep sea biota and on carbon and sulphur turnovers at European margins (Foucher et al., 2009). A challenging issue for the HERMES research community was to understand the temporal variability of fluid flow activity at such seep sites. A comprehensive understanding of fluid flow related systems is only possible through a multidisciplinary integration of studies integrating shallow and deep processes. Hence there is a need for integration of geological, geophysical and geochemical information studying different aspects of fluid flow and sediment mobilization. So far, understanding of marine mud volcanoes has been largely hampered by insufficient seismic imaging capabilities and insufficiently -constrained eruption histories.

As a contribution to the comprehensive and interdisciplinary objective of the HERMES project, my PhD thesis aims to improve the current understanding of complex plumbing systems of submarine mud volcanoes, their trigger mechanisms and their periodic activity. My thesis focuses on two targeted areas by the HERMES research community: a) the Håkon Mosby mud volcano and the

Sørvestsnaget basin salt diapir, both located at the SW Barents Sea margin and b) the Mercator mud volcano located at the western Moroccan margin (Gulf of Cadiz) (Figure 1). The two tectonically different geological settings were chosen to study triggering mechanisms for sediment mobilization and plumbing systems controlled by a) pressure and differential density between sedimentary layers and b) external factors such as the tectonic regime and sediment deposition/erosion.

The main objective of my PhD thesis is to understand and constrain the geological processes that control the evolution of sediment mobilisation structures at two locations including mud volcanoes and salt diapirs (or both) (Figure 1). For this purpose, papers I and II are dedicated to the 3D seismic analysis of the internal structure of mud volcanoes and their plumbing systems that includes an analysis of their feeder conduits, mud extrusion (type, magnitude and periodicity) and trigger, focused on mass-wasting events and salt diapirism. Paper IV is dedicated to the study of the dynamics of a salt diapir (as a structure that results from sediment mobilisation) by using the seismic character to infer kinematic phases and related morphology. In addition, geothermal and geochemical data support seismic observations in papers I and II, respectively. Paper III focuses on the origin of fluids of the Mercator mud volcano, on which I collaborate providing geophysical data to geochemical data and interpretations.

# Introduction

## Fluid and sediment dynamics

Different seabed features (i.e. pockmarks and mud volcanoes) are formed as fluid and sediment migrate upwards and emerge from the seabed. Pockmarks and mud volcanoes may act as “windows” to depths otherwise inaccessible, constituting a natural laboratory of the Earth’s subsurface (Kopf, 2002). Since their discovery in the 60’s, there has been a growing awareness that dynamic geological processes at the seabed-seawater interface are of fundamental importance to the nature and composition of the marine environments, not only to marine geology, but also to chemical and biological composition of the oceans. Methane ($CH_4$) is the most common expelled gas from seabed features (Schoell, 1988) and constitutes the main nutrient for deep-marine seafloor ecosystems that synthesizes methane with other components to organic matter, reducing its discharge to the ocean and atmosphere (Hovland and Judd, 1988; Foucher et al., 2009). When released to the atmosphere, the effect of methane as greenhouse gas is 20 times higher than carbon dioxide ($CO_2$) (Khalil and Rasmussen, 1995). Therefore, the preservation of methane-dependent marine ecosystems is of importance for the global environment.

The nature and distribution of fluid expulsion features on the seabed are dependent upon the supply of deep fluids, the velocity of the flux, the width of feeder systems and the formations (rock and/or sediment) through which fluids migrate. To understand the formation of seabed fluid flow features and processes, various physical forces, including external triggers, must be considered. My PhD thesis integrates geophysical observations with geochemical and geothermal measurements.

In order to understand the complex interaction of multiple processes and how these differ for the completely different study areas (papers I to IV), a brief introduction to fluid migration, sediment mobilization and mud volcano expression is given in the following subsections.

### *Driving forces for fluid and sediment flow: overpressure and buoyancy principles*

Fluid dynamics is the generic term for the discipline that deals with fluid flow, the natural science of liquids and gases in motion. In the subsurface, the pressure difference between the pore fluid within a permeable sedimentary rock and a lower pressured sediment overburden will cause fluids to migrate. The pressure difference consists of two components acting within the pore space of pressurized sediments: 1) a pressure gradient in the water phase, often directly related with the generation of overpressure, and 2) fluid buoyancy that further elevates the pressure difference resulting in increased fluid flow. Flow is composed of water, hydrocarbons (mainly gas) or both, and if it is sufficiently vigorous, unconsolidated sediment may be mobilized as well (Huuse et al., 2010).

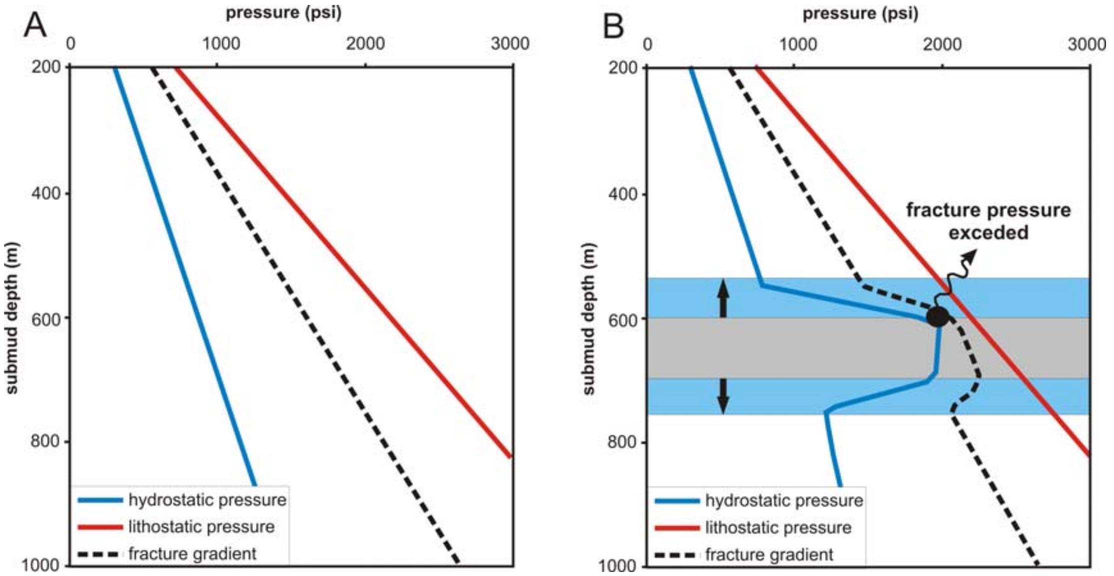

Figure 2. Schemiatic pressure-depth diagrams showing (a) the relationship between the lithostatic pressure, fracture pressure and pore fluid pressure, and (b) the increase of hydrostatic pressure within a low-permeability interval (grey), potential pressure gradients for both upward and downward flow (blue zone). High fluid flow velocities may be attained when the fracture pressure is exceeded. This typically occurs first within the top of the overpressured interval (b). Figure modified from Jonk (2010).

Overpressure: As sediments are deposited, seawater contained into the pore space is expelled upwards and into the water column during sediment consolidation. As water is essentially incompressible, the instantaneous loading of a sediment layer causes an immediate increase in the pore fluid pressure of the entire sediment section below, which creates a pressure gradient that causes fluid to flow upward until sufficient fluid is expelled to reduce the pressure gradient allowing normal compaction (Jonk, 2010) (Figure 2a). The fluid flux ($q$) required to re-establish a normal hydrostatic gradient is described by Darcy's law:

$$q = \frac{\mathrm{K}}{\mu} \nabla P \tag{1}$$

, where $K$ is the 3D permeability tensor of the basin, $\nabla P$ is the potential created by the deviation of fluid pressures from the hydrostatic and μ is the viscosity of the fluid.

If the sedimentation rate exceeds the rate of fluid drainage, the pore fluid will carry some of the weight of the overburden, resulting in the maintenance of anomalously high pore fluid pressure, a process referred to as disequilibrium compaction or undercompaction (Osborne & Swarbrick, 1997), creating overpressure (Figure 2b). The occurrence of overpressure becomes more frequent with depth as porosity (and so, permeability) decreases. In addition to lithostatic loading, a range of additional mechanisms for overpressure built up is possible (Maltman and Bolton, 2003) (Figure 3). Causes for deep-fluid overpressure are several, among the most cited are smectite-to-illite transformation (Paper II and III) and hydrocarbon (gas) generation (Paper I) (Osborne & Swarbrick, 1997). Any amount of fluid overpressure may result in fluid flow, the rate of which is governed by the 3D permeability tensor of the subsurface surrounding the pressure anomaly, regardless of the mechanism of overpressure (Jonk, 2010).

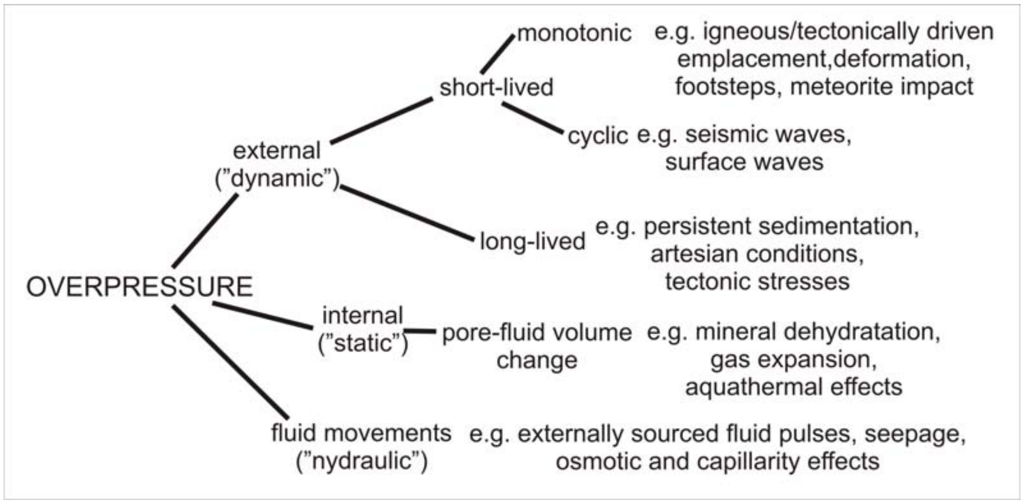

Figure 3. Conceptual figure for the range of overpressure processes that may affect sediments in addition to progressive burial due to continued sedimentation. Figure modified from Maltman and Bolton (2003).

Rapid fluid flow is only established when a significant potential pressure gradient exists along a high-permeability feature, i.e.: a) creating or re-opening of high-permeability fractures connected from normally pressurized to overpressurized formations (e.g. the Håkon Mosby Mud Volcano, Paper I), and b) tilting of high-permeability stratigraphic features that connect deep overpressured formations with shallow normally pressured formations (such as growth faulting or salt withdrawal) (Sibson 2000; Jonk, 2010) (e.g. Mercator Mud Volcano and Sørvesnaget Basin cases, papers II-IV).

Buoyancy**:** Buoyancy of a sediment body is a function of bulk-density contrasts. When bulk density decreases with depth there is a density inversion (Maltman and Bolton, 2003; Jonk, 2010):

$$BF_p = (\rho_p - \rho_{os}) \cdot g \cdot h_p \tag{2}$$

, where $BF_p$ is the buoyancy of the sediment layer (the 'parent' formation); $\rho_p$ is the bulk density of the parent sediment; $\rho_{os}$ is the bulk density of the overlying sediment; and $h_p$ is the height (thickness) of the parent sediment.

It makes no difference whether the inversion is primary (a function of the nature of the sediment) or secondary (resulting from changes caused by diagenesis, metamorphism, or changes to the fluid content or pressure). However, the presence of free gas (methane) within the pore space of sediments is particularly influential due to the low density of gas even when compressed. In near-seabed sediments where methane density is not much higher if compared to the surface (0.0007 g $cm^3$ at 0˚C and atmospheric pressure), the bulk density of typical sediments will be reduced by about 1% for every 1% by volume increase in gas content. There are two potential outcomes of density inversion, i.e., a) the underlying sediment push through the cap rock to flow, or b) the excess of pore fluids cause fluidisation of sediment particles (Jonk, 2010).

Before the underlying, buoyant sediment can flow upwards, its buoyancy force must exceed the strength of the overlying sediments (papers I, II and IV). Typically, upward migration initiates in areas where features such as topographic highs or faults exist. Any vertical inhomogeneities in sedimentary basins may attract fluid migration. Once started, the balance of forces between buoyancy and strength of sediment overburden may favor the continuation of upward movement (Judd and Hovland, 2007; Jonk, 2010).

*Sediment mobilization processes*

Maltman and Bolton (2003) compiled the whole range of mechanisms by which incompletely lithified sediments become capable of the bulk movements associated with subsurface mobilization and their related structures (Figure 4). The red dashed box indicates the area that is relevant for the studied examples within the scope of this thesis (papers I-IV). It shows that sediment mobilization processes such as fluidisation, liquefaction and salt diapirism (among others) can generate seabed structures such as mud volcanoes. The buoyancy principle is also extended to intrinsically weak, ductile and low density materials such as salt. As salt is incompressible, its bulk density keeps constant with burial establishing a high potential for density inversion with increasing denser overburden. Salt movement may occur if the buoyancy forces of the salt overcome the strength of sediment overburden. This may trigger fluidisation of sediments along faults.

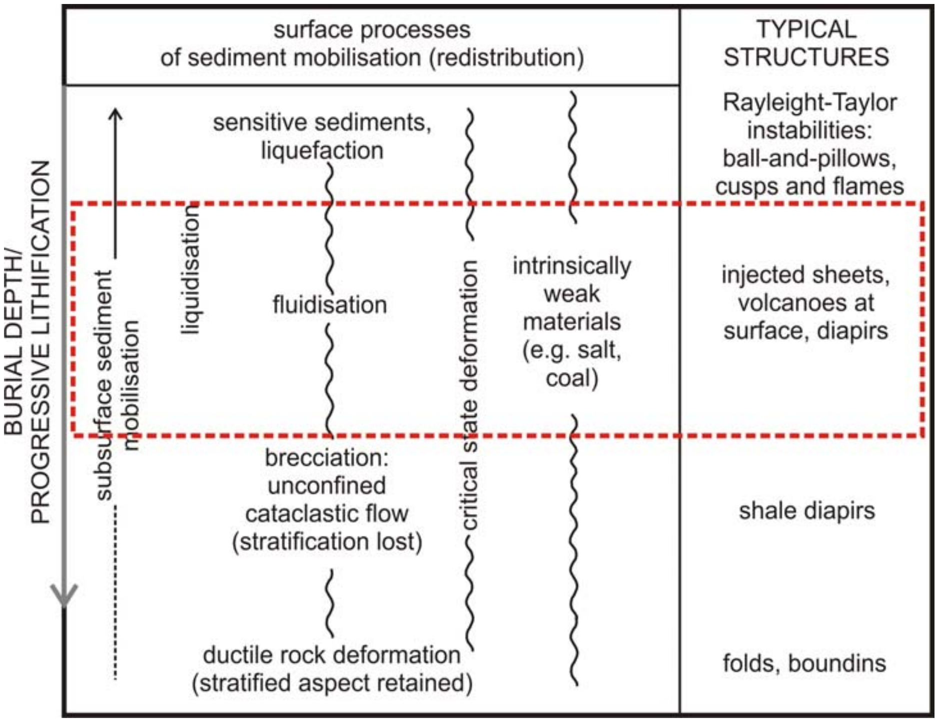

Figure 4. Conceptual view of the range of processes involved in sediment mobilisation. The red dashed area indicates the scope of the present PhD thesis. Figure modified from Maltman and Bolton (2003).

In order for the sediment to be remobilized, it needs to be liquidized or fluidised (Allen, 1982, 1985; Maltman and Bolton, 2003). During liquefaction, the lithostatic load is entirely supported by the internal pore fluid pressure rendering the sediment to behave as a fluid, even if it possessed yield strength. It requires high fluid overpressures (close or at lithostatic pressure). Dissolved gas in the pore fluids also increases overpressure, facilitating liquefaction of sediments. Low-permeability clayrich sediments are prone to the development of strong overpressure as fluids cannot drain rapidly enough to alleviate it.

Fluidisation refers to the lost of sediment strength through moving interstitial fluids. The drag force exerted by the fluid may balance the force exerted by the weight of the particles, in which case the sediment becomes essentially fluid like. In an ideal system, there is a single flow velocity (the minimum fluidisation velocity) at which a sediment layer becomes fluidised (Davidson & Harrison, 1971). The Ergun equation (Ergun & Orning, 1949) (equations 3 and 4) describes fluidisation in terms of the unrecoverable pressure loss across the bed for viscous and inertial conditions (Reynolds number <1 and >1000, respectively). The minimum fluidisation velocity $V_f$ has been described by (Richardson & Zaki, 1954; Davidson & Harrison, 1971; Gibilaro, 2001; McCabe et al., 2001):

$$V_f = K(\rho_s - \rho_f)d^2 g/\mu \quad \text{; for viscuous flow regime} \tag{3}$$

$$V_f = K\sqrt{(\rho_s - \rho_f)dg/\rho_f} \quad \text{; for inertial flow regime} \tag{4}$$

,where $\rho_s$ is the grain density, $\rho_f$the fluid density, $\mu$ the dynamic viscosity of the fluid, *d* the particle diameter (grain size), $g$ the gravitational constant and $K$ is a constant (whose value depends on the units adapted). This is graphically represented in Figure 5. The minimum fluidisation velocity is only valid for particles larger than very fine sand. For grains smaller than coarse silt, the fluidisation velocity would remain the same (Figure 5, dashed line). As grains get larger, their weight prohibits fluidisation and thus the minimum fluidisation velocities increase. In both mud volcanoes studied here, particle grain sizes are very small and therefore the mimimum required velocities for fluidisation are relatively small (Paper I and II).

Extremely high fluidisation velocities are required for pure methane gas, as both the density difference between grains and fluid is large, and the dynamic viscosity is very low (see equations 3 and 4). Gas alone cannot fluidise sediments at typical subsurface flow velocities; however, it may be possible for certain quantities of gas to be present in solution and at very shallow depths to exsolve due to the pressure decrease (Brown & Orange, 1993). Hence, the linkage of gas escape with, for example, mud volcanoes may exist if the rapid flow of deep-seated overpressurized aqueous fluids is accompanied by significant quantities of dissolved gas. However, the driving force for fluidisation is always the movement of aqueous fluids. In this study, all structures presented show evidence for medium to large content of gas within the moving fluids.

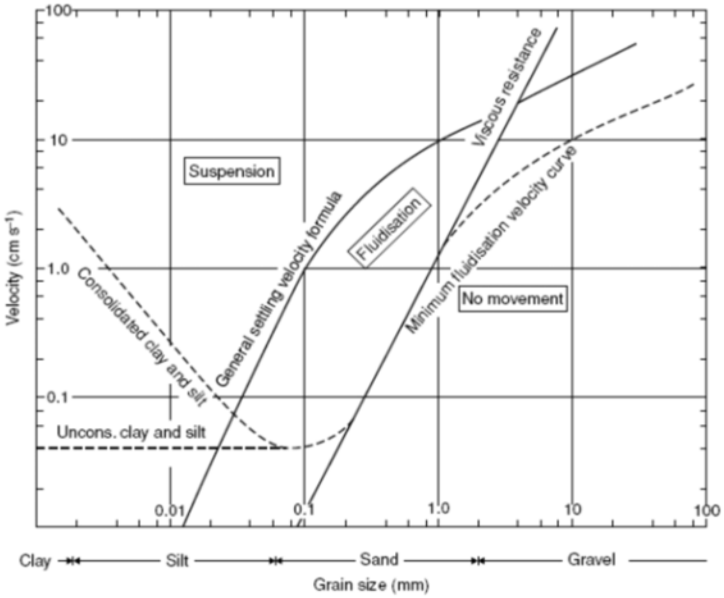

Figure 5. Relationship between sediment grain size and fluidisation velocity. The most easily fluidized sediments are sands with grain sizes between 0.1 and 0.5 mm. From Hovland and Judd (1988); redrawn from Lowe (1975).

We observe fluidisation and liquefaction processes at both the Håkon Mosby and the Mercator mud volcanoes, confined to deeper and shallower depths respectively (see depth distribution of processes in Figure 4) (papers I-III). Although indications for fluid and gas migration are observed in the Sørvestsnaget Basin (polygonal faults and bright spots respectively, Andreassen et al., 2007), expressions of sediment mobilization processes are lacking (apart from the diapir movement itself) (paper IV). The apparent absence of seabed features could be explained by limited amounts of fluids migration and/or too low fluid flow velocity.

### *Mud volcanoes*

Mud volcanoes are some of the world's most dynamic and unstable sedimentary structures and their geomorphic expression at the surface can vary significantly. The geomorphological expressions have been described from many parts of the world, on land and offshore (Milkov, 2000; Dimitrov, 2002; Kopf, 2002) (Figure 1). The typical and simplest morphology of mud volcanoes is represented by a cone with a summit crater. Their size and shape vary in relation to the nature (viscosity, density, grain size) of the emission products, the nature and frequency (slow, rapid, or even explosive) of the emissions, and the volumes of the material and fluids produced (e.g., Kopf and Berhmann, 2000) (Figure 6). The largest examples are 300–400 m in height and up to 3 or 4 km across with a circular or elongate shape. They cover an area of < 100 km$^2$ (Judd and Hovland, 2007).

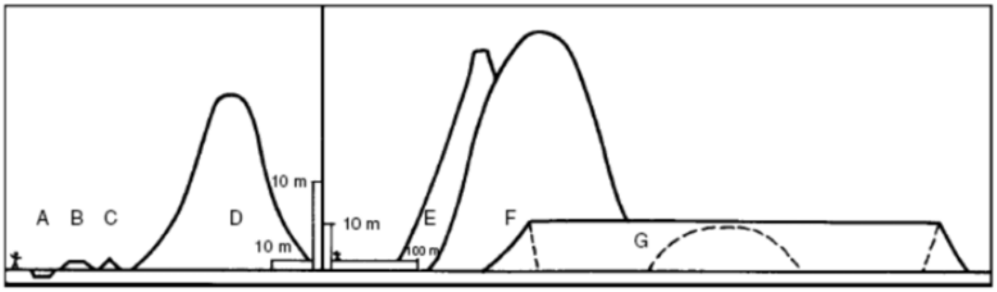

Figure 6. Sizes and shapes of various terrestrial mud volcanoes (note the figure of a man in both frames). Judd and Hovland (2007).

Mud volcanoes typically emit a mixture of gas, water, and sediment derived from deep within underlying sediments. The nature and relative proportions of these products, the volumes in which they are produced, and the rate and frequency of their emission all affect the shape of the surface feature (e.g., Kopf and Berhmann, 2000; Kopf, 2002; Judd and Hovland, 2007). The solid component of the emission products of a mud volcano often takes the form of a liquid mud containing clasts (mud breccia). Individual fragments, which may be angular or rounded, range in diameter from a few millimetres to very large boulders, derived from different stratigraphic layers, sometimes at considerable depths below the surface. Chemical and isotopic analyses enable the source of water to be identified; they may be connate or meteoric waters, and individual mud volcanoes may emit mixed waters of deep and shallow origins. The depths range can be inferred form the chemical compositions of fluids (e.g., paper III). Hydrocarbons are the dominant gases emitted by the majority of mud volcanoes (mainly methane), which may be of microbial or thermogenic origin (Judd and Hovland, 2007). Methane emissions from mud volcanoes may be partly associated to methane-dependent biological habitats, distributed concentrically around the feeder of the mud volcano (Jerosh et al., 2007; paper I).

Mud volcanoes have been identified on seismic sections as vertical features, with a seismically transparent or chaotic internal character, which disrupt or pierce through sediment strata. Collier and White (1990) suggested possible explanations for the seismic transparency: the physical disruption of the sediment layers, ‘overwriting’ of the layering by concentrations of gas, and/or acoustic signal starvation caused by the presence of gas, gas hydrates, or methane derived authigenic carbonates (MDAC) at or near the seabed. Many of the mud volcanoes show a typical “Christmas Tree” structure on reflection seismic cross sections due to the stacking of mud flow edifices (Fernández-Puga et al., 2007; Somoza et al., 2003; Van Rensbergen et al., 2005) (papers II and III), but not all of them (e.g. the Håkon Mosby mud volcano, paper I). Due to its internal structure, the Håkon Mosby mud volcano is referred to as a sedimentary diatreme (Brown, 1990) (paper I).

Besides the visible surface feature (cone and crater), mud volcanoes have a subsurface feeder pipe or channel that may have subsidiary feeder pipes, which determine its plumbing system. Normally, the feeder pipes are not single entities feeding an individual mud volcano but instead show a composition of feeders (Davies and Stewart, 2004) (paper II).

## Plumbing systems of mud volcanoes

The migration of subsurface sediments requires deformation of the host sediment to accommodate the influx of fluid and grains (Jonk, 2010). Among other processes, two of the main processes at mud volcanoes are reviewed: hydrofracturing and along fault migration.

*Hydrofracturing:* Once the fluid overpressure reaches the fracture pressure of the rock, opening-mode fractures can form. The fracture pressure of a rock is typically equal to the minimum effective stress plus an additional force required to overcome the tensile strength of the rock. In most sedimentary rocks, internal hydraulic fractures are oriented subvertically as the overburden stress is typically the maximum stress (Mandl, 1999). Hydraulic fractures drastically increase permeability and thus allow the flow of internal overpressurized fluid along potential gradients (upward and/or downward; Figure 2b). Fracture pressure typically increases first in the transition zone near the top of the overpressurized formation (Figure 2b) (Jonk, 2010). The seismic analysis of the plumbing system at the Håkon Mosby mud volcano suggests the existence of hydrofracturing, because expression of failure is observed neither in the feeder conduit nor in the surrounding sediments (paper I).

*Along fault migration:* Along fault migration of fluids may dominate fluid-flow patterns, facilitating or impeding the upward migration of fluidised sediments. Clayton and Hay (1994) argued that deep-seated faults and fractures (> 1000 m below seabed) act as seals, as the horizontal stress is sufficient to close them, unless they are kept open by sufficiently high pore fluid pressure, or the fault plane brings sand against sand. In shallower sediments processes are different. The migration of fluids along faults is controlled by a pressure gradient and the critical factor is the width of individual discontinuities. Faults and fractures do not only increase the effective permeability and breach barriers, but also sequester gas from the rock/sediment matrix because of the lower existing capillary pressure (Bethke *et al*., 1991). Fluid may flow freely when faults and fractures are held open by cements or asperities. Slopes and salt diapirs make fracture failure easier, therefore their association with seabed features is quite frequently seen. Fluid, sediment and gas migration at the Mercator mud volcano (papers II and III) and the Sørvestsnaget Basin (paper IV) occur through fractures of the sediment overburden that are related to salt diapirism.

## Geodata integration

Due to the complex nature of the investigated sediment mobilisation processes, this PhD integrates geological, geophysical and geochemical data. The data compilation is the result of several oceanographic cruises and inter-institutional collaborations (Figure 7).

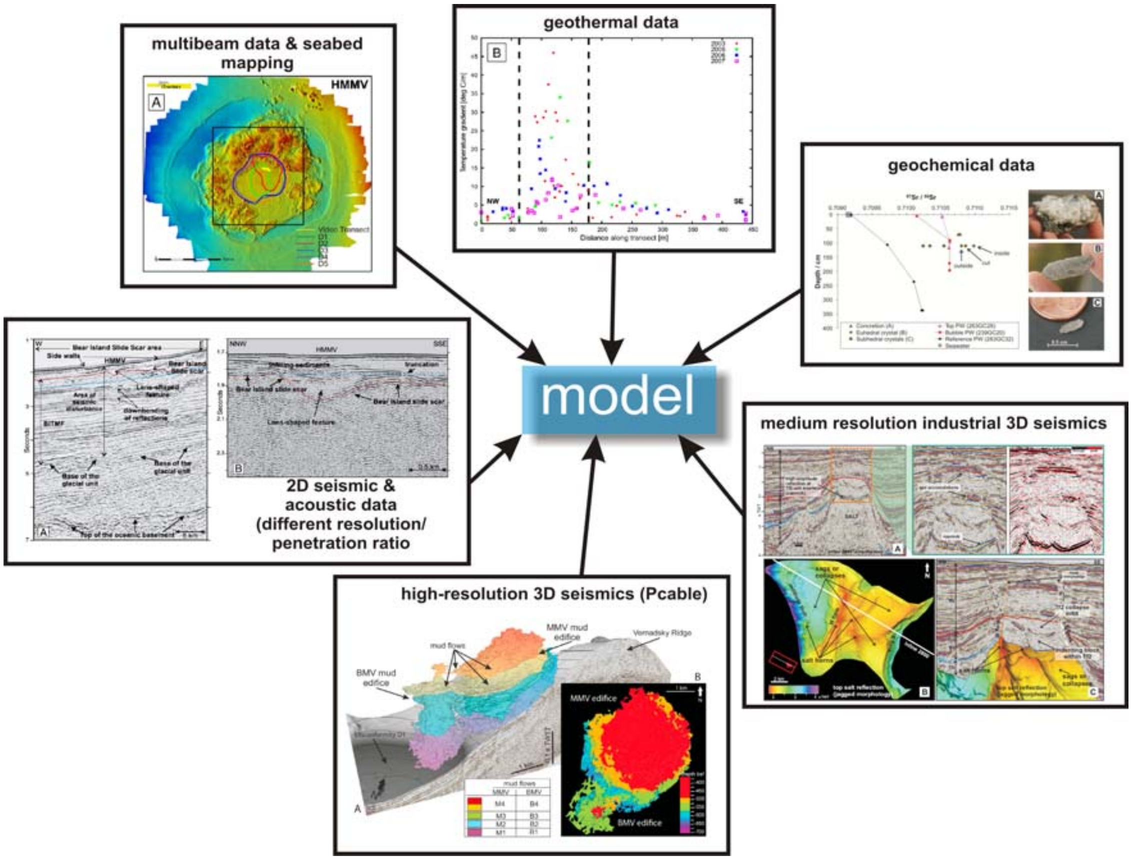

Figure 7. Compilation of different geodata sets used in my PhD thesis.

The PhD thesis integrates 2D (sediment profiler, chirp and multichannel seismic data) and 3D (P-Cable high-resolution seismic (Petersen et al., 2010) and industrial data) reflection seismic, geothermal and geochemical data. The combination of different sets of 2D and 3D seismic data with different resolution/penetration ratios is crucial for determining details of structures such as mud volcanoes. For example, the mud-chamber discovered at the Håkon Mosby mud volcano is possible to image by using chirp data, while it is ‘invisible’ in deep multichannel seismic and sediment profiler data (paper I). At the same time, without 3D seismic data it would be impossible to calculate the amount of sediment extruded from the Mercator mud volcano (papers II and III) or resolve the caprock at the Sørvestsnaget Basin salt diapir (paper IV).

The geothermal, geochemical and seabed mapping are used to provide support to the geophysical observations and interpretations. For example, three consecutive years of temperature measurements over the same transect across the Håkon Mosby mud volcano further supported the geophysical determined limits of the feeder conduit (paper I). The geochemical data confirmed the strong influence of salt at the Mercator mud volcano (paper II) and revealed the source of fluids and the fluctuations of the halite-anhydrite dissolution barrier (paper III).

## Abstracts of individual papers

### __Paper I:__ *The Håkon Mosby Mud Volcano: 330 000 years of focused fluid flow activity at the SW Barents Sea slope*

Carolina Perez-Garcia, Tomas Feseker, Jürgen Mienert and Christian Berndt

Studying the morphology and subsurface geometry of mud volcanoes provides insights into their activity. This paper describes the internal structure of the Håkon Mosby mud volcano (HMMV) in the southwestern Barents Sea and presents a conceptual model of its evolution. The lack of a mud edifice and the profuse gas flares suggest that in the recent past the mud volcano evolution was predominantly controlled by venting of gas-rich fluids and free gas. However, the analysis of high-resolution single-channel seismic (SCS) data reveals for the first time the existence of a pseudo-mud chamber at the top of the 3 km deep central conduit. It was once created at the seabed and is now a buried expression that acts as mud chamber. The pseudo-mud chamber is situated approximately 300 m below the seafloor, directly above the 330 ka Bear Island Slide (BIS) scar reflection and below glacigenic debris flow deposits that constitute the sediment on top. The sediment profiler data indicates a younger mud deposit above the debris flows, which points to a reactivation of the mud volcano. The reactivation was most likely triggered by the contrast in density between the gas-rich mud chamber and the high-density debris flow deposits. Three stages, i.e. initiation, sealing and reactivation, and a second active period define the evolution of this young mud volcano. Both, the morphology and size of the conduit as well as in-situ temperature gradients point towards a focused and rapid fluid flow.

### __Paper II:__ *Linked halokinesis and mud volcanism at the Mercator mud volcano, Gulf of Cadiz*

Carolina Perez-Garcia, Christian Berndt, Dirk Klaeschen, Jürgen Mienert, Laura Haffert, Davy Depreiter and Matthias Haeckel

Mud volcanoes are seafloor expressions of focused fluid flow that are common in compressional tectonic settings. New high-resolution 3-D seismic data from the Mercator mud volcano (MMV) and an adjacent buried mud volcano (BMV) image the internal structure of the top 800 m of sediment at both mud volcanoes, revealing that both are linked and have been active episodically. The total volumes of extruded mud range between 0.15 and 0.35 km3 and 0.02–0.05 km3 for the MMV and the BMV, respectively. The pore water composition of surface sediment samples suggests that halokinesis has played an important role in the evolution of the mud volcanoes. We propose that erosion of the top of the Vernadsky Ridge that underlies the mud volcanoes activated salt movement, triggering deep migration of fluids, dissolution of salt, and sediment liquefaction and mobilization since the end of the Pliocene. Since beginning of mud volcanism in this area, the mud volcanoes erupted four times while there was only one reactivation of salt tectonics. This implies that there are other mechanisms that trigger mud eruptions. The stratigraphic relationship of mudflows from the MMV and BMV indicates that the BMV was triggered by the MMV eruptions. This may either be caused by loading-induced hydrofracturing within the BMV or due to a common feeder system for both mud volcanoes. This study shows that the mud volcanoes in the El Arraiche mud volcano field are long-lived features that erupt with intervals of several tens of thousands of years.

**Paper III:** ***Fluid evolution and authigenic mineral paragenesis related to salt diapirism – the Mercator mud volcano in the Gulf of Cadiz***

Laura Haffert, Matthias Haeckel, Volker Liebetrau, Christian Berndt, Marianne Nuzzo, Anja Reitz, Florian Scholz, Joachim Schönfeld, Carolina Perez-Garcia and S.M. Weise

The making of mud volcanoes in the Gulf of Cadiz is closely linked to diapirism in the deep subsurface. The Mercator mud volcano (MMV) is a rare example where diapiric routing, in addition to being key for upward fluid migration, is also an important zone for fluid and mineral diagenesis. The most intriguing findings in the near-surface muds of the MMV are extremely high salinities of up to 5.2 M of NaCl from diapiric and evaporitic halite dissolution and the occurrence of authigenic gypsum and anhydrite crystals, both of which have not been observed to date in the Gulf of Cadiz. Employing a thermodynamic model we elucidate how the interplay of temperature pulses, strong salinity gradients, and fluid flow dynamically drive mineral dissolution and re-formation. The strong increase in salinity in the pore fluids has important implications for thermodynamic equilibria by significantly lowering the activity of water, thereby raising the gypsum-anhydrite transition zone from >1 km to about 400 m sediment depth at the MMV. This transition is further shifted to immediately below the seafloor during intervals of active mud and fluid expulsion when the MV surface temperature is heated up to at least 30 °C. As a consequence, precipitation of authigenic gypsum near the sediment surface (1-2 mbsf) has been linked to the dissolution of evaporites below the MMV.

More precisely, the mechanisms generating supersaturation in the ascending gypsum-saturated MMV fluids are (1) the slow and constant cooling of these fluids along the geothermal gradient during their ascent leading to formation of ubiquitous micro-crystals and (2) the more rapid cooling after a heat pulse or transport from greater and warmer depth during an active mud volcano phase leading to the precipitation of cm-scale gypsum crystals or even fist-size concretions. The MMV fluids approaching the salt diapir from farther below have experienced a genesis similar to those of other mud volcanoes in the Gulf of Cadiz located above deep-rooted faults. These processes include clay mineral dewatering, thermogenic degradation of organic matter and deep high-temperature leaching of terrigenous sediments or continental crust.

### Paper IV: *Extensional rise and fall of a salt diapir in the Sørvestsnaget Basin, SW Barents Sea*

Carolina Perez-Garcia, Polina Safronova, Jürgen Mienert, Christian Berndt and Karin Andreassen

Regional extension which initiates and promotes the rise of salt diapirs can also make diapirs fall once the supply of salt from its source is restricted. New 3D seismic data from a salt diapir in the Sørvestsnaget Basin suggest salt movement until the end of the Eocene and no reactivation of salt afterwards. Observations of salt horns and sags and an antithetic fault linked to the western flank of the salt diapir reveal a more complex kinematic evolution of the salt diapir than previously described. The salt horns are remnants of a taller salt diapir. Together with the indentation of the Middle-Late Eocene syn-kinematic sediment overburden above the salt, they indicate diapiric fall due to restriction of salt supply by extension. Salt syn-kinematics during Middle-Late Eocene included passive rising of the salt, followed by a fall. Post-kinematic readjustments did not include diapiric reactivation, but subsidence during Plio-Pleistocene and differential compaction of surrounding sediments. The salt diapir appears to be presently inactive and salt supply may have been restricted from its source already since Late Eocene.

## Future research

I wish to propose a few topics here that may be of interest to develop today's knowledge of this dissertation for future studies of mud volcanoes and salt diapirs.

Future mud volcano studies may focus more on strategies for long-term observations for fluid discharge through features onshore and offshore. The offshore Håkon Mosby mud volcano was the focus of a long-term observation within the framework of the ESONET demonstration mission LOOME. The long-term seabed laboratory recorded data on earthquakes, temperature and pore pressure, chemical profiling, sonar detection of gas flares, and hydrography of bottom water, together with the study of colonization patterns, community structure and biodiversity. Long-term monitoring may provide the full range of scientific data required to understand the intermittently active character of mud volcanoes and to decipher the complex and interactive processes. Although it is clearly expensive to investigate many mud volcano areas with long-term observatories, some active mud volcanoes and seep structures on both passive and active continental margin setting may be equipped with seafloor observatories in the near future to assess more accurately their potential role in ocean chemistry and global budgets.

Geomechanical modeling to predict stress and fracture networks around salt/shale diapirs and mud volcanoes may provide new insights into the timing of fluid flow processes. As these structures may be linked to hydrocarbon provinces, serving either as a trap or seal, such numerical models may be important as pre-drilling knowledge for tasks such as borehole stability and seal integrity. To extrapolate geomechanical models into the third dimension one would request to have high- and low-resolution 3D seismic datasets over targeted diapiric and mud volcanic structures. Such data are also essential for a detailed study of the 'chrono-dynamics' of diapirs as they reveal stress tensor directions over each stratigraphic level.

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# Paper I

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# Paper II

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# Paper III

Haffert L., Haeckel M., V. Liebetrau, C. Berndt, M. Nuzzo, A. Reitz, F. Scholz, J. Schönfeld, C. Perez-Garcia, S.M. Weise, **Fluid evolution and authigenic mineral paragenesis related to salt diapirism – the Mercator mud volcano in the Gulf of Cadiz**.

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# Paper IV

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