Faculty of Science and Technology

Environmental response to past and recent climate variability in the Trondheimsfjord region, central Norway

A multiproxy geochemical approach

—

Johan C. Faust

A dissertation for the degree of Philosophiae Doctor – July 2014

"Keep your head up,
keep your heart strong"

- Ben Howard

Preface

This thesis is the result of a three year PhD study at the Department of Geology at the University of Tromsø, Norway. It compromises three scientific papers, which were prepared in the period between November 2011 and April 2014 at the Geological Survey of Norway (NGU) in Trondheim. The project was funded by the European Union and was part of the Marie Curie Initial Training Network *CASE* "The Changing Arctic and Subarctic Environment". In addition to intensive training sessions and progress meetings the CASE Network provided close collaboration with eleven other PhD students from nine different European countries at the Universities of Bordeaux, Amsterdam, Plymouth, Tromsø and Kiel. The existent work was also presented at the Goldschmidt conference in Montreal and Florence as well as at the EGU in Vienna. Additionally, The Geological Society provided a travel and accommodation grant for a conference presentation in London, a research award from Iso-Analytical Ltd. supported isotopic analysis, the Research Council of Norway provided a Marie Curie "toppfinansiering" and the Stiftung Mercator, part of the European Campus of Excellence (ECE), offered the participation in the summer school "Climate Change in the Marine Realm" in Bremen and Sylt, Germany.

Acknowledgment

I would like to thank all people who helped and supported me during the last four years. Foremost, I would like to thank my supervisor Dr. Jochen Knies for his great guidance and allowing the freedom to pursue an interesting topic. Thank you for giving me the chance to attend various cruises, conferences and courses. I am very grateful for the opportunity to continue working with you, it will be great!

I would like to express my gratitude to the CASE group for unforgettable days and adventures. Our meetings have always been very inspiring and encouraging. A special thanks goes to Michi, Danish dynamite Christian and Patricia for intense discussions not only about science. Diane and Sarah, of course, big thanks also to you not only for all your help with my Tromsø University organisation problems. Thanks to the principal investigators: Jacques Giraudeau, Simon Belt, Hans Renssen, Katrine Husum, Jochen Knies, Robert Spielhagen, for providing these wonderful and exciting stays, progress meetings and training courses at your institutes. There was always a smile in your face providing support and the confidence that we will all manage to succeed. It was great with all of you.

This PhD study would not have been possible without the help of the NGU and the marine geology group; in particular I have to express my gratitude to Ola Magne Sæther, Rolf Tore Ottesen, Reidulv Bøe, Martin Klug, Anne Liinamaa-Dehls, Karl Fabian, John Naliboff, Benjamin Snook, Magne Vik Bjørkøy, Alenka Černe and Julian Schilling for their interest, stimulating discussions, and many useful comments. Furthermore, I would like to thank Anne Nordtømme, Bjørn Willemoes-Wissing, Clea Elisatbeth Fabian, Melanie Mesli, and Wieslawa Koziel for the great laboratory assistance, their patience, help and support and captain Oddvar Longva, and the crew of the RV Seisma for their professional support during our expeditions.

The group of "young" scientists at the NGU is acknowledged for being such a likable and sociable lot. For sharing numerous fantastic ski trips, bike rides, mountain and fishing tours and social get-togethers that successfully distracted me from my PhD. I would like to thank my local friends and colleagues. I would also like to mention the NGU football team providing so often the highlight of the week. To all my friends I left behind in Germany and elsewhere in Europe thank you very much indeed for not losing the connection and for your constant support.

Thank you Simone for all the help and the hours you spent listening to all my ideas and problems and for reading my stuff, this thesis is also your thesis. And, of course, I wish to thank my supportive family, Susanne Moebus, Michael Faust, Susanne Würth, Dieter Mazur, Wolfgang Bödecker, Astrid Nahrmann and my brothers Steffen and Anton who provided support and motivation, patiently listened through difficult times during the “PhD race" and making it such a pleasure to come back home.

At last, this work is a contribution to the CASE Initial Training Network funded by the European Community’s 7th Framework Programme FP7 2007/2013, Marie-Curie Actions, under Grant Agreement No. 238111.

Trondheim April 2014

Johan Faust

Table of Contents

1 Introduction

How do natural climate variations affect the environmental conditions on Earth`s different regions? And how sensitive is Earth`s climate to the alteration of its surface and atmosphere by human activity? To answer these basic questions a profound knowledge of the climate system is required which can only be developed by studying long term past climatic changes. However, since climate is the statistical evidence of the average weather over a longer period of time (decades to millions of years) at a certain point (IPCC, 2007) it is not possible to see, feel or directly measure climate. Hence, to estimate climate variabilities over long time scales changes of the internal components of the climate system (air, water, ice, land surfaces and vegetation (Ruddiman, 2001)) are reconstructed by using climate proxies. Thus, it is crucial to identify high-resolution proxy data from key areas characterized by specific climate phenomena where instrumental record data are available to estimate the relative magnitude of past climatic changes (Abrantes et al., 2009).

Norwegian fjords meet all these requirements to decipher past climate signals. Their sediments contain information regarding environmental changes of the hinterland and oceanographic variability on the adjacent continental margins and shelves through water mass exchange (Schafer et al., 1983; Syvitski and Schafer, 1985; Hald et al., 2003; Husum and Hald, 2004; Forwick and Vorren, 2007; Howe et al., 2010; Hald et al., 2011). Moreover, biogenic sedimentation generated in-situ in the fjord through biogeochemical processes and primary productivity can also reflect local and global influences on the environment (Knies et al., 2003; Knies, 2005). General high sedimentation together with the possibility to quantify environmental parameters such as water exchange and freshwater input offer an excellent opportunity for studying land-ocean interactions and can provide ultra-high-resolution records of local responses to short-term variability in the earth’s climate (Mikalsen et al., 2001; Kristensen et al., 2004; Paetzel and Dale, 2010).

Apart from the relatively warm northward flowing North Atlantic Current, the Norwegian coastal climate is strongly influenced by the North Atlantic Oscillation (NAO) (e.g. Hurrell, 1995; Dickson et al., 2000; Cherry et al., 2005). This dominant mode of the atmospheric circulation is most pronounced during winter times (Dec-Mar) and is defined as the difference in atmospheric pressure at sea level between the Icelandic low and the Azorean high (Hurrell, 1995). It controls the strength and direction of westerly winds and storm tracks across the North Atlantic (Olsen et al., 2012) and swings between two phases: A positive (negative) NAO generates periods of warmer and wetter (colder and dryer) climate conditions in north-western Europe (e.g. Wanner et al., 2001; Fig. 1). Moreover, its strong impact on precipitation, temperature and wind intensity changes along the Norwegian coast (Ottersen et al., 2001) affects e.g. energy supply and demand, agricultural, fisheries and marine and terrestrial ecological dynamics (Ottersen et al., 2001; Drinkwater et al., 2003; Hurrell et al., 2013).

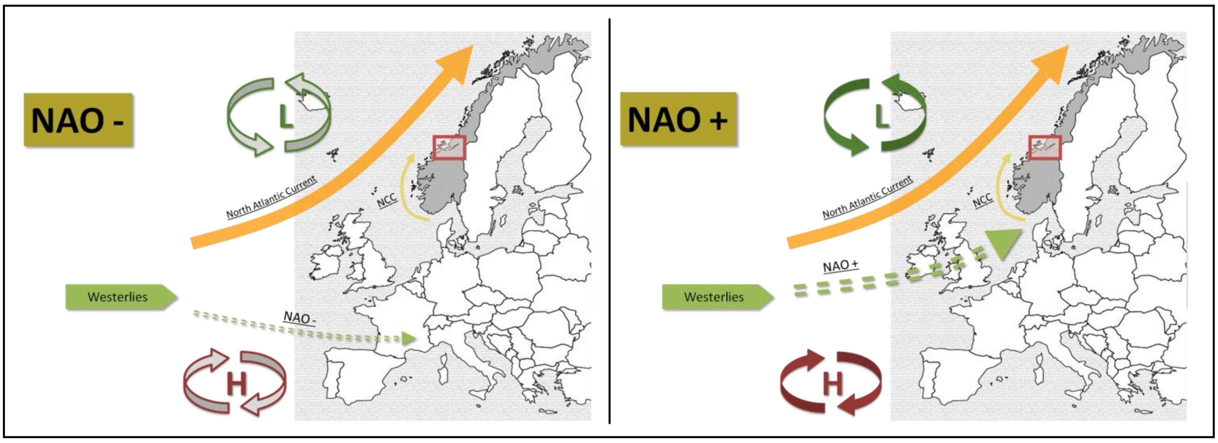


Fig. 1: During a negative NAO phase (left) both, the Azorean high and the Icelandic low are weaker and the Westerlies flow further south which results in colder and drier conditions in Norway. During a positive NAO phase (right), both pressure areas are well developed, the Westerlies are "pushed" further north transporting moisture and heat to Norway resulting in warmer and wetter conditions. The red square is the location of the study area, the Trondheimsfjord. Yellow arrows indicate the North Atlantic Current transporting relative warm water towards the north and the Norwegian Coastal Current (NCC).

To better understand NAO variability and to estimate not only the range of possible fluctuations but also assess their predictability and possible shifts associated with ongoing global warming, long term NAO reconstructions are crucial, but until today rare and often inconsistent (Pinto and Raible, 2012). The general challenges for NAO reconstructions are its possible non-stationarity (a spatial shift of the atmospheric pressure areas) and its strong alteration on very short time scales requiring high resolution (winter) paleoclimatic records which can provide the essential knowledge for its prediction and the quantification of possible anthropogenic induced changes. Reconstructions based on early instrumental and documentary proxy data, tree rings, speleothems, and ice core data gave best results so far (Jones et al., 1997; Appenzeller et al., 1998; Glueck and Stockton, 2001; Luterbacher et al., 2001; Cook et al., 2002; Vinther et al., 2003) but only for the past 950 years (Trouet et al., 2009). Recently, Olsen et al. (2012) extended the NAO record to 5,200 years using a multi-proxy geochemical record from lake sediments in Greenland. However, this record still covers only half the Holocene and needs support from additional studies.

Changes in precipitation and temperature associated with the NAO are assumed to alter the constitution of fluvial sediment flux from land towards ocean basins generated by weathering and erosion of bedrock and soils (e.g. White and Blum, 1995; Lamy et al., 2001; Govin et al., 2012). Exploring such a relationship between terrigenous input and changes in environmental conditions requires detailed knowledge of the transport mechanisms dominating particle supply (e.g. Zabel et al., 2001). To date no systematic organic and inorganic geochemical investigation of the marine sediments as a basis for long term paleoclimate studies has been conducted in any Norwegian fjord. As for most Norwegian fjords, studies from the Trondheimsfjord in central Norway (Fig. 1 and 2) focus on biological processes (e.g. Haug et al., 1973; Sakshaug and Myklestad, 1973; Børsheim et al., 1999; Sakshaug and Sneli, 2000; Öztürk et al., 2002), sedimentary and mass-wasting processes (Bøe et al., 2003; Bøe et al., 2004; Rise et al., 2006; Lyså et al., 2008; L'Heureux et al., 2009; L'Heureux et al., 2010; Hansen et al., 2011; L'Heureux et al., 2011) and oceanography (Wendelbo, 1970; Jacobson, 1983).

The objective of this PhD project is to (a) detect sources of particular sediment components to identify environmental mechanisms controlling their supply and distribution, (b) to identify geochemical proxies for terrestrial input/river discharge and finally (c) apply these findings on Holocene sequences to reconstruct the variability of the North Atlantic Oscillation (NAO) for the last 2,800 years. For this purpose we establish a multiproxy data set from various sediment cores and surface sediment samples from the Trondheimsfjord and compare the results with instrumental data of air temperature, precipitation and river discharge as well as with geochemical bedrock and overbank sediment data from the adjacent drainage area.

2 Study Area

The Trondheimsfjord

The temperate Trondheimsfjord is located in the central part of Norway (Fig.1 and 2) and, with a length of approximately 135 km, it is the third longest fjord in the country (Jacobson, 1983). Like many fjords, its complex morphology is characterised by relatively wide and shallow areas, narrow trenches and steep slopes, up to 30-40 degrees (Bøe et al., 2003). Three sills, the Agdenes Sill at the entrance (max. 330 m water depth), the Tautra Ridge in the middle section (max. 100 m water depth) and the Skarnsund in the inner part (max. water depth 100 m) divide the Trondheimsfjord into four main basins: Stjørnfjord, Seaward basin, Middle fjord and Beistadfjord (Fig. 2).

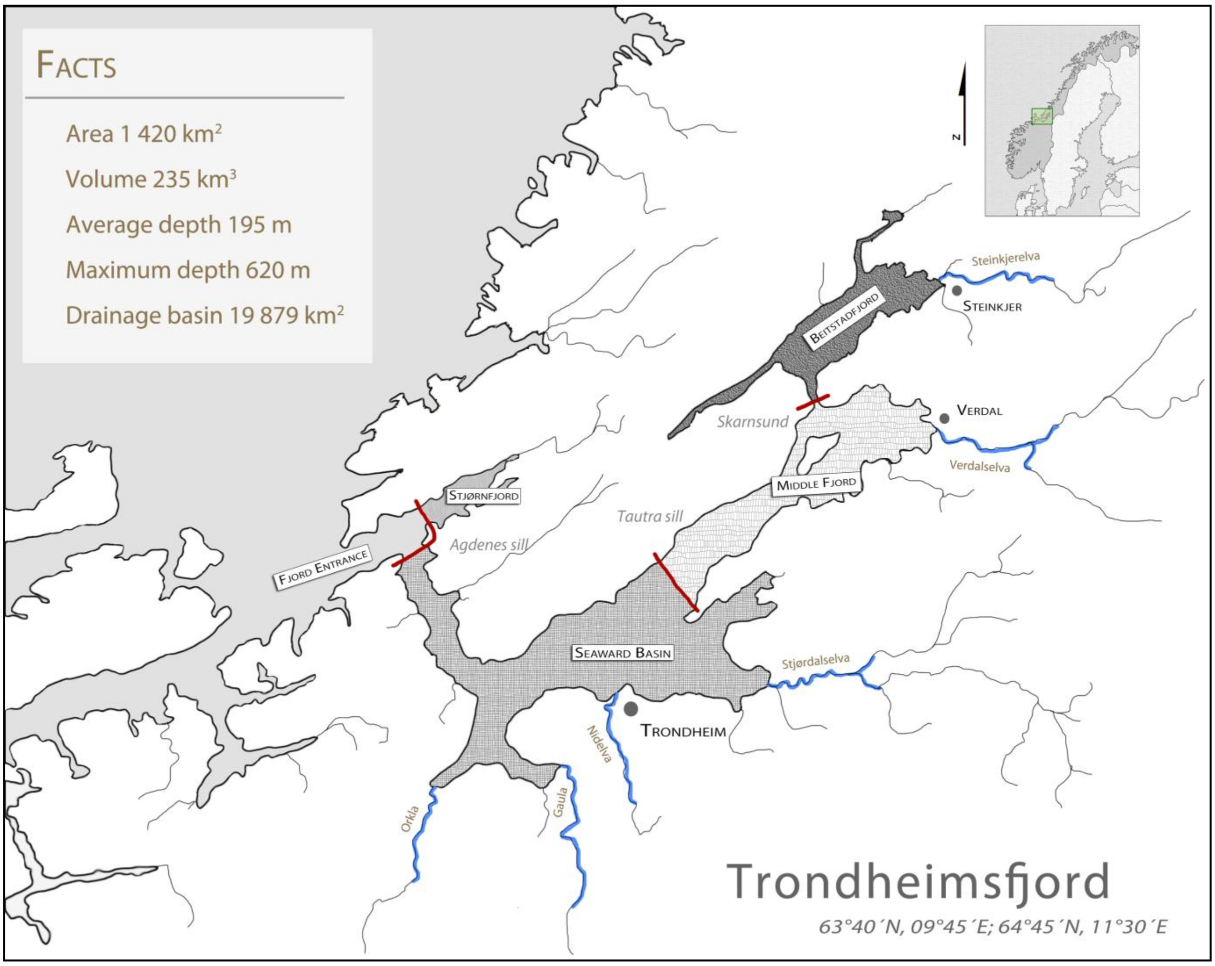


Fig. 2: Map of the Trondheimsfjord showing the three sills (red lines) dividing the fjord into four main basins as well as the six main rivers entering the fjord from the south/southeast. Inset upper right corner: Location of the Trondheimsfjord in central Norway.

The average tide in the Trondheimsfjord is 1.8 m, the average water depth is 165 m and the maximum water depth (620 m) is found at the mouth of the Seaward basin (Sakshaug and Sneli, 2000 and references therein). The total drainage area is approximately 20 000 km^2 (Rise et al., 2006) with a mean precipitation in the north-west area (1700 mm/year) that is twice as high as in the south-east region (855 mm/year). Moreover, the maritime climate in the Trondheimsfjord region is strongly influenced by the North Atlantic Oscillation (NAO) (Wanner et al., 2001), causing warm and wet (+NAO) or cold and dry (-NAO) weather conditions especially during winter times. Additionally, the relative warm (about 7.5°C) Atlantic water flowing into the Trondheimsfjord modulates seasonal air temperatures over the fjord region, resulting in lower (higher) air temperatures in summer (winter) and a strong temperature gradient from the fjord towards the hinterland can be observed, especially during winter months.

Oceanography

In general, interactions between forces governing the fjord circulation, coupled with the complex bottom topography and coastline, result in a complicated flow pattern and distribution of different water masses within the fjord system (Svendsen et al., 2002). The seasonal variation of freshwater supply from the six main rivers entering into the fjord (Gaula, Orkla, Nidelva, Stjørdalselva, Verdalselva and Steinkjerelva; Fig. 2) affect the surface salinity and the three sills hinder a free exchange of water with the open ocean. The water masses in the fjord are, therefore, often stratified and three layers can often be identified (Fig. 3): a brackish water layer on top; an intermediate layer down to the height of the sill top and a deep water/basin water layer beneath the sill height which is usually renewed twice a year (Jacobson, 1983). The level of stratification is the balance between the buoyancy flux, set up by the discharge of freshwater, and processes that work to homogenize the water masses such as tidal mixing and wind acting on the surface layer (Syvitski, 1989). The overall water circulation is marked by the outward flowing brackish water above an

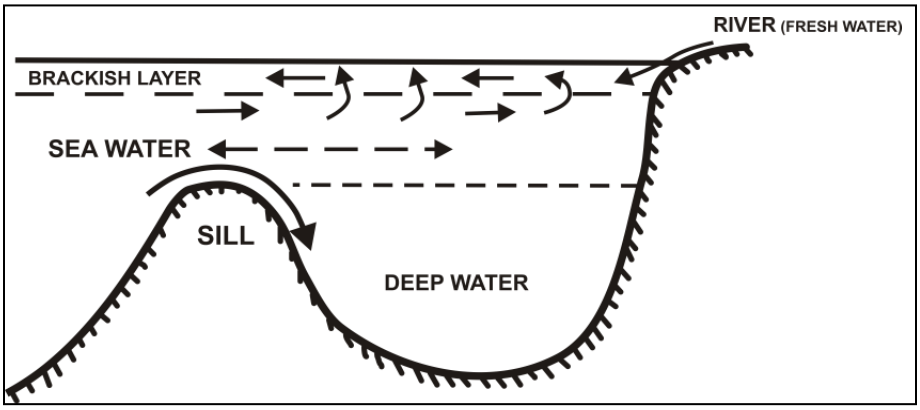
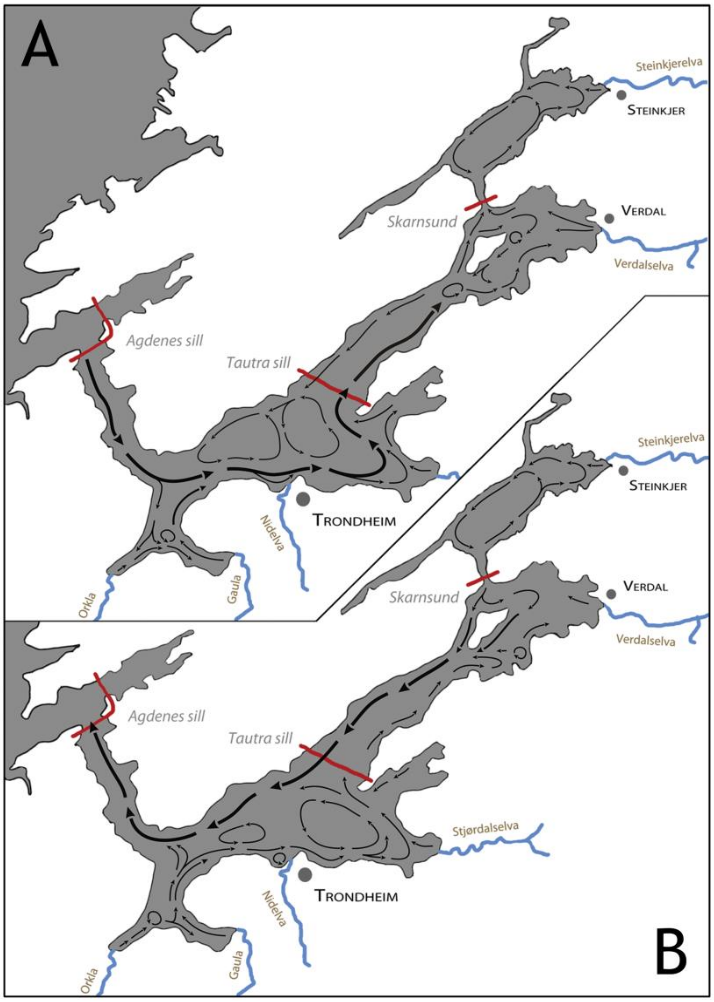


Fig. 3: Sketch of the estuarine circulation of a fjord (modified after Jacobson, 1983)

inward moving compensating marine current with almost constant temperature and salinity of approximately 7.5°C and 34.8, respectively, around the entire year (Sakshaug and Sneli, 2000). The mixing of these two main currents produces a residual compensating current below the surface layer (Jacobson, 1983). This current system is known as the "estuarine circulation" and is shown schematically in Figure 3.

Fig. 4: Surface water circulation pattern during high tide phase A) and low tide phase B) (modified after Jacobson, 1983; and Bierach, 1989).



The Coriolis effect deflects surface currents towards the right, especially in the Seaward basin. Ocean water entering the fjord, therefore, always flows along the south side of the fjord, while outward currents always flow along the north side (Fig. 4). As a result, large volumes of the riverine water recirculate and mix into each basin before leaving the Trondheimsfjord after a residence time of ca. 20 days (Jacobson, 1983).

Sedimentary processes

Depending on the river discharge, which varies with season, rivers can transport all types of grain sizes into the fjords. The coarse component is usually deposited close to the river estuary and the re-sedimentation of these sediments may occur as slide and debris flow events (Bøe et al., 2003; Bøe et al., 2004; Lyså et al., 2008; L'Heureux et al., 2009; L'Heureux et al., 2010; Hansen et al., 2011; L'Heureux et al., 2011). However, the finest component of the inorganic fraction may be transported over long distances even beyond the fjord. The transport takes place in the brackish surface plume (Fig. 3), above the halocline (Hoskin et al., 1978). Thus, the distance a particle is carried out into the fjord depends on its size, the velocity of the surface current and the stratification of the water column. As mentioned above one of the main causes for the surface-layer velocity is the freshwater discharge. During periods of high discharge e.g. due to the snow melt in spring, the velocity of the fjord's surface water is also high and the water column is well stratified. As a result the suspended material can be transported over long distances. Accordingly, although the fjord is partly very deep, the water masses below the estuarine circulation cell can be described as an energetically relatively low environment and the distribution of sediments within the fjord are, therefore, largely controlled by the circulation in the upper part of the water column (Wendelbo, 1970; Syvitski, 1989).

Geology

The geology in the Trondheimsfjord region is characterised by Caledonian nappes along its south-eastern side, autochthonous Precambrian granitoid gneisses and Caledonian slivers along its north-western side, and a basement window (Tømmerås anticline) exposing Precambrian volcanic rocks near its north-eastern end (Roberts, 1997). The Caledonian nappes belong to the Middle and Upper Allochthon and consist mainly of schist, metagreywacke and ophiolitic greenstone, intruded by gabbroic to tonalitic rocks. During the Quaternary, glaciers eroded deeply into the bedrock, forming a 1100-1300 m deep basin between Trondheim and the Agdenes sill (Rise et al., 2006). The hemipelagic sediments of mostly pre-Holocene age have a maximum thickness of up to 750 m (Bøe et al., 2003; Rise et al., 2006).

3 Materials and methods

The results presented and discussed in this thesis were obtained by extensive, mostly geochemical but also mineralogical and sedimentological analyses of sixty surface sediment samples collected across the entire Trondheimsfjord, plus one entire multicore (MC99-3) and the first five meter of a giant piston core (MD99-2292; see also Bøe et al., 2003) both recovered from the same location in the fjords Seaward Basin (Fig. 2).

Organic carbon, bulk elemental geochemistry and grain size analyses

The elemental composition of the surface- and the multicore sediment samples, retrieved from different multicores sliced in 1 cm intervals, were analysed at the ACME Ltd. laboratory in Vancouver, British Columbia Canada. Determination was performed by inductively coupled plasma atomic emission spectroscopy (ICP-AES) following a four-acid digestion, which is considered to be a total digestion method. Prior to sediment sampling the elemental composition of the sediment core MD99-2292 was measured in 0.5 cm steps using an Avaatech X-ray fluorescence (XRF) core scanner at EPOC, CNRS/University of Bordeaux 1, France. Subsequently, sediment slices (1 cm deep, 1.5 cm wide, 7 cm long) were taken in a 4 cm interval for further analyses.

Analyses for total carbon (TC), total organic carbon (C_{org}) and grain size were performed at the Laboratory of the Geological Survey of Norway (NGU). Weight percentages (wt. %) of C_{org} and TC were determined with a LECO SC-444 and Carbonate content was calculated as $CaCO_3 = (TC - C_{org}) \times 8.33$. The determination of grain size distribution was performed by laser diffraction using a Coulter LS 200 instrument. The analysis was carried out on material within a particle diameter range of 0.4–2000 µm.

Total nitrogen and stable carbon isotope analyses

Total nitrogen (N_{tot} in wt%) was determined using a Carlo Erba NC2500 Isoprime elemental analyzer isotope ratio mass spectrometer at EPOC, CNRS/University of Bordeaux 1, France. The inorganic nitrogen (N_{inorg}) content was analysed on sediment subsamples treated with KOBr-KOH solution to remove organic nitrogen (see Knies et al. (2007) for details) using an EA-IRMS (Iso-Analytical Ltd., UK). The organic proportion of the total nitrogen content was calculated by subtracting the N_{inorg} fraction from N_{tot}. Stable carbon isotopes of the C_{org} fraction ($\delta^{13}C_{org}$) were measured on decarbonated (10 % HCl) aliquots using an EA-IRMS (Iso-Analytical Ltd., UK). $\delta^{13}C_{org}$ values are given in per mil vs. Vienna-PDB.

Bulk mineral assemblage analyses

Bulk mineral assemblages were measured via X-ray diffraction (XRD) using a Philips X'Pert Pro MD, Cu-radiation (k(alpha) 1.541, 45 kV, 40 mA) and X'Celerator detector system at the Central Laboratory for Crystallography and Applied Material Sciences (ZEKAM), University of Bremen, Germany. Quantification of the mineral content was carried out with Quantitative Phase-Analysis with X-ray Powder Diffraction (QUAX) (details are given in Vogt et al., 2002).

Chronology

The chronology of the multicore MC99-3 is based on ^{210}Pb and ^{137}Cs content on neighbouring sediment core in the multi-corer rack (MC99-1). ^{210}Pb and ^{137}Cs measurements were performed in a low background, high efficiency, well-shaped γ-detector at EPOC, CNRS/University of Bordeaux 1, France. According to the age model of Milzer et al. (2013), the sedimentation rate is 0.49 cm/year and the core base age is 1959. The dating error increases gradually down core from ±0.07 to ±3.53 years. As changes in sedimentation rate, degree of sediment compaction, sediment remobilisation as well as biological activity and diffusion can influence the accuracy of the ^{210}Pb analysis, the artificial nuclide ^{137}Cs was used to validate the chronology. Distinct ^{137}Cs increases have been found at core depths of 12.5 cm and 36.5 cm. According to the age model these depths correspond to 1986 (±1.7 yr) and 1963 (±3.4 yr), respectively (Milzer et al., 2013). Hence they are in good agreement with the nuclear weapon tests fallouts (max. in 1963) and the power plant accident of Chernobyl in 1986.

The age model of the upper five meters of the MD99-2292 is based on eight accelerator mass spectrometry (AMS) radiocarbon (^{14}C) date measurements and polynomial regression between the dates. The ^{14}C-AMS dates were determined on carbonate shell material at the Leibniz Laboratory (University of Kiel, Germany) and at the Laboratoire de Mesure du Carbone 14 (Gif sur Yvette Cedex, France). We applied a reservoir correction of 400 years ($\Delta R = 0$) and converted the radiocarbon dates into calibrated years with the Calib 6.0.1 software (Stuiver and Reimer, 1993).

Additional geochemical and instrumental data used

To identify geochemical proxies for terrestrial input and river discharge in the Trondheimsfjord we used two additional geochemical data sets including overbank sediments and bedrock analyses from the drainage area. The bedrock analyses reflects the chemical composition of geological units. Overbank sediments (also called alluvial soil, levée or floodplain sediments) accumulate during active widespread erosion related to flooding episodes. They are considered to represent the average lithological input of a whole catchment area upstream from the sampling site (Ottesen et al., 1989).

In order to compare our results with the recent climate variability, seasonal and annual mean air temperature and precipitation records for the Trondheimsfjord region since 1900 were obtained from the Norwegian Meteorological Institute (www.eklima.no). Moreover, time series (1963 - present) of river discharge for the six largest rivers entering the Trondheimsfjord, Gaula, Orkla, Nidelva, Stjørdalselva, Verdalselva and Steinkjerelva (Fig. 2) were obtained from the Norwegian Water Resource and Energy Directorate (www.nve.no).

4 Summary of papers

Paper I

Faust, J.C., Knies, J., Slagstad, T., Vogt, C., Milzer, G., Giraudeau, J., (in review). **Geochemical composition of Trondheimsfjord surface sediments: Sources and spatial variability of marine and terrigenous components.** *Continental Shelf Research*

This first paper aims to investigate the inorganic/organic geochemistry of surface sediments and to identify geochemical proxies for terrestrial input and river discharge in the Trondheimsfjord, central Norway. Sixty evenly distributed surface sediment samples were analysed for their elemental composition, total organic carbon (C_{org}), nitrogen (N_{org}) and organic carbon stable isotopes ($\delta^{13}C_{org}$), bulk mineral composition and grain size distribution. The results indicate carbonate marine productivity to be the main $CaCO_3$ source. A strong decreasing gradient of marine-derived organic matter from the entrance towards the fjord inner part is consistent with modern primary production data. We show that the origin of the organic matter, as well as the distribution of $CaCO_3$ in Trondheimsfjord sediments can be used as a proxy for the variable inflow of Atlantic water and changes in river runoff. Furthermore, the comparison of grain size independent Al-based trace element ratios with geochemical analyses from terrigenous sediments and bedrocks provides evidence that the distribution of K/Al, Ni/Al and K/Ni in the fjord sediments reflecte regional sources of K and Ni in the northern and southern drainage basin of the Trondheimsfjord, respectively. We propose that the application of these findings to temporally well-constrained sediment records will provide a robust reconstruction of past climate changes in central Norway and potentially illuminate both the variability of the North Atlantic Current and the North Atlantic Oscillation since the last deglaciation.

Paper II

Faust, J.C., Knies, J., Milzer, G., Giraudeau, J., (in review). **Terrigenous input to a fjord in central Norway records the environmental response to the North Atlantic Oscillation over the past 50 years**. *The Holocene*

In the second paper we examine instrumental time series and show that the dominant mode of the atmospheric circulation in the North Atlantic region, the North Atlantic Oscillation (NAO), has a strong impact on river discharge, temperature, and precipitation in central Norway. In addition, elemental composition analysis of a short sediment core reveals that from 1959 to 2010 winter precipitation and temperature changes are recorded by changes in the inorganic geochemical composition of Trondheimsfjord sediments. Elemental ratios of Al/Zr and K/Ni in the sediment core MC99-3 show a close relation to small scale, high frequency climate variations and large-scale changes in the Northern Hemisphere climate. Thus, terrigenous input and related erosional processes in the fjord hinterland are highly sensitive to atmospheric circulation variability in the North Atlantic region. A comparison between the elemental ratio of Al/Zr and NAO records derived from ice accumulation rates of Norwegian glaciers, western Greenland ice sheets and river discharge anomalies in the Eurasian Arctic, supports our assumption that it is possible to reconstruct long term NAO variations from sedimentary archives in central Norwegian fjords.

Paper III

Faust, J.C., Fabian, K., Milzer, G., Giraudeau, J. Knies, J., (in prep.). **North Atlantic Oscillation dynamics recorded in central Norwegian fjord sediments during the past 2800 years**. To be submitted to Nature Geos*cience*

The objective of the third paper is to establish the first reconstruction of the North Atlantic Oscillation from marine sediments. By comparing geochemical measurements from a short sediment core from the Trondheimsfjord, central Norway with instrumental data we show that marine primary productivity proxies are sensitive to NAO changes during the past 50 years. This result is used to link a 2800 years paleoproductivity record to a reliable 500-year long winter NAO reconstruction based on early instrumental and documentary proxy data and establish a late Holocene high resolution NAO record. We show that NAO variabilities coincide with climatically associated changes in paleo-demographics, northern hemisphere (NH) glacier advances and compared to the recent (300 years or so) NAO variabilities positive/negative phases are more persistent. Furthermore, a strong volcanic eruption may have induced the onset of the Little Ice Age (LIA), which is marked by a rapid transition from a stable positive to a stable negative NAO phase.

5 Synthesis

Fjord deposits have a great potential for providing high-resolution sedimentary records that reflect local terrestrial and marine processes and, therefore, offer unique opportunities for the investigation of sedimentological and geochemical climatically induced processes. However, the complexity of fjord systems in terms of bathymetry, oceanography and sedimentary processes requires a profound knowledge of the fjord constitution before starting to interpret climatic signals in Holocene sediment sequences. For this reason, we first attempt to provide a comprehensive overview of the Trondheimsfjord environmental system by applying a geochemical multiproxy analysis on sixty surface sediment samples and compare our findings with available geochemical data from the fjords drainage area. Next, we use the gained knowledge to identify possible organic and inorganic geochemical climate proxies. The consistency of these proxies is evident from a fifty year long geochemical record paralleled with instrumental data of regional temperature, precipitation, river discharge and the NAO. The ultimate result is the first high resolution NAO reconstruction established on marine sediments based on a 2,800 year long paleoproductivity record.

The main conclusions of this study are:

- The inorganic geochemical composition of Trondheimsfjord sediments reflects regional differences in the geology of the terrestrial source area. Specifically, greenstones and metagreywackes located along the southern side of the fjord are the main Ni source in Trondheimsfjord sediments. Thus, Ni enters the Trondheimsfjord mainly via the rivers Orkla, Gaula and Nidelva directly into the Seaward Basin. On the other hand, K and Zr originate largely from Precambrian felsic volcanic rocks related to a tectonic window called *Tømmerås anticline* (see Roberts, 1997 for details) in the north-eastern hinterland.
- Changes in the inorganic geochemical composition of the Trondheimsfjord sediments are closely related to the variability of Trondheimsfjord regional winter-spring river runoff, winter air temperature and precipitation which in turn are strongly related to changes of the NAO. In particular, K, Ni, Zr and Al are proxies for temporal changes in the supply of terrigenous material induced by river runoff, air temperature and precipitation and record both small scale, high frequency, and large scale long term shifts in Northern Hemisphere climate.

- Due to its strong impact on changes of wind, temperature and precipitation in Norway the NAO strongly affects marine primary productivity changes within the Trondheimsfjord. Hence, marine primary productivity proxies such as Ca and $CaCO_3$ can be used to reconstruct NAO variability.
- Finally, the NAO reconstruction based on marine primary productivity changes reveals that late Holocene NAO variability coincides with climatically associated changes in paleo-demographics, and Northern Hemisphere glacier advances. Furthermore, a strong volcanic eruption may have induced the onset of the Little Ice Age, which is marked by a rapid transition from a stable positive to a stable negative NAO phase.

6 Outlook

This study shows that Trondheimsfjord sediments have a great potential for high resolution climate reconstruction. Further investigations should focus on the inorganic geochemical climate proxies presented in this study and test their reliability for long term reconstructions. In this context, a detailed elemental source to sink study in the Trondheimsfjord region could provide important knowledge about the transport mechanisms of individual elements from the hinterland into the fjord. Among others, this would help to identify the response time of the different proxies and provide a better understanding of the seasonal variation of the sediment supply from the main rivers entering the fjord.

Long-term observation of primary productivity in the Trondheimsfjord could reveal seasonal and NAO induced changes in more detail. Furthermore, a detailed study of the connection between planktic and benthic marine productivity and their relation to $CaCO_3$ production and sedimentation could help to provide a better understanding of the proposed link between NAO and $CaCO_3$ in Trondheimsfjord sediments.

Moreover, Trondheimsfjord sediments should be used to expand the NAO record for the entire Holocene. Also, the application of physical modeling studies of the NAO could help to constrain potential triggers and main amplifiers for the reconstructed large scale climatic changes.

As shown in this study, fjord sediments provide the possibility to unveil past atmospheric processes. Hence, further investigations of fjord sediments from other parts of the world may reveal other atmospheric modes for example the NAO related Arctic Oscillation (AO). By combining the findings from different fjords from different continents past atmospheric changes can be revealed on a global scale.

7 References

Abrantes F., Lopes C., Rodrigues T., Gil I., Witt L., Grimalt J. and Harris I. (2009) Proxy calibration to instrumental data set: Implications for paleoceanographic reconstructions. *Geochemistry, Geophysics, Geosystems* **10**.

Appenzeller C., Stocker T.F. and Anklin M. (1998) North Atlantic oscillation dynamics recorded in Greenland ice cores. *Science* **282**, 446-449.

Bøe R., Rise L., Blikra L.H., Longva O. and Eide A. (2003) Holocene mass-movement processes in Trondheimsfjorden, Central Norway. *Norw J Geol* **83**, 3-22.

Bøe R., Bugge T., Rise L., Eidnes G., Eide A. and Mauring E. (2004) Erosional channel incision and the origin of large sediment waves in Trondheimsfjorden, central Norway. *Geo-Mar Lett* **24**, 225-240.

Børsheim K.Y., Myklestad S.M. and Sneli J.-A. (1999) Monthly profiles of DOC, mono- and polysaccharides at two locations in the Trondheimsfjord (Norway) during two years. *Mar Chem* **63**, 255-272.

Cherry J., Cullen H., Visbeck M., Small A. and Uvo C. (2005) Impacts of the North Atlantic Oscillation on Scandinavian hydropower production and energy markets. *Water Resour Manag* **19**, 673-691.

Cook E.R., D'Arrigo R.D. and Mann M.E. (2002) A Well-Verified, Multiproxy Reconstruction of the Winter North Atlantic Oscillation Index since a.d. 1400*. *J Climate* **15**, 1754-1764.

Dickson R.R., Osborn T.J., Hurrell J.W., Meincke J., Blindheim J., Adlandsvik B., Vinje T., Alekseev G. and Maslowski W. (2000) The Arctic Ocean response to the North Atlantic oscillation. *J Climate* **13**, 2671-2696.

Drinkwater K.F., Belgrano A., Borja A., Conversi A., Edwards M., Greene C.H., Ottersen G., Pershing A.J. and Walker H. (2003) the response of marine ecosystems to climate variability associated with the North Atlantic Oscillation. The North Atlantic Oscillation: Climatic Significance and Environmental Impact. *AGU*, Washington, DC, pp. 211-234.

Forwick M. and Vorren T.O. (2007) Holocene mass-transport activity and climate in outer Isfjorden, Spitsbergen: marine and subsurface evidence. *Holocene* **17**, 707-716.

Glueck M.F. and Stockton C.W. (2001) Reconstruction of the North Atlantic Oscillation, 1429-1983. *Int J Climatol* **21**, 1453-1465.

Govin A., Holzwarth U., Heslop D., Ford Keeling L., Zabel M., Mulitza S., Collins J.A. and Chiessi C.M. (2012) Distribution of major elements in Atlantic surface sediments (36°N-49°S): Imprint of terrigenous input and continental weathering. *Geochem Geophy Geosy* **13**.

Hald M., Husum K., Vorren T.O., Grosfjeld K., Jensen H.B. and Sharapova A. (2003) Holocene climate in the subarctic fjord Malangen, northern Norway: a multi-proxy study. *Boreas* **32**, 543-559.

Hald M., Salomonsen G.R., Husum K. and Wilson L.J. (2011) A 2000 year record of Atlantic Water temperature variability from the Malangen Fjord, northeastern North Atlantic. *The Holocene* **21**, 1049-1059.

Hansen L., L'Heureux J.S. and Longva O. (2011) Turbiditic, clay-rich event beds in fjord-marine deposits caused by landslides in emerging clay deposits -

palaeoenvironmental interpretation and role for submarine mass-wasting. *Sedimentology* **58**, 890-915.

Haug A., Myklestad S. and Sakshaug E. (1973) Studies on the phytoplankton ecology of the Trondheimsfjord. I. The chemical composition of phytoplankton populations. *Journal of Experimental Marine Biology and Ecology* **11**, 15-26.

Hoskin C.M., Burrell D.C. and Freitag G.R. (1978) Suspended sediment dynamics in Blue Fjord, western Prince William Sound, Alaska. *Estuarine and Coastal Marine Science* **7**, 1-16.

Howe J.A., Austin W.E.N., Forwick M., Paetzel M., Harland R. and Cage A.G. (2010) Fjord systems and archives: a review. *Geological Society, London, Special Publications* **344**, 5-15.

Hurrell J.W. (1995) Decadal Trends in the North-Atlantic Oscillation - Regional Temperatures and Precipitation. *Science* **269**, 676-679.

Hurrell J.W., Kushnir Y., Ottersen G. and Visbeck M. (2013) An Overview of the North Atlantic Oscillation. The North Atlantic Oscillation: Climatic Significance and Environmental Impact. *American Geophysical Union*, pp. 1-35.

Husum K. and Hald M. (2004) A continuous marine record 8000-1600 cal. yr BP from the Malangenfjord, north Norway: foraminiferal and isotopic evidence. *Holocene* **14**, 877-887.

IPCC (2007) Summary for Policymakers. in: Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (Ed.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. *Cambridge University Press*, Cambridge, United Kingdom and New York, NY, USA.

Jacobson P. (1983) Physical oceanography of the Trondheimsfjord. *Geophysical & Astrophysical Fluid Dynamics* **26**, 3-26.

Jones P.D., Jonsson T. and Wheeler D. (1997) Extension to the North Atlantic Oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. *Int J Climatol* **17**, 1433-1450.

Knies J., Hald M., Ebbesen H., Mann U. and Vogt C. (2003) A deglacial–middle Holocene record of biogenic sedimentation and paleoproductivity changes from the northern Norwegian continental shelf. *Paleoceanography* **18**, 1096.

Knies J. (2005) Climate-induced changes in sedimentary regimes for organic matter supply on the continental shelf off northern Norway. *Geochim Cosmochim Ac* **69**, 4631-4647.

Knies J., Brookes S. and Schubert C.J. (2007) Re-assessing the nitrogen signal in continental margin sediments: New insights from the high northern latitudes. *Earth Planet Sc Lett* **253**, 471-484.

Koistinen T., Stephens M.B., Bogatchev V., Nordgulen Ø., Wennerström M. and Korhonen J. (2001) Geological Map of the Fennoscandian Shield, scale: 1: 2,000,000. *Geological Survey of Finland, Norway and Sweden and the North-West Department of Natural Resources of Russia.*

Kristensen D.K., Sejrup H.P., Haflidason H., Berstad I.M. and Mikalsen G. (2004) Eight-hundred-year temperature variability from the Norwegian continental margin and the North Atlantic thermohaline circulation. *Paleoceanography* **19**.

L'Heureux J.S., Hansen L. and Longva O. (2009) Development of the submarine channel in front of the Nidelva River, Trondheimsfjorden, Norway. *Mar Geol* **260**, 30-44.

L'Heureux J.S., Hansen L., Longva O., Emdal A. and Grande L.O. (2010) A multidisciplinary study of submarine landslides at the Nidelva fjord delta, Central Norway - Implications for geohazard assessment. *Norw J Geol* **90**, 1-20.

L'Heureux J.S., Glimsdal S., Longva O., Hansen L. and Harbitz C.B. (2011) The 1888 shoreline landslide and tsunami in Trondheimsfjorden, central Norway. *Mar Geophys Res* **32**, 313-329.

Lamy F., Hebbeln D., Rohl U. and Wefer G. (2001) Holocene rainfall variability in southern Chile: a marine record of latitudinal shifts of the Southern Westerlies. *Earth Planet Sc Lett* **185**, 369-382.

Luterbacher J., Xoplaki E., Dietrich D., Jones P.D., Davies T.D., Portis D., Gonzalez-Rouco J.F., von Storch H., Gyalistras D., Casty C. and Wanner H. (2001) Extending North Atlantic Oscillation reconstructions back to 1500. *Atmos Sci Lett* **2**, 114-124.

Lyså A., Hansen L., Christensen O., L'Heureux J.S., Longva O., Olsen H.A. and Sveian H. (2008) Landscape evolution and slide processes in a glacioisostatic rebound area; a combined marine and terrestrial approach. *Mar Geol* **248**, 53-73.

Mikalsen G., Sejrup H.P. and Aarseth I. (2001) Late-Holocene changes in ocean circulation and climate: foraminiferal and isotopic evidence from Sulafjord, western Norway. *Holocene* **11**, 437-446.

Milzer G., Giraudeau J., Schmidt S., Eynaud F. and Faust J. (2013) Qualitative and quantitative reconstruction of surface water characteristics and recent hydrographic changes in the Trondheimsfjord, central Norway. *Clim. Past Discuss.* **9**, 4553-4598.

Olsen J., Anderson N.J. and Knudsen M.F. (2012) Variability of the North Atlantic Oscillation over the past 5,200 years. *Nat Geosci* **5**, 808-812.

Ottersen G., Planque B., Belgrano A., Post E., Reid P. and Stenseth N. (2001) Ecological effects of the North Atlantic Oscillation. *Oecologia* **128**, 1-14.

Ottesen R.T., Bogen J., Bølviken B. and Volden T. (1989) Overbank sediment: a representative sample medium for regional geochemical mapping. *Journal of Geochemical Exploration* **32**, 257-277.

Paetzel M. and Dale T. (2010) Climate proxies for recent fjord sediments in the inner Sognefjord region, western Norway. *Geological Society, London, Special Publications* **344**, 271-288.

Pinto J.G. and Raible C.C. (2012) Past and recent changes in the North Atlantic oscillation. *Wires Clim Change* **3**, 79-90.

Rise L., Bøe R., Sveian H., Lyså A. and Olsen H.A. (2006) The deglaciation history of Trondheimsfjorden and Trondheimsleia, Central Norway. *Norw J Geol* **86**, 415-434.

Roberts D. (1997) Geochemistry of Palaeoproterozoic porphyritic felsic volcanites from the olden and Tømmerås windows, central Norway. *GFF* **119**, 141-148.

Ruddiman W.F. (2001) Earth's Climate: Past and Future. *W. H. Freeman and Company*, New York.

Sakshaug E. and Myklestad S. (1973) Studies on the phytoplankton ecology of the trondheimsfjord. III. Dynamics of phytoplankton blooms in relation to environmental factors, bioassay experiments and parameters for the physiological state of the populations. *Journal of Experimental Marine Biology and Ecology* **11**, 157-188.

Sakshaug E. and Sneli J.-A. (2000) Trondheimsfjorden. *Tapir Forlag*, Trondheim.

Schafer C.T., Smith J.N. and Seibert G. (1983) Significance of natural and anthropogenic sediment inputs to the saguenay Fjord, Quebec. *Sediment Geol* **36**, 177-194.

Stuiver M. and Reimer P.J. (1993) Extended 14C data base and revised CALIB 3.0 14C age calibration program. *Radiocarbon* **35**, 215-230.

Svendsen H., Beszczynska-Møller A., Hagen J.O., Lefauconnier B., Tverberg V., Gerland S., Ørbøk J.B., Bischof K., Papucci C., Zajaczkowski M., Azzolini R., Bruland O., Wiencke C., Winther J.-G. and Dallmann W. (2002) The physical environment of Kongsfjorden–Krossfjorden, an Arctic fjord system in Svalbard. *Polar Res* **21**, 133-166.

Syvitski J. and Schafer C.T. (1985) Sedimentology of Arctic Fjords Experiment (SAFE): Project Introduction. *Arctic* **38**, 264-270.

Syvitski J.P.M. (1989) On the deposition of sediment within glacier-influenced fjords: Oceanographic controls. *Mar Geol* **85**, 301-329.

Trouet V., Esper J., Graham N.E., Baker A., Scourse J.D. and Frank D.C. (2009) Persistent Positive North Atlantic Oscillation Mode Dominated the Medieval Climate Anomaly. *Science* **324**, 78-80.

Vinther B.M., Johnsen S.J., Andersen K.K., Clausen H.B. and Hansen A.W. (2003) NAO signal recorded in the stable isotopes of Greenland ice cores. *Geophys Res Lett* **30**.

Vogt C., Lauterjung J. and Fischer R.X. (2002) Investigation of the Clay Fraction (<2µm) of the Clay Minerals Society Reference Clays. *Clays and Clay Minerals* **50**, 388-400.

Wanner H., Brönnimann S., Casty C., Gyalistras D., Luterbacher J., Schmutz C., Stephenson D. and Xoplaki E. (2001) North Atlantic Oscillation – Concepts And Studies. *Surveys in Geophysics* **22**, 321-381.

Wendelbo P.S. (1970) Hydrografiske forhold i Trondheimsfjorden 1963-66. PhD Thesis, University of Oslo

White A.F. and Blum A.E. (1995) Effects of Climate on Chemical-Weathering in Watersheds. *Geochim Cosmochim Ac* **59**, 1729-1747.

Zabel M., Schneider R.R., Wagner T., Adegbie A.T., de Vries U. and Kolonic S. (2001) Late Quaternary climate changes in central Africa as inferred from terrigenous input to the Niger fan. *Quaternary Res* **56**, 207-217.

Öztürk M., Steinnes E. and Sakshaug E. (2002) Iron speciation in the Trondheim fjord from the perspective of iron limitation for phytoplankton. *Estuar Coast Shelf S* **55**, 197-212.

Paper I

Faust, J.C., Knies, J., Slagstad, T., Vogt, C., Milzer, G., Giraudeau, J., (in review). Geochemical composition of Trondheimsfjord surface sediments: Sources and spatial variability of marine and terrigenous components. Submitted to Continental Shelf Research, 01.03.2014

Paper II

Faust, J.C., Knies, J., Milzer, G., Giraudeau, J., (in review). Terrigenous input to a fjord in central Norway records the environmental response to the North Atlantic Oscillation over the past 50 years. Submitted to The Holocene, 16.12.2013

Paper III

Faust, J.C., Fabian, K., Milzer, G., Giraudeau, J. Knies, J., (in prep.). North Atlantic Oscillation dynamics recorded in central Norwegian fjord sediments during the past 2800 years. To be submitted to Nature Geoscience