ARTICLE IN PRESS

Continental Shelf Research xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Geochemical characterisation of northern Norwegian fjord surface sediments: A baseline for further paleo-environmental investigations

Johan C. Faust[a,b,*], Thomas Scheiber[a,c], Karl Fabian[a,d], Christoph Vogt[e], Jochen Knies[a,d]

[a] Geological Survey of Norway, Leiv Eirikssons vei 39, 7040 Trondheim, Norway
[b] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom
[c] Western Norway University of Applied Sciences, Sogndal, Norway
[d] CAGE – Centre for Arctic Gas Hydrate, Environment and Climate, Department of Geology, UiT the Arctic University of Norway, 9037 Tromsø, Norway
[e] Central Laboratory for Crystallography and Applied Material Science (ZEKAM) & Crystallography, Geosciences, University of Bremen, Klagenfurter Strasse 2-4, 28359 Bremen, Germany

ABSTRACT

Norwegian fjord sediments are promising archives for very high resolution records of past environmental changes. Recent investigations of the modern depositional environment within fjords revealed that the accurate quantification of the inputs, sources, and sedimentary preservation of organic and inorganic material is crucial to decipher long term past climate signals in the sedimentary record of a certain fjord. Here, we investigate the elemental composition, bulk mineral assemblage and grain size distribution of forty-one surface sediment samples from a northern Norwegian fjord system. We reveal modern geochemical and sedimentological processes that occur within the Vestfjord, Ofotfjord and Tysfjord. Our results indicate a very heterogeneous sediment supply and intricate sedimentation processes. We propose that this is related to the complex fjord bathymetry, a low hydrodynamic energy environment, differences in the hinterland bedrock composition and a relatively small drainage area causing a rather diffuse freshwater inflow. Moreover, we show that marine carbonate productivity is the main calcite and Ca source in all three fjords.

1. Introduction

Sediments accumulating in fjords have the potential to be one of the best high-resolution archives of climate and local environmental changes (Howe et al., 2010). High sedimentation together with the possibility to quantify the fjord's hydrological cycle (freshwater input and marine water exchange) offer an excellent opportunity for studying land-ocean interactions and can provide ultra-high-resolution records of local responses to short-term climate variability (Faust et al., 2016; Forwick and Vorren, 2007; Hald and Korsun, 2008; Howe et al., 2010; Husum and Hald, 2004; Kristensen et al., 2004; Mikalsen et al., 2001; Paetzel and Dale, 2010; Syvitski, 1989).

In general, it is assumed that changes in precipitation and temperature alter the constitution of fluvial sediment flux, generated by weathering and erosion of bedrock and soils, from land towards ocean basins (e.g. Govin et al., 2012; Lamy et al., 2001; White and Blum, 1995). However, a detailed knowledge of the controlling transport mechanisms of the particle supply is required to explore the relationship between terrigenous input and changes in environmental conditions (Zabel et al., 2001). Sediment characteristics, accumulation and distribution vary with climate, seafloor topography, basin geometry, size of the drainage area, oceanographic regime, and distance to river outlets (e.g. Syvitski et al., 1987). Thus, identifying the provenance of the sediment components is the key factor to determine and reconstruct (1) sea-level changes, (2) hinterland weathering processes, (3) climate variability and (4) anthropogenic influences. For this reason numerous studies have focused on the contribution of organic carbon (e.g. Goñi et al., 1997; Knies and Martinez, 2009; Sargent et al., 1983; Stein and MacDonald, 2004; Winkelmann and Knies, 2005) and trace elements (e.g. Calvert et al., 1993; Cho et al., 1999; Govin et al., 2012; Hayes, 1993; Hirst, 1962; Karageorgis et al., 2005; Kim et al., 1999; Mil-Homens et al., 2014; Pe-Piper et al., 2008) in continental shelf sediments.

Fjords comprise a substantial part of the coastal environments and are important sites for carbon burial due to their high inorganic and organic sedimentation rates (Hedges et al., 1997; Knies, 2005; Knudson et al., 2011; Ludwig et al., 1996; Raymond and Bauer, 2001; Sepúlveda et al., 2011; Smith et al., 2015; St-Onge and Hillaire-Marcel, 2001; Syvitski et al., 1987) but only a very few studies exist using surface sediments to investigate modern fjord environmental settings. Studies

* Corresponding author at: School of Earth and Environment, University of Leeds, Leeds LS2 9JT, United Kingdom.
E-mail address: J.Faust@Leeds.ac.uk (J.C. Faust).

http://dx.doi.org/10.1016/j.csr.2017.08.015
Received 26 January 2017; Received in revised form 22 August 2017; Accepted 22 August 2017

Please cite this article as: Faust, J.C., Continental Shelf Research (2017), http://dx.doi.org/10.1016/j.csr.2017.08.015

from fjords in Chile (Bertrand et al., 2012; Sepúlveda et al., 2011; Silva et al., 2011), New Zealand (Hinojosa et al., 2014; Knudson et al., 2011; Smith et al., 2015), east Greenland (Andrews and Vogt, 2014) and Svalbard (Winkelmann and Knies, 2005) reported a significant influence of freshwater inflow on their geochemical composition and suggest a common decreasing gradient of terrigenous-derived organic- and inorganic material from the inner fjords towards the open ocean. In contrast to these findings, Munoz and Wellner (2016) found terrigenous deposits to occur predominantly in the outer bay of an Antarctic fjord. This indicates that the processes controlling the supply and composition of the inorganic sediment fraction of fjords sediments may vary from fjord to fjord. More investigations of fjord sediments are therefore required to recognize and better understand these differences.

Overall, little is known about seasonal and bathymetry-related changes in sedimentation of particulate material in Norwegian fjords. Recent investigations of surface sediment samples from the Trondheimsfjord, mid-Norway, revealed that not only does the input of terrigenous material vary in proximity to their source but also geochemical composition of the material changes with regard to the hinterland geology (Faust et al., 2014b). Moreover, as shown by Faust et al. (2016, 2014a) a detailed study of the modern environmental fjord setting provides fundamental knowledge necessary to interpret climatic signals in long term fjord sediment sequences.

Similar to the Trondheimsfjord, the regional climate of Vestfjord, Ofotfjord and Tysfjord in northern Norway is strongly influenced by the relatively warm northward flowing North Atlantic Current (NAC) and the atmospheric circulation pattern is dominated by the North Atlantic Oscillation (NAO) (Hurrell, 1995). Thus, sediments from these fjords may contain valuable information about regional past climate changes caused by NAO and NAC variability. Moreover, although the study area was an important pathway for ice-sheet drainage during the late Weichselian (Ottesen et al., 2005), ice-sheet dynamics during the Younger Dryas period in the Vestfjord, Ofotfjord and Tysfjord area is still under debate (Bergstrøm et al., 2005; Fløistad et al., 2009; Knies et al., 2007; Rasmussen, 1984). Hence, the identification of geochemical or mineralogical provenance proxies could help to better understand the deglaciation history in this area. The hinterland geology, bathymetry and oceanography of the Vestfjord, Ofotfjord and Tysfjord are overall similar to the intensively investigated Trondheimsfjord in mid Norway. Our hypothesis is that these similarities of the environmental settings make the Vestfjord, Ofotfjord and Tysfjord sediments a promising archive for paleo-environmental studies. To test our hypothesis, we investigate geochemical, mineralogical and sedimentological data obtained from forty-one surface sediment samples from the Vestfjord, Ofotfjord and Tysfjord in northern Norway (Fig. 1). Our goal is to acquire a better understanding of the modern processes that control the supply and composition of the inorganic sediment fraction of the fjords. We discuss the general trends within these deposits, assess how local variations affect sediment distribution and provide implications for paleo-environmental interpretations.

2. Regional setting

The Vestfjord, Ofotfjord and Tysfjord are the three main fjords of a fjord system between the Norwegian mainland and the Lofoten archipelago in northern Norway (Fig. 1). With a length of about 180 km and its cone shape the Vestfjord is an *"atypical"* fjord and has characteristics more similar to a coastal bay (Fig. 2, Mitchelson-Jacob and Sundby, 2001). The fjord becomes shallower and widens from about 15 km at its junction with the Ofotfjord and Tysfjord in the NE to about 70 km at the entrance in the SW. Moreover, the boundaries between the deeper Vestfjord basin and its shallower coastal areas on the SE and NW sides are marked by up to 300 m high side-edges (Fig. 1). This is interpreted to be the result of enhanced glacial erosion of the downfaulted Vestfjord basin as the Vestfjord functioned as a major ice-sheet drainage route during the last glacial period (Ottesen et al., 2005). The Ofotfjord and Tysfjord morphologies are, as is typical for fjords, characterised by narrow trenches, steep slopes and an entrance sill with varying water depths of 140–350 m (Fløistad et al., 2009). The fjord basins on both sides of the sill are elongated and remarkably deep (500–725 m, Fig. 1).

The total drainage area of the three fjords spans about 7100 km^2 (Fig. 2) and is marked by a relatively sparse vegetation cover and an alpine landscape. Mountains in this region are frequently higher than 1000 m and several small glaciers are present in the drainage area of the Tysfjord and Ofotfjord (Fig. 2). February air temperatures (monthly average) are around 0 °C at the coast and minus 5 to minus 10 °C in the hinterland. During August, hinterland air temperature (monthly average) rises to about 14–15 °C and around 11 °C at the coast. Precipitation varies strongly over short distance with topography (500–2000 mm/a) and is highest during summer/autumn and lowest in spring (The Norwegian Meteorological Institute (met.no)). No large river exists and the runoff is generally low during winter when inland water is frozen and high during summer due to snow melt and rainfall. On average two thirds of the annual runoff occurs from June to August (Mitchelson-Jacob and Sundby, 2001). For more detailed information of the topography, rivers and further hydrological information of the drainage area, we refer to the Norwegian Mapping Authorities (http://kart.statkart.no) and the Norwegian Water Resources and Energy Directorate (http://atlas.nve.no).

The oceanography of the fjord system is driven locally by wind and bathymetry and regionally by tides and the adjacent North Atlantic and Norwegian Coastal Current systems (Furnes and Sundby, 1981; Mitchelson-Jacob and Sundby, 2001). Due to the seasonal variation of freshwater supply, temperature and salinity of the surface water layer (up to 150 m deep) vary between 2–4 °C and 33–34 (PSU) during winter and about 14 °C and 28 (PSU) during summer. The surface layer overlies an Atlantic water layer, which has constant temperatures and salinity of 6.5–7 °C and 34.7–35 (PSU) throughout the year. There are no observations of anoxic conditions in the fjords (Gitmark et al., 2014). The general surface circulation can be described by inflowing Atlantic water along the southeast side (mainland) and an outflow current along the northwest side (Lofoten) with cyclonic circulation in between (Mitchelson-Jacob and Sundby, 2001). Yet, this major current regime is strongly affected by the dominant wind direction. SW winds reverse the flow direction and may induce upwelling on the Lofoten side and downwelling on the mainland side (Fig. 2). Additionally, the SW winds cause an enhanced flow of upper water masses into the Vestfjord, Ofotfjord and Tysfjord, which presses the underlying Atlantic water out of the fjords (Furnes and Sundby, 1981). NE winds cause the opposite effect. They force the upper water layer out of the fjords which results in an inflow of Atlantic water and may induce downwelling on the Lofoten side and upwelling on the mainland side (Fig. 2).

The bedrock geology in the drainage areas of the Vestfjord, Ofotfjord and Tysfjord can be subdivided into Precambrian basement units and overlying Caledonian nappes (Fig. 2). The basement is largely composed of Paleoproterozoic plutonic rocks of the anorthosite-mangerite-charnockite-granite (AMCG) suite intruding older metamorphic rocks (Corfu, 2004). The Caledonian nappes predominantly contain metamorphosed Ordovician-Silurian sediments such as micaschist, metasandsone and subordinate marble (Andresen and Steltenpohl, 1994; Corfu et al., 2014).

3. Methods and data

3.1. Fjord surface sediments: sampling and preparation

In June 2014, forty-one surface sediment samples were collected at water depth between 59 and 634 m across the Vestfjord, Ofotfjord and Tysfjord (67°40´N, 13°00´E, 68°40´N, 17°40´E) (Fig. 1 and ES-1). In general, sediments are mainly transported by rivers into fjords and the main controlling factors of their distribution are the bathymetry of the fjord and oceanography. Therefore, sampling locations where selected