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Geochemical composition of Trondheimsfjord surface sediments: Sources and spatial variability of marine and terrigenous components

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ABSTRACT

High sedimentation rates in fjords provide excellent possibilities for high resolution sedimentary and geochemical records over the Holocene. As a baseline for an improved interpretation of geochemical data from fjord sediment cores, this study 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. Our results indicate carbonate marine productivity to be the main $CaCO_3$ source. Also, 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 analysis from terrigenous sediments and bedrocks provides evidence that the distribution of K/Al, Ni/Al and K/Ni in the fjord sediments reflect regional sources of K and Ni in the northern and southern drainage basin of the Trondheimsfjord. Applying these findings to temporally well-constrained sediment records will provide important insights into both the palaeoenvironmental changes of the hinterland and the palaeoceanographic modifications in the Norwegian Sea as response to rapid climate changes and associated feedback mechanisms.

1. Introduction

The Norwegian coastal climate is strongly influenced by the relatively warm northward flowing North Atlantic Current (NAC) and the North Atlantic Oscillation (NAO) which is the leading mode of atmospheric circulation variability in the North Atlantic region (e.g. Cherry et al., 2005; Dickson et al., 2000; Hurrell, 1995). Thereby, both factors have strong impact on precipitation, temperature and wind intensity changes which are assumed to alter marine and terrestrial ecological dynamics as well as the constitution of fluvial sediment flux from land towards ocean basins generated by weathering and erosion of bedrock and soils (e.g. Govin et al., 2012; Lamy et al., 2001; White and Blum, 1995). As consequence, sediments delivered to Norwegian fjords contain information regarding environmental changes of the hinterland and oceanographic variability on the adjacent continental margins and shelves through water mass exchange (e.g. Howe et al., 2010; Schafer et al., 1983; Syvitski and Schafer, 1985). 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. As such, sediments accumulating in Norwegian fjords 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.

Before deciphering the past climate signals in the sedimentary record, however, it is important to understand the modern depositional environment within the fjords and to accurately quantify inputs, sources, and sedimentary preservation of the organic and inorganic material (e.g. Inall and Gillibrand, 2010; Smith et al., 2010). Here, we investigate the environmental

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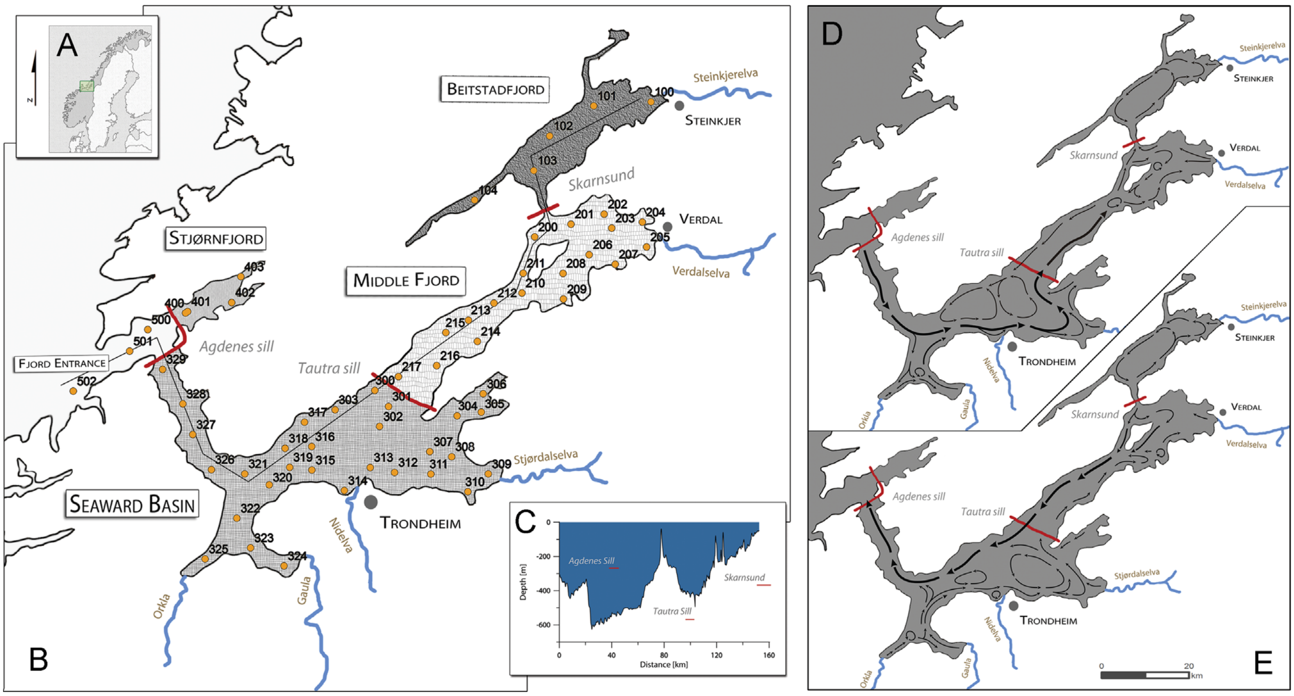

Fig. 1. (A) Location of the study area. (B) Map of the Trondheimsfjord showing the sampling positions (yellow circles. ES-1) and the three sills (red lines) dividing the fjord into four main basins as well as the six main rivers entering the fjord from the south/southeast. The thin black line is the path of the bathymetry profile (C). Inset: surface water circulation pattern during high tide phase (D) and low tide phase (E) (modified after Jacobson, 1983; and Bierach, 1989). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

constraints in the Trondheimsfjord, central Norway, based on sixty surface sediment samples from the entire Trondheimsfjord (Fig. 1). We used these samples to study the modern geochemical and sedimentological processes that occur within the fjord and to identify possible proxies for past environmental changes. For these purposes, we analysed all surface sediment samples for elemental composition, total organic carbon (C_{org}) and total organic nitrogen (N_{org}) content, organic carbon stable isotopes ($\delta^{13}C_{org}$), bulk mineral composition and grain size distribution. To the best of our knowledge, no similar systematic organic and inorganic geochemical investigation of fjord surface sediments has been conducted in the Trondheimsfjord or in any other Norwegian fjord.

To identify marine/terrigenous sources in continental shelf sediments, 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 (Calvert et al., 1993; Cho et al., 1999; Govin et al., 2012; Hayes, 1993; Hirst, 1962; Karageorgis et al., 2005). But although fjords comprise a substantial part of coastal environments at higher latitudes and are assumed to be 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; St-Onge and Hillaire-Marcel, 2001; Syvitski et al., 1987) only a very few studies exist using surface sediments to investigate the environmental processes that control the organic and inorganic geochemistry of fjord sediments. Sepúlveda et al. (2011), Silva et al. (2011) and Bertrand et al. (2012) conducted inorganic and organic geochemical surveys on surface sediments obtained from oxic fjords in northern Patagonia, Chile. They reported a significant influence from freshwater inflow on their geochemical composition and a decreasing gradient of terrigenous-derived organic- and inorganic material from the inner fjords towards the open ocean. Similar distribution patterns of marine versus terrigenous organic matter was also found in fjords of New Zealand and Svalbard (Knudson et al., 2011; Smith et al., 2010; Winkelmann and Knies, 2005). In anoxic fjords such as Framvaren, southern Norway, or Saanich Inlet, western British Columbia, environmental conditions are characterised by enriched hydrogen sulphide in the water and organic-rich bottom sediments, with no significant distribution patterns of marine and terrigenous organic matter (Gucluer and Gross, 1964; Skei, 1983).

In the current study, we took a high spatial surface sediment sample distribution and combined our results with geochemical and geological field mapping datasets from the drainage area of the Trondheimsfjord. We aim to detect sources of organic and inorganic sediment components and to better identify environmental mechanisms controlling their supply and distribution in the Trondheimsfjord.

2. Study area

The temperate Trondheimsfjord is located in the central part of Norway (Fig. 1) 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° (Bøe et al., 2003). Three sills, the Agdenes Sill at the entrance (max. water depth 330 m), the Tautra Ridge in the middle section (max. water depth 100 m) 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 Beitstadfjord (Fig. 1) (for detailed maps of bathymetry and topography of the drainage area, we refer to http://kart.statkart.no). 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 maritime climate in the Trondheimsfjord region is strongly influenced by the NAO (Wanner et al., 2001), causing warm and wet (+NAO) or cold and dry (−NAO) weather conditions especially during