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The impact of submarine copper mine tailing disposal from the 1970s on Repparfjorden, northern Norway

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ABSTRACT

We investigate the state of sedimentological environment and contaminant status of Repparfjorden (N Norway) impacted by submarine disposal of mine tailings during the 1970s using sedimentological and geochemical properties of seventeen sediment cores. The impact of tailings disposal is mainly restricted to the inner fjord where the discharge occurred. Sediment cores retrieved from the inner fjord contain layers of mine tailings up to 9-cm thick, 3–9 cm below the seafloor. Spreading of the tailing-related metal Cu and particles is limited to the inner fjord and to a 2 cm layer in one core from the outer fjord. Two interrelated factors, fjord morphology and sedimentation rate, controlled the distribution of contaminant-laden tailings in the fjord. The mobility of Cu from buried contaminated sediments to the sediment-water interface in the inner fjord indicates that benthic communities have been continuously exposed to elevated Cu concentrations for nearly four decades.

1. Introduction

Coastal zones are of great ecological, economic and social importance (Martínez et al., 2007) and with increasing human activities they are particularly prone to anthropogenic pollution. Especially vulnerable are estuaries, forming a natural sink for (contaminated) sediments, that due to their dynamic regime may also act as sources of sediments, both seaward and up-estuary (Ridgway and Shimmield, 2002). There are different types of marine contaminants, originating from e.g. sewage effluents, agricultural run-offs, industrial effluents, oil spills, litter, etc. (e.g. Islam and Tanaka, 2004). Among them, although more marginal in a global scale, are mine tailings.

Mine tailings are a waste product resulting from the mechanical and chemical separation of minerals from geological material retrieved during mining. They contain a mixture of milled ore (often of high residual metal concentrations), water and sometimes process chemicals. The most common way of disposing and storing mine tailings is on-land (up to 99%) but an alternative, marine disposal, is practiced in Norway and Papua New Guinea, and at some locations in Turkey, England, Greece, France, Chile and Indonesia (Vogt, 2013). Marine tailings disposal approaches are differentiated based mainly on the depth of tailings discharge, an important factor from the perspective of potential ecological and environmental impacts (for review see e.g. Ramirez-Llodra et al., 2015). However, recent legal frameworks limit all types of marine disposal with exceptions under specific conditions, as for example described within the London Protocol (IMO, 2016), a globally leading initiative to protect marine environment.

Post-discharge studies of historical submarine tailings disposal operations have identified impacts on the environment. They are primarily confined to the area of the disposal and may include physical and geochemical alteration of the bottom sediment, smothering of benthic organisms, reduction of marine biodiversity, risk of bioaccumulation of heavy metals in aquatic organisms (e.g. Burd, 2002; Elberling et al., 2003; Hughes et al., 2015; Josefson et al., 2008; Larsen et al., 2001; for review see also Ramirez-Llodra et al., 2015). Even though operators are required to establish practices to minimize the potential environmental consequences, some of the documented historical disposal activities have impacted a wider area than expected (e.g. Edinger, 2012; Perner et al., 2010).

Submarine tailings discharge has been carried out in Norwegian fjords for more than 100 years. There are at least 26 historical sites where relatively large discharges and/or discharges with the release of potentially toxic metals have occurred (Kvassnes and Iversen, 2013). However, as underlined by Ramirez-Llodra et al. (2015), there are no reports providing information on the exact composition of discharges, i.e. neither detailed chemistry and their changes, nor the fate of these

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materials once they enter the marine environment. This gap of knowledge is of particular significance since fjords are estuaries with characteristic morphological features, circulation and stratification patterns. The presence of basin(s) separated by sill(s) makes them depocenters for (contaminated) sediments, thus rendering them particularly susceptible to pollution impacts.

Various analytical tools are used to map the historical contaminations of the marine environment (e.g. estuaries) recorded in sediments (e.g. Ridgway and Shimmield, 2002). However, the choice of applied techniques strongly depends on the type of pollutants. The disposed mine tailings comprise large quantities of processed geological material, usually enriched in concentrations of extracted metal(s). Therefore, the basic method used include analyzing multi-element geochemistry (e.g. Edinger et al., 2007; Elberling et al., 2003; Larsen et al., 2001; Little et al., 2015; Odhiambo et al., 1996; Perner et al., 2010), often supplemented by analyses of organic carbon content and grain-size distribution, both being closely interrelated with most of the investigated elements/metals (Elberling et al., 2003; Edinger et al., 2007; Little et al., 2015). They are occasionally supported by radionuclide activity measurements to provide an independent time scale (e.g. Elberling et al., 2003; Odhiambo et al., 1996; Little et al., 2015; Perner et al., 2010). In a perspective of the processes governing the spreading and potential impacts of the discharged mine tailings on the marine environment it seems equally important to track the distribution of the tailing particles themselves, and not only the tailing-related contaminants. Grain-size analysis may provide additional evidence to understand material dispersion pattern, as exemplified by Okada et al. (2009) in their research on the spatial distribution of dredged material disposed in UK coastal waters.

The main aim of this study is to assess the state of the sedimentological environment and the potential impacts of submarine tailings disposal from copper (Cu) mine activities on the fjord Repparfjorden (northern Norway), nearly 40 years after its cessation. The fjord has two basins, the inner and outer basin separated by a sill. Mine tailings were discharged into the inner part of the fjord during copper mining operations in the 1970s in an amount estimated at ~1 million tons (Kvassnes and Iversen, 2013).

Previous investigations of Repparfjorden are sparse and only reported in grey literature and in consultancy reports (Christensen et al., 2011; Dahl-Hansen and Velvin, 2008). These authors mainly examine surface sediment samples, characterizing primarily the present state of the Repparfjorden environment. They document elevated concentrations of heavy metals in surface sediments in the vicinity of the discharge point, while finding no significant differences between the inner and outer fjord in benthic organisms or in benthic biodiversity. In addition, one ^{210}Pb-dated core collected from the central part of the fjord (Fig. 1) was investigated for heavy metal concentrations revealing that only pollution of a negligible level occurred in surface sediments (Christensen et al., 2011). The characteristics of the tailings discharged during the 1970s were partly a focus of Pedersen et al. (2016) in terms of metal availability and its potential mobilization. In their study, a 10-cm-thick sediment sample taken 5 cm below the seafloor from the inner fjord was investigated, assuming to be representative of the mine tailings. Chemical analyses revealed a relatively high Cu concentration that was associated with more available fractions.

Here we examine the sedimentological and geochemical records obtained from seventeen short sediment cores retrieved from the entire fjord. We give particular attention to the reconstruction of sedimentation based on grain-size characteristics and sediment accumulation rates, as well as potential sediment transport paths with prime focus on lateral and vertical spreading of mine-tailing related contaminants (metals) and particles. In light of the obtained results, we also address questions of potential long-term impacts of environmental pollution in the fjord.

2. Study area

Repparfjorden, located in Finnmark County (northern Norway), is an approximately 13 km long, up to 4 km wide and c. 37 km^2 large fjord (Fig. 1). Water exchange with the open ocean occurs through Kvalsundet and Sammelsundet. The fjord comprises two main basins, a smaller basin with maximum water depth of c. 65 m in the inner fjord and a larger basin with up to c. 120 m depth of the outer fjord. They are separated by an ENE-WSW orientated sill reaching a maximum water depth of 50 m. An additional sill, interpreted to be part of an end moraine (Marthinussen, 1960) crosses the fjord mouth. Repparfjorden is a temperate non-glaciated, river-influenced fjord, with the main river Repparfjordelva at the fjord head. This river drains an area of 1019 km^2. A delta and a tidal flat occur at the transition from the river to the fjord.

Copper deposits of the Ulveryggen and Nussir ore formations occur south of Repparfjorden. They are associated with the Repparfjord Tectonic Window within the Caledonides (Sandstad et al., 2012). The first mining activities of Repparfjorden ore deposits commenced in the beginning of the 20th century, however, large-scale operations started in the 1970s. Between 1972 and 1978 (1979) approximately 3 Mt of ore were mined from open pits in the Ulveryggen formation (Sandstad et al., 2012) and approximately 1 million tons of tailings were subsequently discharged at the inner fjord bottom (Kvassnes and Iversen, 2013). The exact composition of the tailings before disposal (particle size, geochemical characterization and chemicals used) along with the location of the discharge outlet are uncertain and the information provided below are based on disparate sources, namely brochures issued by the mining company in the 1970s and community interviews (Svendsen J., pers. comm.). The mine tailings were discharged about 1.5 km away from the processing plant through a pipeline at a depth of about 60 m (for location see Fig. 1C). The pipeline, suspended 20 m above the seafloor, had openings at its outlet over a length of 600 m spaced at intervals of 100 m. About 80% of the ore was milled to the size of 74 μm, subjected to the flotation process and thereafter mixed with flocculent chemical and disposed at the fjord bottom. The flocculent (likely Separan NP10) was used to prevent mobilization and facilitate rapid settling of the tailing particles. According to recently conducted chemical characterization of tailings from the Ulveryggen deposits, that were produced using similar methods as in the 1970s, the Cu concentrations vary between 707 and 1090 mg/kg depending on the grain-size fraction of analyzed subsamples (Kleiv, 2011).

3. Material and methods

3.1. Sampling procedure

The material for this study was collected during two cruises in April 2013 and June 2015 with R/V Helmer Hanssen of UiT The Arctic University of Norway in Tromsø (UiT). Sediment cores, up to 21 cm long, were taken from seventeen stations covering the entire fjord (Fig. 1, Table 1). They were retrieved with a multi corer (MC) or with a box corer (BC), respectively. The MC contains six plastic liners (up to 80 cm long; 11 cm outer diameter), whereas BC consists of a metal box with dimensions of 50 cm × 50 cm × 50 cm into which plastic liners were pushed to sub-sample individual sediment cores. The surfaces of all of the cores analyzed in this study were undisturbed. Whenever possible a duplicate of each core was retrieved to ensure enough amount of (dry) material for the purpose of this study (~40 g) as well as for the foraminifera analysis (preferable > 100 g) (Skirbekk et al., in prep.) and detailed chemical analyses (~30 g) (Pedersen et al., subm.). The seventeen cores together with one of their duplicates were sliced into samples of 1-cm thickness and frozen immediately after retrieval. All samples were freeze-dried prior to the analyses (for an