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In situ characterisation of complex suspended particulates surrounding an active submarine tailings placement site in a Norwegian fjord

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ABSTRACT

Suspended particle measurements over flood and ebb transects of a Norwegian fjord (Frænfjorden) with an active submarine mine tailings placement are presented. Measurements focused on characterisation of spatial variability in particle and floc size, and determination of suspended mine tailing concentrations. Such information is crucial for understanding transport and flocculation dynamics, which in turn can contribute to improvements of numerical models, and thus to more accurate predictions of settling fluxes and transport processes. Multiple instruments were used to ensure that all relevant particle sizes could be observed. These included a LISST-100x, a LISST-Holo and a bespoke particle imaging system, which were deployed together on a profiling frame at multiple stations transecting the fjord. Measurements were obtained close to the high-concentration plume from the tailings discharge and extended several kilometres horizontally. We observed a combination of few-micron fines, densely packaged flocs and large string-like flocs, several mm in length; a range which could not be captured by a single instrument. Such a range of floc sizes and complexities has significant implications for the transport and settling of the material suspended within the fjord.

1. Introduction

Mining in Norway is currently in a phase of increased growth and subject to evolving environmental regulations and requirements. For many mines, both in Norway and globally, sustainable waste management remains the main challenge, as they often produce large quantities of waste rock and tailings from land-based mineral processing during resource extraction (Skei, 2013). To overcome problems with deposition of this waste, some mines place their tailings at the sea floor of fjords as submarine tailings placements (STPs) (Dold and Bernhard, 2014; Ramirez-Llodra et al., 2015; Skei, 2013). In Norway, there are currently 33 sites that have been identified as possible locations for STPs, of which 6 are active today (Ramirez-Llodra et al., 2015).

The best available techniques should be used to ensure that the environmental impact from STPs are reduced to an absolute minimum, and that ecosystems are given the chance to recover as quickly as possible following the closure of mines. The discharged mine tailings have the potential to affect sea bed ecosystems, through smothering, change of grain size or dissolved metals and chemical toxicity, as well as organisms living in the water column, either through dissolved substance toxicity or from suspended fine-grained tailings (Doe et al., 2017; Morello et al., 2016; Tye et al., 1996). It has been long known that pelagic filter feeders can ingest mineral particles upon exposure (Anderson and Mackas, 1986; Kach and Ward, 2008), and more recently, it was shown that fine-grained mine tailings can also attach to the surface of a calanoid copepod species (Calanus *finmarchicus*) (Farkas et al., 2017). No acute effects were observed in that study, but longer term effects from the mine tailings could not be ruled out. The potential for environmental exposure of such organisms to fine grained tailings is therefore important to assess. In addition, large flocs can act as carriers of hazardous substances (Lyons et al., 2005) and increase the exposure of contaminants on the seabed due to the loosely-packaged sediment layer that forms from floc settling (Milligan and Law, 2013). Knowledge on how best to dispose of mine tailings in the marine environment to minimise ecological impacts requires a detailed understanding of exposure pathways and mechanisms of biological impact, which in turn requires a thorough understanding of the transport mechanisms.

A key process determining the transport and fate of mine tailings in the sea is aggregation, or flocculation, whereby small mineral particles collide with each other and with biological and mineral particles already present in the water, to form flocs of various shapes, sizes and densities. This alters the fate and transport of the discharged material by changing the settling behaviour

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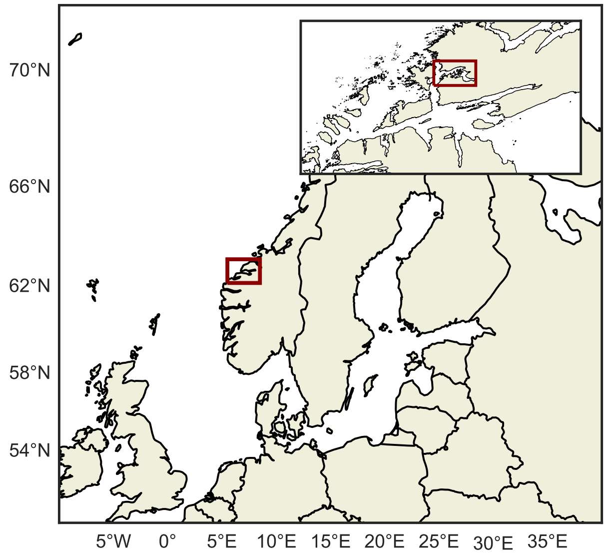

Fig. 1. Map showing the location of Frænfjorden (red rectangle). The inset shows a closeup with Frænfjorden and the STP area indicated (red rectangle in inset). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

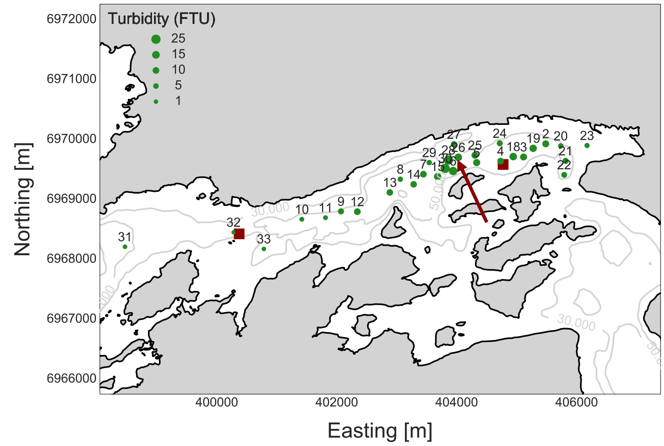

Fig. 2. Detailed map of Frænfjorden, showing the location of the release point during the measurement period (red arrow), the acoustic current profilers on bedframes (red markers), and the profiling stations (green markers). The size of the profiling station indicators are proportional to the maximum turbidity at that location. eastings and northings are given in UTM zone 32 V coordinates. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

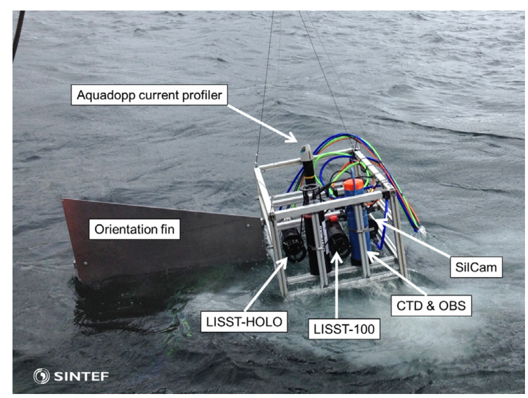

Fig. 3. Photograph of the profiling frame during recovery at the end of a profile. A white cloud of mine tailings can be seen surrounding the frame, as the accumulation of material collected on the frame 'feet' at the seabed, is released.

of the particles (Hill et al., 2000; Skei and Syvitski, 2013). Two things change in relation to particle settling fluxes that result from flocculation: (1) increase in particle size; (2) decrease in particle density. The result is the formation of flocs which sink faster than the individual component particles (flocculi) but slower than would be predicted from solely the increase in size and no consideration of reduction in density (Mikkelsen and Pejrup, 2000; Graham and Nimmo-Smith, 2010b; Bowers et al., 2014). This means that some large flocs have the potential for significant horizontal transport if their density is sufficiently low. In order to understand the degree to which flocculation alters these transport processes it is necessary to characterise the size distribution and concentration of particles using methods that span a size range of several orders of magnitude. A single instrument or technique cannot obtain measurements over such ranges (Boss et al., 2015). Thus, a combination of instruments must be adopted (Mikkelsen et al., 2005; Reynolds et al., 2010).

Here we present detailed *in situ* measurements of the distribution of suspended mine tailings within Frænfjorden, Norway, where approximately 35 mt/h of dry mass material is discharged into the fjord in a solution of saline water with approximate dry–wet ratio of 8%. These measurements were targeted at obtaining information at multiple locations throughout the fjord, covering flood and ebb flows and intersecting the STP area. Detailed information about the nature of the particle populations present was also of interest in order to assess the degree to which flocculation may affect the fate of discharged material. This insight is necessary in order to improve our understanding of environmental consequences within the pelagic zone, and ultimately within the benthic zones following sedimentation.

1.1. Study site

The STP site investigated is located in Frænfjorden, near the city of Molde, Norway (see map in Fig. 1). Owned by Omya Hustadmarmor AS, the STP has been in operation since the early 1980s. The main component of the discharged tailings is calcium carbonate from limestone production, with a significant fraction of very fine particles (31% less than 2 μm, and 71% less than 20 μm. Before discharge, the tailings, which contain some residual fresh water, are mixed with sea water for an approximate final concentration of 8% solids. For more information, see Ramirez-Llodra et al. (2015).

Frænfjorden is a narrow and shallow fjord, connected to the larger Romsdalsfjord on the outside (Fig. 1 inset). The main part of the fjord extends east–west about 7 km and is about 1 km wide. Depths are mostly less than ∼70 m in the inner part of the fjord. The mine tailings discharge was located at UTM coordinate 404 000 E, 6 969 600 N, and a depth of 20 m at the time of this study (June 2015).

2. Method

Two acoustic current profilers were deployed on bedframes, one close to the main inlet to the fjord, and one close to the release point (red markers in Fig. 2). These provided a three-day time-series of water column currents at each location.

A suite of instrumentation for quantifying the size distribution and concentration of suspended particles was deployed from a profiling frame (Fig. 3) along flood and ebb transects, comprising a total of 33 profiling stations. Each station where profiles were obtained is plotted as a green marker in Fig. 2. Turbidity – a relative measure of the optical clarity of the water – was measured