Distribution, deposition and impact of submarine mine tailings disposal on the fjord bottom in Frænfjorden, western Norway

Keywords:

- Submarine tailings placement
- Submarine slide
- Seafloor stability
- Seabed morphology
- Sedimentary environment
- Environmental impact
- Overpressure

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Frænfjorden, a fjord on the west coast of Norway, has been studied to increase our knowledge of the environmental effects of submarine tailings placement (STP). Fine-grained tailings consisting primarily of calcite are disposed of by Omya Hustadmarmor. The dataset, including multibeam echosounder data, shallow seismic, video data, grab samples and sediment cores, demonstrates that tailings are primarily deposited in an up to 2 km-wide area with a tailings thickness of up to 20 m. Minor quantities of tailings are spread outside the STP by tidal currents. Sediment cores show the difference in colour, mineralogy and grain size between the natural sediments and the tailings. The tailings have a white/grey colour, are very fine grained, contain high amounts of calcite and have a lower water content than the natural sediments. A series of multibeam echosounder data from 2013 to 2017 show that deposition of tailings has triggered several small gravity flows and slides. The tailings within the STP have a low stability compared to the natural sediments outside the STP because of their fine grain size and higher sensitivity, high slope angles, high sediment accumulation rates preventing normal consolidation, and loading of tailings causing overpressure in the underlying sediments.

Introduction

The mining sector is growing in parallel with societal demands for minerals (Ramirez-Llodra et al., 2015). Renewable energy sources like wind and solar infrastructure, batteries and electric vehicles all require vast amounts of mined (and recycled) minerals. The mining of these minerals is therefore a necessity for a green energy transition (e.g., NGU, 2016; Giurco et al., 2019).

Tailings are the waste produced after the extraction of the targeted material/metal from the ore through crushing/milling and separation (Vogt, 2013; Ramirez-Llodra et al., 2015). The tailings generally consist of a fine-grained slurry and can contain high proportions of the ore and processing chemicals (Ramirez-Llodra et al., 2015).

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Traditionally, tailings have been stored in land dams, which, however, bear a potential risk of dam failure with major environmental and societal consequences, including the devastation of large areas, the leaching of toxic chemicals and heavy metals, and acidification of waterways (Arnesen et al., 1997; Koski, 2012). Mineral resources in Norway commonly occur in coastal areas but because of the rugged terrain, storage on land is usually not an option. Moreover, the local rainy climate along the Norwegian coast may cause dams to burst if overstressed by floods (Kvassnes & Iversen, 2013). An alternative to land storage is the disposal of tailings in the marine environment. There are three different types of tailing disposal in the sea: coastal shallow-water disposal (CTD), submarine tailing placement (STP) and deep-sea tailing placement (DSTP; Ramirez-Llodra et al., 2015). It has been argued that STP and SDTP are more stable than disposal of tailings in an impoundment or dam as the access of oxidants can be more limited in the submarine environment, thereby hindering the oxidative breakdown of minerals and release of toxic metals (Franks et al., 2011). STPs are not common worldwide, but do occur in e.g., Papua New Guinea, France, Greece, Chile, Canada, Indonesia and Turkey (Vogt, 2013; Ramirez-Llodra et al., 2015). There are 18 STPs in Norway, of which 7 were active in 2015 (Skei, 2014; Ramirez-Llodra et al., 2015).

Environmental impacts from STPs result from (1) hyper-sedimentation, (2) metal toxicity, (3) process chemicals, (4) changes in organic content, grain size and angularity, (5) sediment plumes and turbidity, and (6) materials re-suspension, upwelling and slope failure (Ramirez-Llodra et al., 2015). There is still a limited understanding of the impacts of STPs and how they can best be monitored. To fill in some of these knowledge gaps, the NYKOS (New Knowledge on Sea Disposal) project was started with objectives (1) to increase knowledge of the environmental effects of submarine deposition of fine-grained tailings and (2) to develop new sound environmental criteria and monitoring technologies that prepare for a sustainable mineral industry in Norway. These effects have been studied in different work packages focusing on; chemical processing of tailings, high-resolution bathymetric maps and substrate information, high-resolution modelling of particle transport and flocculation, process chemicals in the environment, trace metals and benthic and pelagic studies (SINTEF, 2019).

In this study, we use multibeam echosounder data, results of shallow seismic profiling, seafloor video observations, grab samples and sediment cores to investigate the distribution, deposition and impact of disposed tailings in the Frænfjorden, western Norway.

Bathymetry, oceanography and geological setting

Frænfjorden is located on the west coast of Norway, in Møre og Romsdal county (Fig. 1). The fjord is approximately 12 km long from the Malme village in the east, where it is named Malmefjorden, to the Julsundet strait at the mouth of the fjord in the west, which connects to the larger Romsdalsfjorden (Fig. 1) (Davies & Nepstad, 2017). Frænfjorden is up to 70 m deep in the western part whereas water depths are 20–40 m in the east. Its mouth towards Romsdalsfjorden is a shallow area with a channel that is up to 45 m deep. The Moaelva river enters the fjord between Malmefjorden and Elnesvågen, while the Malmedalselva river enters the fjord in Malmefjorden (Fig. 1). Both rivers are prone to flooding during snow melting in the spring and during periods of heavy rain. The main circulation within the fjord is controlled by a diurnally asymmetric, tidally driven flow with a tidal range of 2 m and has the anti-clockwise current movement typical to western Norwegian fjords (Brooks et al., 2015; Davies & Nepstad, 2017).

The bedrock in the Frænfjorden area consists mostly of dioritic and granitic gneisses with migmatite in some areas. Amphibolite and mica schist run through the central part of the fjord between two old thrust faults (Bryhni et al., 1989). Small patches of eclogite, periodite and pyroxenite occur east and south of the fjord. Quaternary deposits consist mostly of poorly sorted moraine with thickness up to several tens of

metres. Glacimarine deposits occur in the northeastern part of the fjord close to Elnesvågen (Bøe, 1987; Fig. 1). Some areas have exposed bedrock at the seafloor, but basins in the south of the fjord towards Malme contain mostly postglacial clay. Marine sediments and peat/bog occur along the southern shoreline, further inland and on some of the islands (Bøe, 1987).

Figure 1. Location of Frænfjorden (data from Kartverket). The locations of the Omya Hustadmarmor processing plant and the discharge location are indicated.

Processing of the marble, tailings composition and submarine tailings placement

Omya Hustadmarmor processes marble supplied from mines in Eide and Fræna (Møre og Romsdal county, close to the study area) and from Brønnøysund (Nordland county, northern Norway). Raw marble is transported to the facility in Elnesvågen (Frænfjorden) by boat. The marble is ground, purified and micro-sized at the production/processing plant in Elnesvågen (Fig. 1). The final product is a liquid marble which is mostly used in the paper industry. The rest products, silicates and some fine calcite particles, are separated in a flotation process using chemicals. The tailings have been discharged into the fjord since 1982. The discharge takes place through extendable pipes at a distance of 390 – 760 m from the shore, at a depth of 20 m. The pipelines are fixed to the seafloor by concrete weights (Fig. 2). The tailing disposal in Frænfjorden qualifies as an STP, with the disposal of tailings through an underwater pipeline at relatively shallow (<100 m) water depths but below the euphotic zone (Ellis & Ellis, 1994; Shimmield et al., 2010; Vogt, 2013; Skei, 2014). The deposit area in Frænfjorden outlined in Fig. 3 will be referred to as the STP. A transition area is also indicated. The deposition in the transition area is not allowed to exceed 6 mm/year over a 5-year period (DNV GL, 2016).

Figure 2. Principle sketch showing the deposition of tailings in Frænfjorden (from Omya Hustadmarmor).

The marble arriving at the processing plant consists of c. 96% calcite (calcium carbonate) and 4% other minerals (mainly quartz, feldspar, mica and some iron sulphide) (DNV GL, 2016). The tailings contain 50–60% calcium carbonate (DNV GL, 2018) with more than 80% of the solids finer than sand, mainly in the fractions below 20 μm . The silicates are coarser ($>100 \mu\text{m}$) as they are harder minerals. The tailings contain c. 10% of grains $>100 \mu\text{m}$ and 60–70% $<20 \mu\text{m}$. According to the operator, the tailings do not contain elevated levels of environmentally significant metals, as they are low in raw marble and are neither mined nor disposed. Process chemicals are expected to be associated with the solids (DNV GL, 2014).

Use of flocculation chemicals and mixing of tailings with seawater to increase slurry density increases the rate of settlement at the deposition location and minimises the dispersion of the tailings (Fig. 2). Most of the tailings are deposited close to the end of the pipeline. Only a small amount of particles spreads outside the area allocated for the STP ($<6 \text{ mm/year}$; DNV GL, 2018). The water quality (turbidity, temperature and salinity) is measured continuously by a buoy with measuring equipment, moving up and down in the water column. Sediment quality and soft bottom communities are measured regularly. The water quality, including turbidity, has generally been good ($<10 \text{ FTU}$ (Formazin Turbidity Unit), with just short periods $>5 \text{ FTU}$ within the STP, and $<5 \text{ FTU}$ outside the STP (DNV GL, 2014, 2018).

Since 2007, discharges have been approximately 400–500 kilotons per year (DNV GL, 2014), reducing to approximately 200 kilotons in 2017 (DNV GL, 2018). There has been a massive reduction in tailings discharge because of higher quality raw materials, improvements in the production process, and measures taken by Omya Hustadmarmor to reuse tailings, e.g., for farming (used as agricultural lime) and deacidification of lakes and rivers. The amount of fresh water used has also decreased (DNV GL, 2014).

Material and Methods

Multibeam bathymetry data were collected with NGU's research vessel FF Seisma in 2015 and 2016, using a Kongsberg EM 2040 Dual RX multibeam echosounder. The echosounder was set to transmit signals

(FM pulse, 200 kHz) in a fan of 130 degrees, and multibeam bathymetry and backscatter data were recorded. The data collected with FF Seisma were gridded at 1 m. A Kongsberg Seapath 300+ was used for the positioning, and sound velocity profiles were recorded using a Valeport 650 sound velocity profiler with tidal corrections obtained from the Norwegian Mapping Authority (www.havnivå.no). The data were processed using Caris software.

Multibeam bathymetry data collected by Omya Hustadmarmor and DNV GL (Det Norske Veritas Germanischer Lloyd) in 2013, 2014 and 2017 were used to study changes in bathymetry over time. The datasets collected in 2013 and 2014 have lower resolution and contain more noise than the later datasets and were gridded at 2 m, while the 2017 dataset was gridded at 1 m. ArcGIS software was used to produce all the maps.

High-frequency seismic data (Fig. 3) were acquired using a Kongsberg TOPAS PS 40 parametric sub-bottom profiler. TOPAS uses a parametric acoustic source that forms a 5 degrees wide beam. The profiler was operated in chirp mode with primary frequencies of 36–39 and 41–44 kHz, and chirp length of 10 milliseconds (ms). The returning signal was sampled within the frequency range 2–8 kHz with a median frequency of 5 kHz. This sampling frequency gives a maximum vertical resolution ($\lambda / 4$) of 7.5 cm. However, it is not possible to distinguish features on the seismic data smaller than ($\lambda / 2$) 15 cm (Lepland et al., 2009, Bøe et al., 2018). The seismic data were processed using TOPAS software (Kongsberg) and converted to jpeg2000 files using SegYjp2 software (Courtney, 2018). The data are visualised and interpreted using SegYjp2Viewer software (Courtney, 2018). An acoustic velocity of 1520 m/s was used to estimate the thickness of tailings along the seismic profiles (Lepland et al., 2009).

Altogether, 20 grab samples, 8 Niemistö cores and 21 video transects were collected in August 2015 with FF Seisma (Tables 1 & 2; Fig. 3). The Niemistö cores were logged at NGU using a multisensor core logger (MSCL) measuring wet bulk density (WBD) and magnetic susceptibility (MS), and the fractional porosity was derived from the wet bulk density. After lengthwise splitting and surface cleaning, core surface images were taken with the GeoScan IV colour line-scan camera. X-ray images (XRI) of split cores were taken with the Geotek MSCL-XCT (Geotek Ltd., UK) (see Knies et al., (2018) for a more detailed description of the

Figure 3. Multibeam bathymetry data collected by NGU in 2015 and 2016 with locations of TOPAS profiles, Niemistö cores, grab samples and video transects. The locations of Figs. 4, 5, 6 & 10 are indicated. The deposit area (STP) and transition area are indicated with dark pink and light pink lines, respectively.

Table 1. Cores collected by FF Seisma in Frænfjorden in August 2015.

Core number	Equipment	Water depth (m)	Core length (cm)	UTM zone	Degrees N	Degrees E
P1509021	Niemistö corer	63	29	32	62.814538	7.173444
P1509022	Niemistö corer	51	26	32	62.83003	7.168949
P1509023	Niemistö corer	39	60	32	62.845651	7.113796
P1509024	Niemistö corer	39	60	32	62.845865	7.112997
P1509025	Niemistö corer	38	30	32	62.84373	7.094453
P1509026	Niemistö corer	64	59	32	62.840731	7.098438
P1509027	Niemistö corer	54	27	32	62.837061	7.105902
P1509028	Niemistö corer	54	20	32	62.834322	7.07674

methods). Analyses of total (TC) and organic carbon (C_{org}) were performed with a LECO SC-632. The grain-size distribution (0.4 μm –250 μm) was determined with a Coulter LS 200. To compensate for erroneous recording of clay contents by the Coulter LS 200 instrument (compared to traditional methods such as pipette and Sedigraph), we applied the correction method published by Rise & Brendryen (2013). The undisturbed and remolded shear strength of the sediments were measured using a fall cone test. The sensitivity is the ratio of undrained shear strength in undisturbed and remolded conditions.

Mineralogical analyses were carried out by XRD on unoriented preparations scanned by a Bruker D8 Advance diffractometer (Cu Ka radiation in 3–75° 2 θ range). Mineral identification was carried out with an automatic and/or manual peak search and match function in Bruker's Diffraction EVA V3.1 software. Mineral quantification was performed using Rietveld modelling with software TOPAS 5 (see also Bøe et al., 2018).

Results

Seabed morphology and changes over time

The discharge of tailings takes place through an extendable pipeline that builds cone-shaped deposits on the seafloor. The pipeline is extended when the deposit reaches a minimum water depth of 30 m, as stated in the permit for the activities under the Pollution Control Act granted by the Norwegian Environment Agency on 20 November 2015. In 2011, the practice changed from the use of a single pipeline ending to the use of both a single ending and a split ending to assure more stable deposits, giving it an octopus seafloor shape (Fig. 4). The cones have slope angles of 10–30°, decreasing to 5–9° just outside the cones (Fig. 5). The fjord bottom further away from the discharge locations has slope angles typically below 3° (Fig. 5) while the sides of the fjord may be steep and reach 40°, e.g., close to the processing plant (Fig. 5).

Multibeam bathymetry datasets acquired between 2013 and 2017 show changes in the STP over time (Fig. 6A–E). All three pipeline endings have been extended during this period, and a considerable amount of tailings has been deposited between 2013 and 2017, as shown in Fig. 6F. The deposits at the northern and eastern outlets have a thickness of up to 8 m. At the southern outlet, the deposits reach a thickness of up to 10 m (Fig. 6F).

Figure 4. Shaded relief map (2016 multibeam bathymetry dataset) of the central part of the STP. The morphological interpretation and the different pipeline endings are indicated in the figure.

Figure 5. Slope map (2016 multibeam bathymetry dataset) of the central part of the STP, with the slope angle in degrees.

Figure 6. (A–E) Shaded relief of the central part of the STP in 2013 to 2017. Yellow arrows indicate changes in seafloor topography between the different years. Note slides A and B in 2015 and 2016. (F) Bathymetric difference between the 2013 and 2017 data visualised on the 2017 shaded relief bathymetry.

Gravity-flow channels originate from the cones formed at single pipeline endings (Figs. 4 & 5). Two slides (Fig. 4) occur at the endings of pipelines 2.1 and 2.3 (Fig. 4). Slide A was triggered in the beginning of 2015 (Fig. 6C) possibly because of the placement of concrete weights on the seafloor that are connected to the floating pipeline to keep it in place (Fig. 2). The slide was noticed because the concrete weight and the pipeline moved downwards. A bathymetry survey conducted on the 5th of February 2015 confirmed the presence of a slide. Slide A has a defined sediment lobe below the slide scar (Fig. 4). Slide B was triggered in the end of 2015 or the first half of 2016 (Fig. 6D). The slide scar is visible on the bathymetry data (Fig. 4).

Sediment waves occur within the gravity-flow channels and the slide scars. Downslope, the sediment waves spread out over a wider area as the gravity flows are no longer confined by gravity-flow channels (Figs. 4 & 5). The sediment waves are also visible on the seismic data (Fig. 7). Smaller slides flow down from the fjord side outside the processing plant, with defined sediment lobes below the slide scars (Fig. 4).

Pockmarks occur at the base of the slope, below the area with sediment waves (Fig. 4). The pockmarks are circular, ‘fresh-looking’ and 2–7 m in diameter. Two larger depressions are visible within the basin (Figs. 3 & 4). The one in the east is circular and has a diameter of 135 m (Fig. 4). The depression in the west has a more oval shape and is 120 m across. Both depressions have flat bottoms. Numerous anchoring marks occur on the seabed in the eastern part of the STP (Fig. 4).

Figure 7. TOPAS profile showing sediment waves in the central part of the STP. See Fig. 3 for location.

Seismic stratigraphy

A seismic profile (Fig. 8) from the inner part of Frænfjorden shows four stratigraphic units. Unit 1 displays chaotic to laminar internal reflections and has a sharp and continuous lower boundary. It is present in the central part of the STP, where it is up to 2 km wide and 20 m thick. Unit 1 also occurs as an up to 40 cm-thick layer in the basin west of the discharge location (Fig. 8).

Unit 2 can be traced throughout most of the inner fjord and has a transparent signature with a single, strong, continuous reflection approximately in the middle of the unit. It is up to 5 m thick and has a clear lower boundary in some areas and a more diffuse boundary in other areas. Unit 3 consists of laminated sediments draped over the undulating topography of Unit 4. This unit can be traced throughout the entire fjord, and has a variable thickness of up to 17 m.

Unit 4 has a transparent signature and an undulating, diffuse upper boundary. It can be traced throughout the entire fjord, but its lower boundary is not visible on the seismic data.

Figure 8. TOPAS profile along the inner part of Frænfjorden. See Fig. 3 for location.

Seabed sediments (grain size)

Multibeam backscatter intensities are very low around the pipeline endings used in 2016 (2.1, 2.3 and 1.2; DNV GL, 2017), the year in which the data were collected. These low backscatter intensities indicate fine-grained sediments (Fig. 9). Further away from the pipeline endings, the seafloor is characterised by low to medium backscatter intensities, while the steep fjord sides show high backscatter intensities, indicating the presence of coarse-grained sediments.

Grab sample P1509009, collected close to the northern side of the fjord (Fig. 9), consists of olive-grey sandy mud changing gradually to a laminated light-grey mud on top (Fig. 9A, Table 2). Sample P1509010 was collected in the central part of the basin within the STP, west of the discharge location. It consists of very soft, laminated white/grey mud with a light-brown 2 cm cap (Fig. 9B). Sample P1509015 was collected southeast of the discharge location (Fig. 9). It consists of very soft, laminated white/grey mud (Fig. 9C). Sample P1509011, collected southwest of the discharge location, consists of dark olive-grey mud changing gradually to a 5 cm unit of light grey mud on top (Fig. 9D). Both P1509010 and P1509015 are poorly consolidated, and the sediments ‘flow’ out on deck as seen on the photographs (Fig. 9B, C). Grab samples P1509009 and P1509011 show a gradual change from dark olive-grey mud to light-grey mud and appear more consolidated than P1509010 and P1509015.

Four still images from the videos are shown in Fig. 10. Fig. 10A–C illustrates the change in sediment character along a transect from the southern fjord side towards the basin (see Fig. 3 for location). At the side of the fjord (Fig. 10A, water depth 20 m), the sediments consist of sand, gravel and cobbles, and they are only partly covered by a thin layer of greyish-white sediments. Further down, the sediments consist of gravel, cobbles and boulders, and the cover of greyish-white sediments increases (Fig. 10B, 27 m water depth; Fig. 10C, 33 m water depth). Fig. 10D (water depth 55 m) is from the basin, where the surface is completely covered by fine-grained, greyish-white sediments.

The grain-size map of Frænfjorden (Fig. 11) shows very fine, muddy sediments throughout the inner fjord, with coarser sediments at the sides of the fjord (a mixture of mud, sand, gravel, cobbles and boulders, and

some areas with a thin or discontinuous sediment cover on bedrock). The discharge location is visible as an area of muddy sand at the pipeline outlets (Fig. 11). Sand-sized tailings deposit at the outlet of the pipeline while the fines travel further into the fjord.

Figure 9. Multibeam backscatter intensity draped on shaded relief bathymetry from 2016. (A–D) Grab samples 1509009, 1509010, 1509015 and 1509011, respectively. See Table 2 for further details.

Core descriptions

Core P1509028 is situated outside the STP in the central part of the fjord, about 2.2 km southwest of the discharge location (Fig. 3; Table 1). It shows a gradual change from dark, olive-grey muddy sand at the bottom of the core to white/light-grey sandy mud at the top (Fig. 12). Bioturbation occurs between 5 and 12 cm depth while shell fragments occur in the middle and lower part of the core. Calcite content increases from 2% in the lower part of the core to 35% at the top (Table 3). The water content appears to be constant throughout the core. It was not possible to do a fallcone test on this core because of the high sand content.

Core P1509026 is situated within the STP in a basin about 850 m southwest of the discharge location (Fig. 3; Table 1). The lowermost lithological unit consists of dark, olive-grey massive to laminated sandy mud with a high content of silt, with greyish-white laminated mud with a high content of clay in the lithological unit on top (Fig. 13). A gradual transition between these two lithologies occurs between 37 and 39 cm depth. Calcite content increases from 3% at the bottom of the core to 90% in the upper part of the core (Table 3). The water content and the content of organic material are slightly higher in the sediments in the lower part of the core. Two fallcone tests show an increase in sensitivity towards the top of the core (from 2.5 to 5.2 kPa; Fig. 13).

Table 2. Grab samples collected by FF Seisma in Frænfjorden in August 2015.

Grab number	Equipment	Water depth (m)	Grain-size	Colour	Comments	Degrees N	Degrees E
P1509001	Grab	70	Muddy sand	Olive grey	Gravel <3 cm	62.831091	7.000175
P1509002	Grab	21	Sand, gravel and cobbles		Empty grab twice, large rock (3-10 cm) in opening	62.836881	7.024842
P1509003	Grab	38	Sand, gravel and cobbles	Olive grey		62.834231	7.027985
P1509004	Grab	26	Muddy sand	Olive grey		62.82572	7.037645
P1509005	Grab	53	Muddy sand	Olive grey	Light grey mud	62.833575	7.055698
P1509006	Grab	40	Muddy sand	Light grey on top of dark olive grey	Top layer 3 cm sandy mud on top of muddy sand	62.831799	7.082678
P1509007	Grab	28	Gravelly muddy sand	Light greyish brown		62.838471	7.077451
P1509008	Grab	64	Gravelly sandy mud	Light greyish white on top of olive grey	Top layer mud 7 cm on top of muddy sand with cobbles	62.837549	7.08953
P1509009	Grab	39	Sandy mud	Light greyish white on top of olive grey	Top layer mud 15 cm on top of sandy mud	62.843839	7.094583
P1509010	Grab	64	Mud	Light grey	Light brown top layer (2 cm)	62.841413	7.100417
P1509011	Grab	58	Mud	Light greyish white on top of olive grey	Top layer 5 cm	62.837202	7.105736
P1509012	Grab	39	Mud	Olive grey	Top layer of 1 cm with light grey brownish mud	62.833669	7.118825
P1509013	Grab	16	Muddy sand	Dark olive grey		62.827469	7.10701
P1509014	Grab	24	Gravelly muddy sand	Light grey on top of dark brown	Top layer with 5 cm sandy mud on top of muddy sand	62.840261	7.126378
P1509015	Grab	41	Mud	Light greyish white		62.843864	7.131963
P1509016	Grab	33	Mud	Light grey	Light brown top layer	62.848279	7.137243
P1509017	Grab	17	Muddy sand	Dark olive grey		62.849676	7.145819
P1509018	Grab	22	Sandy mud	Dark grey/dark greyish brown	With a light grey brownish top layer	62.846997	7.160545
P1509019	Grab	28	Muddy sand	Light grey on top of dark brown	Top layer 3 cm	62.842771	7.15256
P1509020	Grab	39	Mud	Dark greyish brown	Brown top layer	62.837757	7.154308

Figure 10. Still images of the seabed from video transects. Horizontal scale: 10 cm between the red laser dots. See Fig. 3 for location.

Core P150924 is situated in the STP within Slide A (Figs. 3 & 4; Table 2). It consists of greyish-white, laminated mud at the bottom of the core and grey, laminated sandy mud at the top (Fig. 14). A sharp, inclined boundary between the two lithologies occurs at 25–28 cm depth. The calcite content decreases slightly from 90% at the bottom of the core to 82% at the top of the core (Table 3). Water content and sensitivity are stable throughout the core. The content of organic material is slightly higher at the top of the core.

Core P1509022 is situated outside the STP in the northern part of the Malmefjorden basin (Figs. 1 & 3; Table 1), about 3 km southeast of the discharge location. It consists of sandy mud with a very high content of silt (Fig. 15). The colour changes from black at the bottom of the core to brown at the top. The content of organic material is 7–10%, and the water content is very high (300% compared to 50–75% in the other sediment cores). The calcite content increases from 2% to 27% towards the top of the core (Table 3), and the sensitivity is relatively low (1.5 kPa; Fig. 15).

Discussion

In this chapter we discuss the character of the tailings and the natural sediments, the distribution of the tailings in the fjord, the processes behind their spreading, and the redeposition by mass movements.

Figure 11. Seabed sediments (grain size) of the investigated area.

Figure 12. Lithostratigraphy, physical properties and mineralogy of core P1509028. See Fig. 3 for location.

Composition and distribution of tailings

The sediment grain-size map in Fig. 11 shows that fine-grained sediments (mud) dominate the seafloor within the STP in the inner part of Frænfjorden. The tailings being disposed in Frænfjorden contain 50–60% calcium carbonate (DNV GL, 2018). However, sediments collected some distance away from the

Table 3. Mineral composition (% of total) of both natural sediments and tailings from cores P1509022, P1509024, P1509026 and P1509028. Abbreviations: qtz – quartz, amph – amphibole, K-fsp – K-feldspar, crs – cristobalite, plag – plagioclase, ilm – ilmenite, ill/musc – illite/muscovite, tlc – talc, chl – chlorite, graph – graphite, cal – calcite, hal – halite, dol – dolomite, py – pyrite, n.d. – not detected.

Core-depth (cm)	Sediment	qtz	K-fsp	plag	ill/musc	chl	cal	dol	amph	crs	ilm	tlc	graph	hal	py
P1509022-31	mix	13	8	25	5	5	27	n.d.	5	n.d.	n.d.	n.d.	n.d.	11	1
P1509022-49	natural	17	11	32	5	8	2	n.d.	9	n.d.	n.d.	n.d.	n.d.	12	4
P1509024-8	tailing	2	2	7	1	1	82	n.d.	2	n.d.	n.d.	n.d.	1	2	n.d.
P1509024-23	tailing	2	2	7	1	1	82	n.d.	2	n.d.	n.d.	n.d.	1	2	n.d.
P1509024-43	tailing	1	1	4	1	1	89	n.d.	1	n.d.	n.d.	trace	1	1	n.d.
P1509024-54	tailing	1	1	4	trace	1	90	n.d.	trace	n.d.	n.d.	trace?	2	1	n.d.
P1509026-7	tailing	1	1	3	trace	1	89	n.d.	1	n.d.	n.d.	trace?	2	2	n.d.
P1509026-26	tailing	1	1	3	trace	1	90	trace	1	n.d.	n.d.	trace?	1	2	n.d.
P1509026-40	mix	12	4	17	2	3	56	n.d.	4	n.d.	n.d.	n.d.	n.d.	2	n.d.
P1509026-58	natural	31	12	31	4	5	3	n.d.	8	3	n.d.	n.d.	n.d.	3	n.d.
P1509028-43	mix	25	6	22	3	2	35	n.d.	5	n.d.	n.d.	n.d.	n.d.	2	n.d.
P1509028-51	mix	31	10	31	4	3	11	n.d.	5	3	n.d.	n.d.	n.d.	2	n.d.
P1509028-60	natural	34	10	40	3	2	2	n.d.	6	1	1	n.d.	n.d.	1	n.d.

Figure 13. Lithostratigraphy, physical properties and mineralogy of core P1509026. See Fig. 3 for location.

Figure 14. Lithostratigraphy, physical properties and mineralogy of core P1509024. See Fig. 3 for location.

Figure 15. Lithostratigraphy, physical properties and mineralogy of core P1509022. See Fig. 3 for location.

pipeline ending typically contain 80–90% calcite because calcite mainly occurs as fine fractions below 20 μm , which move away from the pipeline in suspension. The coarser silicate particles (mainly above 100 μm) are deposited directly at the ending of the pipeline.

The tailings have a greyish-white colour (Fig. 2), distinctly different from the dark-grey natural sediments that contain just a few percent calcite. Tailings are therefore easily recognisable in videos and core/grab samples (Figs. 9, 13 & 14). Core P1509026 (Fig. 13), from the basin west of the discharge location (Fig. 3), intersects the transition from natural sediments to tailings and provides a representative example of change in colour (from dark-grey to greyish-white), grain size (from sandy silt to clay) and calcite abundance (from 3 to 90%).

In the central part of Frænfjorden, about 2.2 km southwest of the discharge location (core P1509028), calcite content increases from a natural level of 2% to 35% at the core top, indicating that most recent sediments represent a mixture of tailings and natural sediments. In Malmefjorden, southeast of the STP, calcite content increases from 2 % to 27% towards the top in core P1509022. This indicates mixing of natural sediments with increasing amounts of tailings towards the top of the core, albeit less than in core P1509028. The natural silt-dominated sediments in Malmefjorden are very rich in organic material with a TOC content of 7–10% and a very high water content (dry weight of 300% compared to 50–75% in the other sediment cores).

Right next to the discharge location, core P1509024 consists of tailings with a calcite content of 82–90% (Fig. 14). A sharp, inclined boundary between 25 and 28 cm depth separates two units with a distinct colour difference. The dark-grey upper unit is coarser grained (siltier-sandier), has a higher TOC content (Table 3) and contains slightly higher amounts of silicate minerals compared to the lower unit. This colour and compositional contrast between two units in core P1509024 is likely caused by compositional heterogeneity of the raw material. As this core is situated within a slide scar (Figs. 3 & 4), the sharp inclined boundary could be the base of a smaller (translational) slide.

The lateral extent of tailings and their thickness can also be estimated using data from seismic profiling. Unit 1 on the seismic data has been interpreted to represent the tailings, based on its chaotic seismic

signature and its occurrence in the central part of the STP (Fig. 8). This unit is up to 2 km wide and 20 m thick at the discharge location. An up to 40 cm-thick unit was found within the sediment accumulation basin west of the discharge location (Fig. 8 & 13). Unit 1 was not found anywhere else, indicating that the thickness of tailings elsewhere is less than the resolution of the seismic data of approximately 15 cm. The lateral extent of Unit 1 (excluding the thin deposit found in the basin west of the discharge location) allows contouring of the edges of the STP visible on the seismic data (Fig. 16A).

Seismic Unit 2 (Fig. 8), immediately below Unit 1, has been interpreted to consist of homogeneous, fine-grained sediments deposited from suspension during the Holocene. The strong reflection in the middle of the unit could be interpreted as a turbidite or a debris-flow deposit. Two prominent reflections in Julsundet (about 11 km south of the mouth of Frænfjorden; Fig. 1) are interpreted to represent local climate-triggered sedimentation irregularities with a minimum age of 3222 cal. BP, and a turbidite with a maximum age of 9447 cal. BP related to the Storegga Slide tsunami (8200 cal. BP) (Bøe et al., 2004a). It is possible that the prominent reflection within Unit 2 in Frænfjorden can be correlated to one of these two events.

Unit 3 is interpreted to consist of glaci-marine sediments because it occurs draped on the undulating topography of Unit 4 and because of its laminated seismic signature (see also Bøe, 1987). Similar glaci-marine units with laminated seismic signatures occur in most Norwegian fjords (e.g., Bøe et al., 2003, 2018, Rise et al., 2006, Hjelstuen et al., 2013, Bellwald et al., 2016, Hansen et al., 2018). This unit can be

Figure 16. (A) Outer boundary of tailings in Unit 1 (red stippled line) interpreted from TOPAS profiles plotted on multibeam bathymetry from 2016. Note the location of pockmarks along the western boundary. (B) TOPAS profile showing interpreted locations of pore-water escape forming pockmarks along the boundary of the tailings in Unit 1 due to overpressure.

traced throughout the fjord and changes in thickness (up to 17 m). Because of its undulating topography, Unit 4 is interpreted to comprise bedrock, probably with a local drape of till (Fig. 8). The till, however, cannot be discerned in the TOPAS data due to lack of penetration.

Comparison of bathymetric datasets demonstrates that between 2013 and 2017, an up to 8–10 m thick package of tailings has been deposited within the STP (Fig. 6F) giving a maximum tailings accumulation rate of 2–2.5 m/year, and an average rate of 1–1.25 m/year during this time period. This correlates well with findings by Hustadmarmor/DNV GL of a depth reduction of up to 10 m since 2014 close to the outlet pipes (DNV GL, 2018).

Considering that the thickness of tailings visible on the seismic data varies between c. 0.4 (in the basin) and 20 m (at the discharge location; Fig. 8) and discharge started in 1982, the average accumulation rate of the tailings is c. 30 cm/year over a period of 34 years. The difference between these calculations could be attributed to increased discharge in more recent years. The thickness of tailings can also be influenced by compaction and consolidation of the older tailing deposits. The factory as it is today was established in the 1990s, and the disposal of tailings increased from <100,000 tons/year to almost 500,000 tons/year in 1999–2000. The disposal was on average about 350,000 tons/year in the following 10 years, and was reduced to 200,000–250,000 tons/year during the most recent years (personal communication with OMYA Hustadmarmor).

Bathymetric (Fig. 6F), seismic (Fig. 8), and sediment core (Figs. 12, 13, 14 & 15) data show that the majority of the tailings are deposited in the immediate vicinity of the discharge location with minor quantities being spread outside the STP (Core P1509022 and P1509028; Figs. 12 & 15). Findings by DNV GL (2016) confirm that tailings are spread outside the boundary of the STP, but historical data show that the area with tailings does not expand. The estimated deposition of tailings at the STP boundary was 6 mm/year (30 mm/5 years), which is within the acceptance criteria (DNV GL, 2016).

Two circular depressions in the seafloor occur in the west side of the STP (Figs. 3, 4 & 8). A current model from SINTEF (Nepstad et al., submitted) shows the presence of eddies close to the depressions and thus infers a close relationship between the two. The eddies might have caused erosion of the depressions and/or prevented deposition of sediments within. At present, however, they appear to be filled in. The depressions might have originated as pockmarks related to vertical fluid flow in the past, possibly before the start of the Holocene.

Tailings found outside the STP have been transported in a suspension plume, spread by winds, currents and waves (Nepstad et al., submitted). The spreading of particles in suspension depends on several factors such as particle size, settling velocity and water column stratification. The dispersion of a sediment plume will be greater during periods of stronger stratification (Taylor, 1953; Ramirez-Lodra et al., 2015). There are several measures that can minimise the dispersion of tailings; thickening and de-aeration of tailings and particle flocculation (see Fig. 2). Prior to de-aeration, the tailings are usually thickened to recycle water and process chemicals (Skei, 2014).

Redistribution of tailings by mass movements

Slope failures in and around STPs are important because they may result in re-suspension and dispersal of tailings to areas outside the STP (Burd et al., 2000; Ramirez-Lodra et al., 2015). Slope failures are generally not considered in risk assessments for STP/DSTPs and are often poorly documented (Burd et al., 2000). It is therefore important to understand the processes leading to slope failures in STPs.

In Frænfjorden, two slides and several gravity-flow channels originate from the deposited cones at the discharge locations (Fig. 4). The multibeam bathymetry data shows that the slides were triggered in 2015 and 2016 (Fig. 6).

Most of the gravity-flow channels contain sediment waves, indicating periodically strong bottom currents with sediments transported down the channel by density/turbidity currents. Similar active sediment waves, gravity-flow processes and slides are observed from tailings disposal in, for example, Stjernsundet (northern Norway). In Stjernsundet, these gravity-flow processes and slides transport mine tailings from their discharge location at the shoreline in the bay of Lillebukt, to deeper waters (Bøe et al., 2018).

The sediment waves continue down the slope, below the gravity flow channels (Fig. 4 & 5) where they occur over a wider area not confined to channels (Fig. 5). On the seismic data (Fig. 7), the waves seem to migrate upslope, towards the east. Similar seismic signatures have been observed on the seafloor in Trondheimsfjorden, where turbidity currents and density currents overflow the margins of the Gaulosen Channel to create sediment waves that migrate upslope (Bøe et al., 2004b). The sediment waves in the lower part of the slope in Frænfjorden resemble creep folds caused by slow, downslope mass movement under gravitational stress (Fig. 7; e.g., Syvitski et al., 1987; Lee & Chough, 2001; Bøe et al., 2004b; Shillington et al., 2012), and may be influenced by such a process. The sediment waves are clearest on the seismic data in the upper part of Unit 1 (Fig. 7) and are therefore most likely relatively young.

Most of the gravity-flow channels originate from cones deposited by single pipeline endings (not split pipeline endings) (Fig. 4), suggesting that tailings discharge from split pipelines gives more stable deposits on the STP.

Several preconditioning factors and triggering mechanisms lead to slope failures within the STP. Sediment accumulation rates are high, preventing normal consolidation of the sediments (Sultan et al., 2004). High sediment accumulation rates (anthropogenically-induced hyper sedimentation) produce thick packages of unconsolidated fine sediments that are susceptible to natural disturbances, which may again cause large-scale slope failure (Burd et al., 2000). The grab samples in Fig. 9 illustrate the difference in consolidation between tailings close to a discharge location with loose and unconsolidated sediments (Fig. 9B, C), and semi-consolidated tailings mixed with natural sediments farther away from the discharge location (Fig. 9A, D). The tailings have a finer grain size, and a higher sensitivity (2.2-5.2 kPa) than the natural sediments, (1.5 kPa; Fig. 13, 14 & 15), making them more susceptible to failing.

The natural sediments in Frænfjorden, especially in the inner part of the fjord, have a high water content (Fig. 15). The water content within the natural sediments is slightly higher than within the tailings, also in the basin west of the discharge locations (Fig. 13). The loading of up to 20 m of tailings on top of these natural sediments can cause overpressure, and possibly lead to pore-water flow at the interface between natural sediments and tailings, and expulsion to the seafloor at the outer boundary of Unit 1 (defined from seismic data). The occurrence of a chain of pockmarks along the boundary (Fig. 16A, B) is an indication of such loading triggered pore-water expulsion. Excess pore pressure generated by high sedimentation rates during peak glaciation has been suggested to precondition large submarine landslides on the Norwegian continental margin (e.g., Bryn et al., 2005, Kvalstad et al., 2005, Leynaud et al., 2009).

Deposition of tailings beside the discharge pipe leads to build-up of cones, creating higher slope angles. Slope angle is a key parameter for slope-stability assessment because it drives the destabilizing loading forces through gravity (Wilhelm et al., 2016). Slope stability typically decreases with increasing slope angle (Ai et al., 2014). Fig. 5 shows that the slope angles of the cones created by the discharge of tailings, and at the sides of the fjord (5–40°) are higher than the slope angles in the rest of the fjord (<4°). Slides and gravity flows are triggered by increasing slope angle/oversteepening related to continuous deposition on the STP cones.

Slide A, in 2015 (Fig. 6C), was most likely triggered by the placement of a concrete weight on the seafloor to extend the floating pipeline. These concrete weights add extra pressure on the already unstable seafloor and can thus trigger slides.

Conclusions

The main findings of this study are:

1. The tailings are primarily deposited within the STP within an up to 2 km-wide area with a tailing thickness of up to 20 m. Minor quantities are spread outside of the STP by tidal currents.
2. The tailings have a white/grey colour, consist of very fine-grained sediments, contain high percentages of calcite, and have a lower water content than the natural sediments on which the STP rests.
3. A series of multibeam echosounder data collected between 2013 and 2017 shows that deposition of tailings has triggered several small gravity flows and slides.
4. The tailings within the STP have a low stability compared to the natural sediments outside the STP because of their fine grain-size and higher sensitivity, high slope angles, high sediment accumulation rates preventing normal consolidation, and loading of the tailings causing over-pressure in the underlying sediments.

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