4.7. OVERVIEW OF ISLAND COPPER PROJECT

George Poling
University of British Columbia

Note: The following was extracted from: D.V. Ellis, T.F. Pedersen, G.W. Poling, C. Pelletier and I. Horne, "Review of 23 Years of STD: Island Copper Mine, Canada" Marine Georesources and Geotechnology, Volume 13, pp. 59-99

The submarine tailings disposal (STD) system at Island Copper Mine has been subjected to a comprehensive environmental monitoring program initiated
d in 1970 some 20 months before the mill started processing ore. The program has been extended and modified as new factors became relevant or it became clear that particular factors were not of concern at this site. The major environmental issues have concerned (1) tailings resuspension and upwelling, (2) smothering of benthos, and (3) trace metal contamination from acid rock drainage (ARD). A closure plan has been prepared for implementation in 1995. Tailings were resuspended and upwelled to surface close to the fiord sill due to unpredicted periodic high-density tidal jets scouring the deposits at that point. The localized elevated turbidity has not affected biological productivity. Benthos hare been smothered under rapid tailings deposition such that areas under thick tailings (> about 20-30cm) showed reduced biodiversity. At deposition rates of <1cm p.a. benthic biodiversity on tailings was Indistinguishable from areas without tailings. A fishery on bottom-feeding crabs has been maintained throughout the fiord system and was not affected by this reduction in benthic biodiversity. Trace metals monitoring shows some elevation of copper in mussels on the concentrator loading wharf fugitive dust.2), but no clear evidence of contamination related to tailings. Tailings deposits appear to act as a sink for trace metals other than manganese. Traces of acid rock drainage (ARD) seepage from a beach waste dump are undetectable away from the face of the dump. Monitoring of tissues of crabs (a predator and scavenger) provides evidence that there is no food chain biomagnification of trace contaminants.

In 1968, Utah Mines, Ltd. announced plans to develop a large open-pit copper molybdenum mine on the north shore of Rupert Inlet, one of the reaches of Quatsino Sound on northern Vancouver Island. The company commenced investigations of the feasibility of submarine disposal of tailings in April 1968 and carried out bathymetric surveys of the inlet, studies of the settling characteristics of the tailings, and bioassay tests of effluent from a pilot plant operation. Consideration was given to the potential effects of tailings on the aquatic flora and fauna in Rupert Inlet; to design, engineering, and siting of the outfall; and to the physical oceanography of the basin. In 1971, the company was granted formal permission to discharge mill tailings and waste rock into the inlet. This followed discussions with the then Department of Fisheries of the government of Canada and a public inquiry requested by the Pollution Control Board of the Province of British Columbia. Construction of the Island Copper Mine was completed in 1971, and the first concentrates were produced in September of that year (BHP, 1994).

The mine initially processed about 33,000 metric tonnes per day (mtpd) of ore; as of the spring of 1993, the daily throughput was about 50,000 mtpd (Island Copper Mine, 1994). Between startup and June 1993, 347 million tonnes of tailings have been discharged by STD into the adjacent Rupert Inlet. Closure is anticipated in 1996 upon exhaustion of the ore body. Waste rock has been deposited along the northern margin of the inlet since 1971, resulting in the addition of more than 260 ha of land to the foreshore.

Under the terms of the discharge permit issued by the British Columbia Waste Management Branch, the mine has been required to maintain a comprehensive marine monitoring program and to make the results public through annual reports. The program is supervised by an independent advisory body consisting of several professors from the Universities of British Columbia and Victoria, as well as an environmental consultant. The program is extensive and has been modified several times since data collection commenced in 1970, prior to the opening of the mine. A voluminous body of information spanning some 25 years is now available. In concert with a suite of data generated by independent, university- and government-based research, the monitoring results permit a rigorous evaluation to be made of the short- to long-term impact of the mine on the local inlet system. Both the continuity and the breadth of the available information are unparalleled by any other marine tailings disposal operation. Reports have been distributed annually, of which the most recent refers to 1993 data and is referenced as Island Copper Mine, 1994. The 1993 report is the source of most of the data reported here. This article is an update, and condensation, of a prior review to 1990 in Poling and Ellis (1993).

The Ore Body

The Island Copper deposit lies in the upper portion of the Bonanza Volcanic Formation and is hosted by andesitic pyroclastic rocks and a complexly brecciated and altered quartz-feldspar porphyry dike. The principal ore minerals are chalcopyrite and molybdenite, which occur as fracture fillings and smears on fractures and slips. The mean mill head grade through 1993 was 0.45% Cu and 0.017% Mo. The mineral assemblage of the gangue (Poling, 1982) is dominated by quartz (50-70%), feldspar (2-20%), and biotite and chlorite (5-10%). Magnetite is present at concentrations on the order of 2-4%, as is calcite (~ 2.5%). Sulfide minerals identified in the ore body include pyrite (3%), chalcopyrite (~ 1.5%), sphalerite (0.02%), molybdenite (0.02%), bornite, and galena (0.01 %). The chalcopyrite contains approximately 90% of the copper in the ore, and the molybdenite about 60% of the Mo present in the feed to the mill.

The Milling Process and Characteristics of the Effluent

The milling circuit at Island Copper includes primary grinding with six semiautogenous mills, secondary grinding with five ball mills, and rougher flotation with 300-ft3 (8.5 m3) Wemco cells. First cleaning is accomplished with Outokumpu cells, second cleaning with Agitair cells, and third cleaning with column cells.

Tailings remaining at the end of the concentrating process are thickened in two 114-m diameter thickeners to about 45% solids by weight. The slurry flows by gravity to a mixing chamber where it is typically mixed with twice the volume of seawater and discharged through the outfall at about 40m depth. The solids consist largely of silt-sized aluminosilicate particles (about 60% is < 63 , µm in diameter) with average copper and molybdenum contents of 700 and 40 ppm, respectively. Figure 1 shows mine lifetime values for dissolved copper in the effluent. Values stabilized after the first 5 years around 5-10 , µg/L. Molybdenum values show a different pattern (Figure 2), being affected by use of stockpiled marginal ore in recent years. Several monitored components have been consistently near or below detectable levels: lead, cadmium, total mercury, and dissolved cyanide.

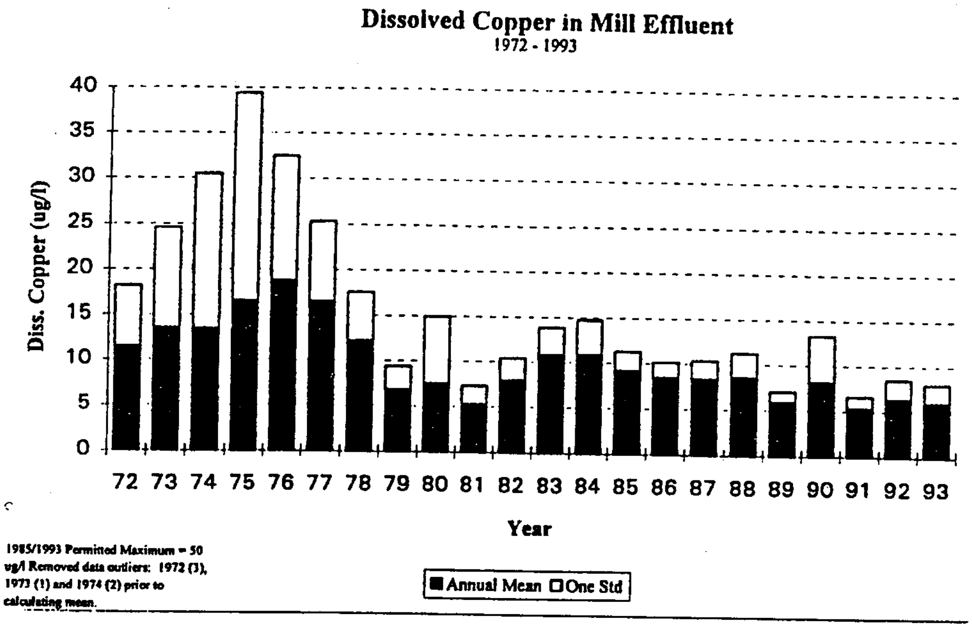

Figure 1. Dissolved copper in mill effluent 1972-93.

Waste Rock Dump Characteristics and Impacts

Under the terms of a foreshore lease, waste rock has been dumped along a 3.5-km stretch of the north shore of Rupert Inlet since the mine commenced operation in 1971 and has created some 260 ha of new land (Figure 3). While the dump was developing, the leading edge prograded into deep water (50-90 m) over previously discharged tailings. This resulted in dump instability and failure, with the debris being spread across the floor of the inlet toward the south shore. Concern that the progressive eastward advancement of the dump would have a deleterious effect on crab habitat has not been borne out by extensive catch data collected over 20 years (see below).

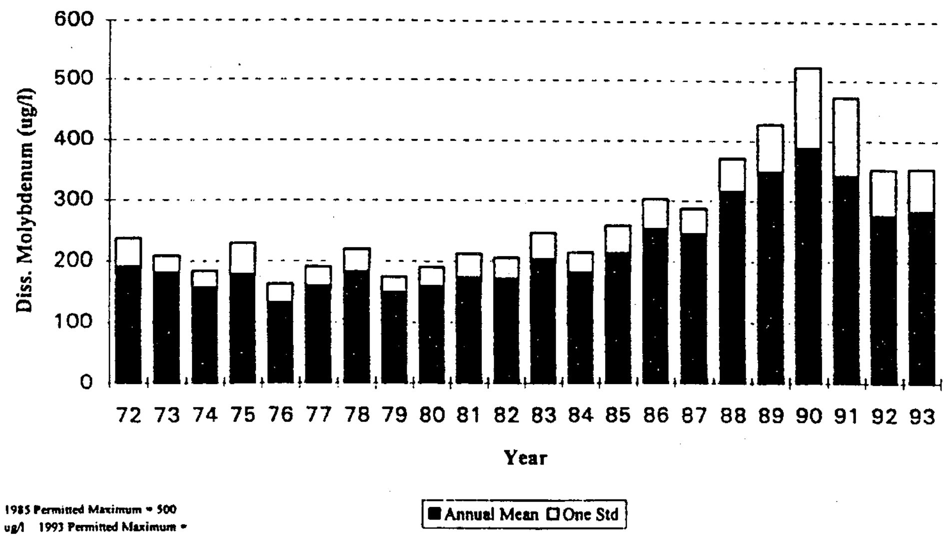

Figure 2. Dissolved molybdenum in mill effluent 1972-93.

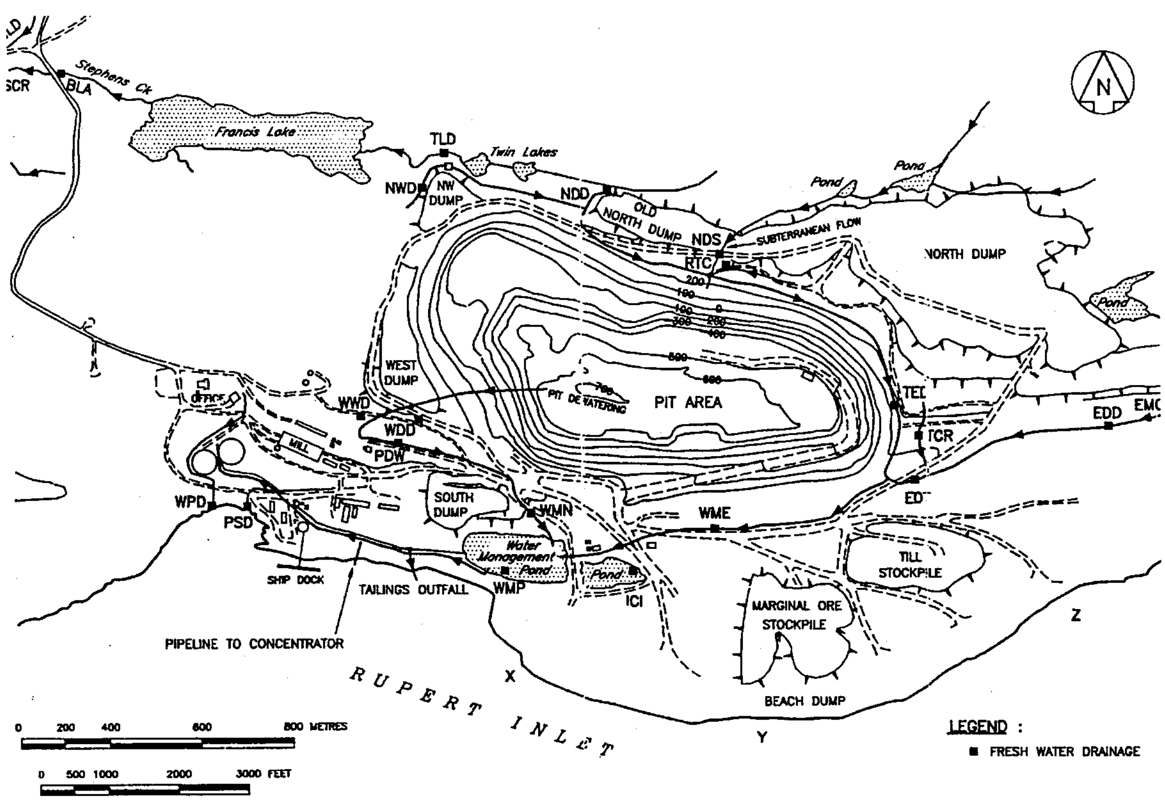

Figure 3. Layout of the mine site with beach-dump sampling stations.

The development of acid rock drainage in terrestrial waste dumps at Island Copper during the 1980s heightened concern about the release of dissolved heavy metals into Rupert Inlet. Since 1987, the majority of the acid seepage has been collected and conducted to a settling/treatment pond (water management) and exfiltration pond adjacent. Both the pH and metals levels in the drainages vary seasonally with lower values in the fall and winter that apparently reflect a flushing effect during the winter rains.

Up to the summer of 1990, the collected drainages were allowed to dissipate into the beach dump, where they were diluted as a result of slow tidally driven mixing within the submerged portion of the dump. The effect of this disposal on the metals concentrations in proximal inlet waters, plus the potential influence of oxidation of sulfide minerals within the beach-dump waste rock itself, has been monitored approximately bimonthly for several years at three stations established directly off the face of the dump (stations X, Y. and Z. Figure 3). Dissolved copper and zinc values have been quite variable (Island Copper Mine, 1991) (Table 1) and 2-3 times higher than the mean (time-averaged) concentrations measured in surface waters near the center of the basin south of the mine site.

Table 1 Dissolved metals in seawater off the beach dump (ug/L)

	Station X (Narrow Island)				Station Y (Mid Dump)				Station Z (Red Island)				
Year	**n**	**mean**	**min**	**max**	**n**	**mean**	**min**	**max**	**n**	**mean**	**min**	**max**	**Grand Mean**
Dissolved Zinc													
1985	9	4.4	1.6	9.8	9	3.2	1.8	4.7	8	6.6	2.5	15.5	4.7
1986	9	8.9	2.0	26	9	8.0	3.2	21	9	29.0	3.7	150	15.3
1987	12	4.5	1.3	8.9	12	5.3	0.8	9.5	12	5.7	2.1	8.9	5.2
1988	9	9.7	2.X	32	9	6.5	3.1	10)	9	7.4	2.0	24	7.9
1989	18	9.6	2.9	28	18	10.3	3.0	25	18	12.5	2.5	40	10.8
1990	18	7.3	2.4	29	18	10.0	3.5	45	18	9.2	3.6	23	8.8±7.0
1991	21	11.2	3.2	24	21	11.4	2.8	33	21	10.8	3.2	38	11.1±6.7
1992	12	8.0	3.2	16	12	11.7	6.3	26	12	9.9	3.2	20	9.9±5.7
1993	15	9.4	2.0	22	15	8.3	2.6	18	15	6.8	2.5	13	8.2±4.8
Dissolved Copper													
1985	9	4.9	2.2	11.7	9	4.3	2.3	9.3	8	5.7	2.4	10.1	5.0
1986	9	3.2	1.7	4.8	9	3.3	1.8	5.0	9	4.6	2.7	18.0	3.7
1987	12	2.5	1.0	3.7	12	2.1	0.7	4.6	12	2.4	1.1	3.8	2.3
1988	9	5.0	1.6	12.8	9	3.3	2.2	7.6	9	4.5	1.3	8.1	4.3
1989	18	4.5	1.3	9.2	18	3.9	1.6	9.7	18	4.3	1.6	14.0	4.2
1990	12	3.4	2.0	9.3	18	3.9	1.9	10	18	3.3	1.6	10.0	3.6±1.9
1991	21	3.9	2.0	7.3	21	3.7	2.0	5.8	21	2.8	1.8	4.7	3.5±1.2
1992	12	4.3	1.7	8.8	12	4.8	2.2	11	12	3.6	1.9	5.6	4.2±2.0
1993	15	3.4	2.0	7.0	15	4.0	1.4	11	15	2.8	<0.8	6.2	3.4±1.9

The contrast between the two data sets in part reflects the sampling time strategy. All samples off the face of the beach dump were collected during the last hour of an ebb tide during the time when water in the dump was draining into the inlet. A 24-hour study conducted in April 1990 to determine if the metal concentration at the dump face varied with tidal phase showed that the zinc concentration decreases during a flood tide and increases as the tide ebbs (Figure 4). The existing monitoring scheme therefore records maximum values for Zn off the face of the dump.

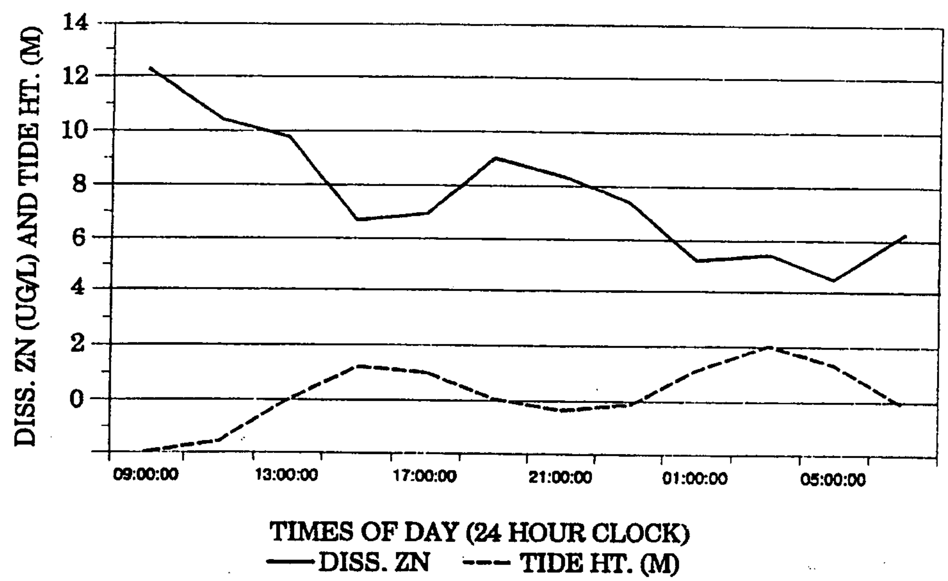

Figure 4 24-hour study of dissolved zinc off the face of the beach dump (April 26-27, 1990)

Dissolved metals in seepage taken from the beach dump exceeded provincial objectives and were likely to continue doing so. The mine therefore constructed a water management system in the summer of 1990. The land dump drainages are now carried to a water management pond southwest of the open pit (Figure 3). When the water in the pond meets objectives it is allowed to exfiltrate through the beach dump. When water quality is unacceptable, the water is pumped to the mill for use as process water.

Mean annual concentrations of Cu compiled from data collected at six stations in the Rupert-Holberg-Quatsino system since 1971 show that the ambient levels fluctuated around predischarge levels of 2 ,ug/L through 1993. Other metals monitored were similar except Mn which fluctuated from predischarge levels of 3, µg/L to about 10 ,ug/L.

Tailings Disposal System

Island Copper Mine designed and installed its then novel STD system in 1970-71. It consisted of a tailings line discharging to an open seawater mix chamber. A seawater intake line originated at 20-m depth and provided a self-maintaining flow mixing with the tailings slurry, with subsequent gravity flow to the outfall discharge point at 50-m depth. In 1974 the original outfall was converted to standby use as a redesigned and enlarged system became operational. In this, the tailings line discharged the slurry below the surface of the seawater mix chamber, minimized air entrainment, and allowed deaeration of the slurry.

In 1989, a new outfall line and seawater intakes were installed. The earlier continuous down-slope flow pattern established near the outfall had changed and tailings were accumulating within 400 m of the discharge point before periodically sloughing away. This appeared to be due to gradient reduction of the seabed by encroachment of the submerged apron of the shoreline waste rock dump.

The tailings slurry turns southwest after discharge and flows by gravity down-inlet. The deepest part of the fjord at the confluence of Rupert and Holberg Inlets and Quatsino Narrows is the principle locus of accumulation, and some 40-m thickness of tailings have now accumulated there.

Chemical analyses of heavy metals in sediments indicates that trace quantities of tailings occur in surface sediments in the near part of Quatsino Sound and for some distance up Holberg Inlet. In Hecate Cove, for example, the presence of tailings has been defined chemically since 1976 (> 100 ppm Cu in deposits). Tailings are now visually detectable in Hecate Cove mixed with natural organic mixed sediments to a depth of about 10 cm (Ellis et al., 1995). As documented later, there have been no impacts on benthos in these distal areas, despite the detectable increase in tailings accumulation.

Environmental Issues

Bathymetry, Physical Oceanography and Tailings Resuspension

Rupert Inlet is 10 km long, on average ~1.8 km wide, and ranged in depth prior to tailings disposal from about 110 m in the axial channel immediately south of the mine site to ~ 165 m at the deepest location directly south of Hankin Point. The adjoining Holberg Inlet is ~ 34 km long, ~1.3 km wide on average, and shallower, the mean axial channel depth being about 80 m. The two fjords are connected to the Pacific Ocean via Quatsino Sound through Quatsino Narrows, a long, narrow and very turbulent, shallow (18 m deep sill) tidal channel. The water column is generally well-mixed by tidal currents and turbulence, particularly near the confluence of the two fjords at Quatsino Narrows. The principal river affecting the water properties of the Rupert-Holberg basin is the Marble River, which flows into Rupert Inlet near the junction with Holberg and Quatsino Narrows. This discharge location contrasts with the typical British Columbia fjord in which the freshwater enters near the head.

Time-series temperature, salinity, and dissolved oxygen data collected by Drinkwater and Osborn (1975) showed that a relatively homogeneous water body exists in the Rupert-Holberg basin basin below 30-m depth. Comparison with data for other fjords (Pickard, 1963) indicates that the water properties of most British Columbia inlets are not as uniform as those in the Rupert-Holberg system (Drinkwater & Osborn, 1975). Oxygen content in the deep water varies seasonally, being generally 3-4 mg/L in summer (about 55-70% saturation) and up to ~ 5.5 mg/L in winter. The near-uniformity of the oxygen content throughout the deep water column implies frequent mixing. The lower summertime values may reflect an influx of low-O2 water from the Pacific Ocean into Quatsino Sound during upwelling episodes as well as increased oxygen demand in deep waters following the spring phytoplankton bloom (Drinkwater & Osborn, 1975).

Tailings are discharged to Rupert Inlet via a submerged pipe 1.07 m in diameter at a depth of about 40 m as a slurry of solids, freshwater, and seawater in the respective ratio 1:4:5 parts by volume. Time-series seismic and echo-sounding profiles and side-scan sonar information defined a leveed submarine channel in Rupert Inlet for the first time in 1974, three years after startup (Hay, 1981, 1982; Hay et al., 1983a,b). At that time, the channel started close to the outfall, ran southerly down-slope and across the inlet before hooking to the west to follow the axial trend of the basin toward Hankin Point. The presence of the channel and its well-developed flanking levees was particularly well illustrated by bathymetric (echo-sounding) data collected in November 1976. Hay noted that levees in the proximal zone near the outfall are steep-walled and are sites of rapid deposition characterized by noncohesive sands and silts. These features appear to be the origin of slump-generated turbidity currents that deposit turbidites on levees in the middle and lower reaches.

The submarine channel in Rupert Inlet has two important consequences. Lateral divergence of the tailings is constrained, and the velocity and excess density of the continuous flow are maintained to greater distances and depths, which reduces deposition near the outfall. Because the levees are subject to intermittent failure, sporadic surge-type turbidity currents will transport material down the relatively flat floor of an inlet to greater distances than would otherwise be the case. Although such phenomena may prove to be advantageous in terms of outfall performance, by dispersing the tailings further from the source, under certain circumstances such distal transport may have unforeseen effects.

In the case of the Rupert-Holberg fjord system, resuspension of tailings to the surface has occurred repeatedly during each year since the spring of 1972 in the vicinity of Hankin Point. Two major influences cause the resuspension. First, tidal exchange through the constricted Quatsino Narrows is exceptionally turbulent and is manifested by high current velocities. Second, during the spring and summer, upwelling off the coast of northern Vancouver Island brings to the surface relatively cold, dense water, which is transported into Quatsino Sound on the tide. During flood tides, this well-mixed water plunges downward as a jet after crossing the Quatsino Narrows sill. Depending on the density contrast between the incoming and resident waters, the jet may penetrate to the bottom south of Hankin Point before being deflected surfaceward after colliding with the fjord wall on the north side of the confluence. The momentum of the jet plus associated physical displacement can carry deep waters containing resuspended tailings to the surface. Such resuspension is most pronounced during spring tides when upwelling is significant off the coast and when the density of the water resident in Rupert Inlet has been lowered by precipitation and runoff, particularly after the fall and winter (Drinkwater & Osborn, 1975). The resuspension is exacerbated by the distal transport of tailings via turbidity current flow to the Hankin Point area.

As of 1993, the tidally dominated circulation off Hankin Point was continuing to resuspend tailings, most of which have settled out in the shallow waters around Hankin Point. However, some material is transported through Quatsino Narrows on the ebb tide and settles out around Hecate Cove. The seasonality of sediment accumulation in shallow water near shore at Hankin Point (Island Copper Mine, 1991) illustrates the strong influence of summer upwelling off Vancouver Island. The highest settling rate to date was observed in September 1987.

The mean depth of Rupert Inlet along the mid-channel has been decreasing by roughly 2 m per year (Island Copper Mine, 1987). By closure, the thickness of the tailings in the central trough of the fjord will be about 50 m; the mean mid-channel depth of the fjord will have been reduced from the premine depth of 145 m to about 96 m.

Resuspension and dispersal of tailings over broad areas in Rupert and Holberg inlets, and to a lesser extent into Quatsino Sound, were unforeseen in the original planning for the submarine disposal program. The tailings were expected to flow from the outfall as a continuous density current, settling progressively down-inlet. Although the density flow was expected to reach the deepest part of the inlet south of Hankin Point, it was thought that the deposition would occur at a depth below about 120 m, "in a zone of vertical stability well below any significant influence from tidal effects coming through the Narrows." (Utah Mines, 1969). This prediction appears to have arisen from an inadequate appreciation of the controls on deep-water renewal in the Rupert-Holberg inlet system. This example underscores the need for detailed, site-specific physical oceanographic surveys and modelling studies to be carried out prior to the selection of particular sites for submarine discharge.

Tailings Geochemistry

Two aspects of the post-depositional (diagenetic) chemical behavior of both tailings and natural sediments in the Rupert-Holberg basin have been considered in detail previously (Pedersen, 1984, 1985): benthic nutrient regeneration and remobilization of metals. Both studies used interstitial water and solid-phase measurements made on a trio of cores raised from the basin in 1980. The cores represented three different sedimentary facies: natural sediments in upper Holberg Inlet, rapidly accumulating tailings collected from the presumably stable flank of the deposit slightly down-inlet from the original outfall, and slowly accumulating tailings overlying natural deposits near the head of Rupert Inlet.

Profiles of dissolved nutrients (ammonia and phosphate) in the three cores have been documented (Pedersen & Losher, 1988). Ammonia and phosphate are clearly regenerated from organic matter in the natural sediments in a typical stoichiometric molar N: P ratio of 10. However, no phosphate regeneration was observed in either of the tailings-bearing cores, despite the presence of significant concentrations of dissolved ammonia. Pedersen (1984) attributed the phosphate deficiency to the precipitation in situ of carbonate fluorapatite. Supersaturation of the tailings pore waters with respect to this phase appears to be fostered by the addition of lime during milling of the ore and in the thickeners. Continuing dissolution of this additive following deposition of the solids on the inlet floor promotes supersaturation of the apatite phase by driving up the pH and the calcium concentration in the pore waters.

The removal of phosphate from pore waters in the submerged Island Copper tailings appears to eliminate any regenerative flux of phosphorus from the sediments to the overlying water. Although such regeneration can be important to the nutrient budgets of many coastal water bodies (see, for example, Fisher et al., 1982), it does not appear to be a factor in Rupert Inlet where the phosphate budget appears to be dominated by the tidally promoted advection of nutrients into the fjord. Nevertheless, the potential for phosphate consumption by submerged tailings should be taken into account in the planning of future STD operations.

Pedersen (1985) showed that the distribution of dissolved copper in surface sediments was similar at three sites examined in the Rupert-Holberg basin. The dissolved Cu concentration decreased at depth in the deposits, strongly in the natural sediments and less so in the tailings. It was suggested by Pedersen (1985) that these distributions reflected control by three factors: (a) release to solution from a labile copper-bearing phase at or near the sediment-water interface; (b) release to solution by freshly deposited tailings, possibly as a result of oxidation at the exposed sediment surface, which is more likely to be a factor in areas with a slow accumulation rate; and (c) precipitation of authigenic sulfides at depth. Pedersen (1985) noted that the magnitudes of the copper enrichments in surficial pore waters in the tailings were similar to or less than concentrations observed in natural sediments collected from unpolluted environments (e.g., Heggie, 1983). Therefore, at the time of sampling in 1980, the tailings in Rupert Inlet were not supporting a benthic flux of Cu to inlet waters greater than the evasion of the metal from most natural coastal sediments.

The dissolved molybdenum content in tailings pore waters in 1980 was enriched in the rapidly accumulating deposits by a factor of six over normal sea water, and in the slowly accumulating facies by a factor of two. In contrast, lower concentrations were observed in the natural sediments, where consumption of the element with depth was attributed to the precipitation of authigenic molybdenum sulfide. The profiles indicated that the tailings were releasing Mo to the overlying water in 1980 to an extent not witnessed in natural deposits. The efflux was thought to be supported by the dissolution of MoO3, a soluble oxidation product of molybdenite that can form during the atmospheric weathering of molybdenitebearing ore (Chander & Fuerstenau, 1972). Pedersen (1985) calculated that the incremental addition of the benthic efflux of Mo to the dissolved molybdenum inventory in Rupert Inlet is extremely small (< 0.002So at steady state). This insignificant impact is partly a reflection of the relatively short residence time of water in the basin, calculated by Drinkwater and Osborn (1975) to be on average 13 days. It should also be noted that Mo occurs naturally at relatively high concentrations in seawater (~11 ppb) as the oxyanion MoO_4^{2-}, which is essentially a biounavailable species.

The distribution of dissolved arsenic species in pore waters from the Rupert-Holberg-Quatsino system is of interest. As it is toxic to biota, and because the element occurs in oxic seawater as arsenate (AsO_4^{3-}), which is isoelectronic with phosphate, it is readily assimilated. Arsenopyrite is a trace constituent in the Island Copper ore; Poling (1982) reported 5 ppm As in the tailings, and the study allowed the extent of arsenic release from these deposits to be determined. The total dissolved As content in interstitial water extracted from tailings surface samples in each of the 3 years from 1981 to 1983 was very low (< 6 ppb). Much higher concentrations characterized surficial pore waters extracted from natural sediments in upper Holberg Inlet and Quatsino Sound, where levels exceeding 30 ppb were observed. The dissolved As contents correlated well with dissolved phosphate measured in the same samples (r= 0.75, n = 12), suggesting that the arsenic distribution in the Rupert-Holberg-Quatsino system is controlled by natural biogeochemical cycling and is not influenced by the tailings distribution.

The Monitoring Program

Island Copper was required by the terms of its tailings discharge permit to monitor a substantial number of parameters. Each parameter has an extensive set of sampling stations diagrammed in the annual environmental reports, e.g., Island Copper Mine (1994), with earlier versions in Ellis (1989) and Pelletier (1982).

Fisheries

Pacific salmon and Dungeness crabs are fished commercially in Rupert and Holberg Inlets, at periods regulated by the Canada Department of Fisheries and Oceans. Stock estimates and catch figures for these two major fisheries are kept by the regulatory agency. They are in a form that does not distinguish the stocks in the Rupert/Holberg Inlets from other inlets, other than very crude estimates of numbers of salmon in some of the spawning streams each fall.

Accordingly, Island Copper monitors Dungeness crab by its own test trap fishery. The size frequencies have differed in the three inlets since 1981. In Rupert Inlet the modal size of trapped crabs has been relatively large at 14-16-cm body width with the exception of a few years (1984 and 1987-89). Holberg Inlet has been similar, but Quatsino Sound shows more irregular size frequencies and usually smaller crabs.

The figures in combination are suggestive of a pattern of irregular stock overfishing followed by recoveries. There is no sign of a consistent reduction of catch in Rupert Inlet due to the mine tailings discharge.

The Aquatic Ecosystem

Manne Benthos. The most extensive sampling of the aquatic ecosystem is of mud-bottom benthos. Tailings being fine grained, they become after deposition a mud-bottom similar in grain specifications to natural deep fjord deposits. At Island Copper the benthic sampling stations are located with those for sediment metal analyses (Figure 3). The set of 26 stations (stations 1-25, plus station B), mostly sampled in triplicate annually since 1970 prior to mine operation, provides a time-series of benthos surveys unique in duration, spatial extent, and replication. In addition, aiding consistency in species biodiversity assessment, the scientist responsible for the species identifications has been with the project almost from the start.

The benthos of Rupert and Holberg Inlets, and Quatsino Sound, have been monitored since January 1970, some 20 months prior to discharge. Monitoring will continue into the postclosure period.

Benthos selected for monitoring comprise the infauna (burrowing organisms), as these can be quantitatively sampled by routine procedures using a seabed grab. The sampling station pattern was designed to monitor within and beyond the   an

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Annual reviews of the data have summarized impacts to date each year (Island Copper Mine, 1972-94). The reportable details improved considerably from 1988 onward, with the development of a computerized multivariate analysis procedure. This utilized a custom-designed data-processing system based on dBase III software (SAAMP) and the SIGTREE software package (Nemec & Brinkhurst, 1988). The system allowed comparing the biodiversity (abundance and diversity of organisms) between stations for each year's surveys and, for any one station, comparing differences between surveys.

There have been three reviews commissioned over the years (Ellis, 1975, 1987; Burd & Ellis, 1995). The first two largely reviewed and recommended procedures. The pattern of impact was not clear in 1975, and by the mid-1980s the need for computerization and data quality assurance had become urgent. There were major changes in procedures in 1977, when sample processing protocols were definitively established, and in 1988 when computerized data processing and analysis were introduced. The 1995 review has further updated data processing, developed software for transferring data from database to spreadsheets, and undertaken analyses on mainframe rather than microcomputer.

Counts of different species present show that some sampling stations have an almost consistently reduced diversity. These are stations 15, 16, and 17, the stations closest to the outfall. Other deep-trough sampling stations down the inlet (stations 13, 9, and B) show species reductions, but the effect progressively reduces and is not detectable by this simple index at station 6 and beyond in Holberg Inlet nor in Quatsino Sound.

This index establishes that only rarely has the fauna been totally obliterated at the times of sampling (e.g., station 15 in 1982 and station 16 in 1978). Generally the reductions are down to 1-5 species.

At the least impacted of these stations, B and 9, species reductions are followed within a year by return to a more consistent diversity in the tens of species. At the remaining stations, 13 and 15-17, species reductions are generally followed within 1-4 years by an increase. Only at station 15 has there been a species reduction extending over most years. This is the sampling station closest to the outfall, where tailings are actively moving and where there may also be impact from deposit slips at the face of the nearby beach dump.

It can be concluded from the diversity table that this pattern of impact was initiated in 1972 soon after discharge started and developed more strongly during the years 1973-76, when biodiversity data was not obtained. Abundance data (numbers of organisms per m2) show a generally similar pattern of reductions in Rupert Inlet and are summarized below in relation to tailings deposits.

The distribution of tailings in the inlet system has been monitored at the benthos stations since 1971. The thickest tailings deposits (100% tailings) sampled by a 60-cm core are limited to sampling stations along the deepest part of the Rupert-Holberg Inlet trough, i.e., > 50-m depth. Less tailings, mixed with natural deposits, occur in the cores further up Rupert and Holberg Inlets and into shallower water. (Tailings on occasion have deposited in visible shallow beds extending onto the shoreline near Hankin Point due to deep current scouring, resuspension, and upwelling. In this high-energy habitat, these shallow tailings beds erode and reform aperiodically.) Visual evidence of tailings mixed with natural sediments beyond Quatsino Narrows was first observed in 1987 at station 22, Hecate Cove. There has been no development of a continuous tailings layer in Quatsino Sound. Copper concentrations in sediments are monitored to track the deposition of tailings at levels too slight to be visible. Ambient levels of copper in sediment prior to discharge and at stations remote from the mine are in the range 30-70 ppm. Values above 100 ppm are arbitrarily taken as indicating some tailings deposition. There is a gradual decline in high copper levels with distance from the outfall, but some low values occur close to the outfall (at shallow-water stations). Burd & Ellis (1995) report a correlation between reduced abundance and diversity with four coinciding environmental parameters: > 50-m depth, 7 km distant from the outfall, 15-20 cm accumulated tailings, and 400 ppm Cu. The relationship between tailings distribution at any one time and the infaunal benthos is complicated as the measured thickness of tailings, and copper levels in the sediments, do not reveal tailings settlement rates. Benthic impact, in the defined region where it occurs, in principle must be at least partly if not primarily a function of the rate of deposition, i.e., a physical smothering effect on organisms. Impact is also likely to occur secondarily on recolonizing benthos due to erosion of the density current levees with consequent tailings resuspension followed by redeposition. In contrast, there is no evidence from routine water analyses that the tailings deposits (largely inert chalcopyrite) leach copper.

Sampling stations with thickest tailings (generally greater than about 20 cm) are impoverished in terms of number of species and the number of individual organisms. Sampling stations with little or no tailings have not been separable by the similarity analyses since their introduction in 1988. Polychaete worms have dominated the biodiversity in the inlet system during the period of record, with several different species dominant at different times (Ellis & Hoover, 1991). The species *Cossura pygodactylata* tends to be the most abundant species on thickest tailings. At shallower stations (< 50-m depth) with lesser tailings, the bivalve mollusc *Axinopsida serricata* has often been the most abundant species.

Similarity analyses have repeatedly shown that sampling stations with little (< 20 cm) or no tailings are not distinguishable. It appears that a slow rate of tailings deposition approximating 1 cm p.a. has no detectable impact on the infaunal benthos. It is only in the area close to the outfall where tailings flow persists that there have been consistent or periodic major reductions in biodiversity. These often last only a single year, indicating that the reduction is due to a major deposition, or erosional, event followed by larval recolonization the next year if the beds remain stable. These similarity analyses have been extended by Burd and Ellis (1995). They compared station 16, close to the outfall, and remote station 23 with the other stations over all years. Similarities were substantially higher in 1970-72 (values from 0.4 to the maximum of 1.0 before and within 9 months after discharge started) than from 1977 onward, when many stations had virtually zero similarities with station 16.

Originally, the infaunal population had considerable similarities throughout the inlet system. The pattern was presumably determined, as is usual, by depth and sediment characteristics (sand, silt, clay). The tailings discharge has imposed a new pattern of infaunal distribution in the inlet, summarized as impoverished on the thick and active tailing beds along the trough of Rupert Inlet, grading to a fauna on little tailings not noticeably different from the area without tailings. Tailings consist of fine silts and clay particles. Where the infauna can survive the tailings deposition and recolonize, it is to be expected that there will be some similarity with the infauna on the equally fine silts and clays naturally occurring along a Lord trough.

In summary, the tailings deposits support benthos. There can be a diverse and abundant fauna present with characterizing species, and this fauna appears to be able to colonize within 1-2 years of deposits settling and stabilizing. In addition, benthic populations on tailings deposits of a few centimeters thickness appear not to be different from those at similar depths without tailings. These conclusions are reexamined annually with each year's data and newly available analytical systems. Sudden declines of benthic diversity on thick tailings have usually been followed by reappearance of organisms (often by the following year) at levels that remain established until a later sudden decline. These declines are taken to be the result of erosion and resuspension (by a dynamic tailings density current) of settled tailings beds with their stabilized infauna. This can be followed by other periods of stability and biological recolonization. A recolonization rate of about a year has been separately documented by Taylor (1986) and also reported in Ellis and Taylor (1988). Artificial substrate boxes recolonized within 1 year, but to a different population than control boxes and surrounding tailings and slower than the control boxes. In spite of faunal differences, the time scale to recolonization was similar to that indicated by the monitoring program.

Recovery prediction has two components. On stabilized tailings beds after mill closure, benthic biodiversity can be expected to return to high levels within 1 or 2 years. The actual populations may be measurably different from those present on stations with similar substrates at similar depth, as has been found at other mine sites (Burd 1991; Ellis & Hoover, 1990). This is not expected to affect the food chain in the receiving area, as the commercially fished Dungeness crab stock has maintained itself for 20 years during the period of mine operations and tailings impact. Crabs are opportunist feeders taking a wide variety of live and dead food. The second component of recovery prediction is the extent to which destabilization of the tailings beds will occur. As recurring destabilization reduces, the benthic consequences of such destabilization will also reduce, but trailing the physical effect by 1-2 years.

Other Aquatic Stocks. There is no suggestion from the data that any of these stocks show reduction spatially or temporally related to the mine tailings discharge, other than mud-bottom benthos under rapidly depositing or unstable tailings.

Trace Metal Contamination. The maximum elevations for copper from the Island Copper Mine's concentrate loading docks in Rupert Inlet. The levels are more likely due to fugitive dust from loading than tailings discharge. Results for most stocks either provide no suggestion of trace metal contamination or are ambiguous, i.e., no clear evidence due to population variability. The common rockweed (Focus) shows raised levels of zinc near the mine; this is taken as due to an inability to wash all particulate off the plant.

Prior Resource Uses. The major fishery resource present in the area at the time of mine development was the stock of several species of Pacific salmon. A then estimated 10,000 salmon return from the sea annually through the Rupert/Holberg Inlets and spawn in the inflowing streams and rivers (Ellis & Jewsbury, 1974). Hence several million young salmon annually use the inlets as nursery area and/or highway to the offshore growing areas. This salmon resource was (and remains) occasionally fished commercially in the inlets, but contributed to the near-shore regional fishery. There was also an accompanying recreational fishery. There have been suggestions that water extraction for the mine from an important salmon spawning river (the Marble River) might contribute to salmon spawning losses (e.g., Waldichuk & Buchanan, 1980; Buchanan. 1982). Although this has not been demonstrated, Island Copper has cooperated in the establishment and operation of a salmon hatchery there since 1982. Other fishery potential was little used commercially and is not well documented. It is to be expected that in addition to salmon and crab a variety of other fish, crustacea. and bivalve molluscs were used by local residents. There had been a whaling station at Coal Harbour nearby in the 1950s, but this was closed with little prospect of the whale fishery ever being revived. Otherwise. the major resource was forestry, which was heavily utilized, with small and large logging operations scattered around the two inlets. One coastal mine had previously operated: Yreka in the adjacent Neroutsos Inlet. Other mines had been located inland, hence there was potential for other mineral prospects. There were a number of native American reserves scattered around the inlets. and these drew on the local fishery and land resources for subsistence living, for traditional purposes, and in some cases for commercial fishing. A few commercial fishermen lived in the inlets.

Community Concerns. Many concerns were expressed prior to and at the public hearing in 1969. They included trace metal contamination, the general concern that mining was an environmentally unclean industry, and resistance to marine disposal of industrial wastes due to unknowns about waste impacts in the sea. There were many applications by interest groups to formally protest at the hearings, but only four were selected as having the proper legal standing. This in itself exaggerated the controversy (Lucas & Moore, 1973), which became a substantial media event. In 1969, with so many environmental unknowns, application of contemporary appraisal concepts might have denied the permit. Regional public resistance to the mine was strong, although there was significant local support. The hostile opinions were defused to some extent by the monitoring requirement of the permit under supervision of an independent university group. Nevertheless, controversy continued through the 1970s, until a regulatory agency inquiry in 1978 (Waldichuk & Buchanan, 1980; Buchanan, 1982) confirmed the conclusions from the routine monitoring: that STD was preferred over land tailings disposal and that the environmental impact of STD was slight, tolerable (after 10 years), and almost certainly recoverable after mine closure. There has been little further review of community concerns, although there is information in Dorsey and Martin (1986). A short social review was included in Ellis (1989), Chapter 11, Fact-Finding and Social Input."

Mine Closure. Island Copper Mine initiated closure planning in 1988 with an initial expectation of closure in the mid-1990's. The closure plan is now developed (BHP, 1994). It has five components: plant site, land dumps, beach dumps, open pit and ARD passive treatment, and the marine environment. The general target is return to prior use, which was wildlife and forest habitat. The plant site will be reclaimed by removing buildings and stored wastes and remediating contaminated soil. The area will be contoured and revegetated. There are four land dumps for waste rock. These have been progressively contoured and reclaimed using glacial till and revegetation. Some acid rock drainage (ARD) developed in the mid-1980s and is currently collected and drained to a waste management pond. Pond water is either recycled through the mill or, if waste discharge criteria are met, exfiltrated through the beach dump.

The beach dump consists of waste rock dumped along the shoreline of Rupert Inlet and contains marginal ore stockpiles. These stockpiles will be processed before closure, and the remaining waste rock contoured and revegetated. Slopes to the sea have been contoured to provide shallow embayments facilitating foraging by juvenile salmon. Experiments starting in 1991 have shown that natural revegetation produces substantial biodiversity within 2-3 years. ARD is occurring to the extent that at the beach dump marine face there are slightly elevated levels of trace metals compared with levels in the water column: Cu up from about 0.002 to values of 0.002-0.005 mg/L, Zn up from 0.002-0.005 to 0.005-0.015 mg/L. There is no evidence that this seepage is raising trace metal levels in the inlet system. The mine pit is flooded with seawater. It may be convertable into a meromictic lake, i.e., a deep anoxic layer of seawater with an overflow of river water draining to the sea, although wall stability will determine this. Meromictic lakes occur naturally in western Canada. Residual ARD from the land dumps will be injected to the lake bottom, which will then function as a passive ARD treatment system. An alternative option considered was to use the pit as a controlled sanitary landfill for regional wastes transported by barge and truck from urban centers. Pit capacity was predicted at about 125 years. The marine environment has been little impacted by the tailings disposal. It is expected that tailings deposits will stabilize within a few years, and be covered by natural deposits. Benthos will repopulate to a high biodiversity within 1-2 years on such stabilized deposits. The slightly elevated ambient turbidity will decline within weeks of closure. One unknown is the time to terminal stability of tailings deposits in the high-energy environment close to the fjord sill at Quatsino Narrows.

Conclusion

The STD operation at the Island Copper Mine is clearly the best-documented example of positive aspects of such technology. This example also demonstrates that unexpected aspects such as irregular upwelling events can cause sporadic surface turbidity. As a result of comprehensive monitoring now spanning 24 years and ancillary studies of the chemical behavior of the tailings following deposition, it is recognized that STD can produce deposits that do not contaminate the overlying water column and permit commercial fisheries (i.e., for Pacific salmon and Dungeness crabs) to be maintained in the receiving basin. There is no evidence that either the major regional fishery based on migrating stocks of Pacific salmon or the crabbing have been deleteriously affected by the Island Copper submarine tailings disposal. The only major ecosystem compartment to be impacted, the benthos, can support a diverse and abundant fauna on tailings. Losses in regions of high tailings sedimentation rates, such as occur close to the tailings outfall, have been shown to rehabilitate within 1-2 years.

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