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Potential for Retrofitting STD

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Submarine tailings disposal (STD) systems have been retrofitted, designed, or appear to be possible at several existing or abandoned coastal and island mines. At Atlas Copper Mine, the Philippines, the system is somewhat different from the norm: a 500-m pipe pier, with a discharge point just below the surface, extends offshore to 30-m water depth. Little environmental information is in the public domain, but there appears to be some nearshore turbidity and deposition. A system was designed for the Toquepala and Cuajone mines, Peru, but was not implemented. The discharge depth was to have been at 20 m to a sloping offshore bank, with low-oxygen water and sediments. The Marcopper Mine, the Philippines, elected for nearshore disposal, but extended this by causeway to surface discharge over deeper water. Reviews of potential STD sites showed at least three locations with apparently suitable depth and slope close to shore. At Bougainville Copper Mine, Papua New Guinea, the tailings disposal option was to a river with flow westward to the sea. Nearshore deep water beyond a fringing reef in an easterly direction was closer to the mine and could have been investigated for STD. The Jordan River Mine, Canada, in its most recent reopening (1972–74), installed a tailings pipeline to discharge at 12-m depth to a nearshore depression. It broke repeatedly at this high wave energy site, which appears unsuitable for an STD system. Screening criteria that can be applied in STD retrofit proposals include coastal accessibility and a complex of technical and geophysical factors allowing generation of a tailings density current flowing coherently to a final deposition site.

Keywords breaks, Canada, nearshore discharge, Papua New Guinea, Peru, Philippines, river discharge, screening criteria, tailings lines

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We very much appreciate cooperation with the mining companies and their staff in providing us access to documents and in some cases to the mine sites.

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There are many coastal and island mines that discharge, or previously discharged, their tailings to land, to rivers, or to shorelines. Some of these have investigated the potential for submarine tailings disposal (STD), either for reopening, as at Kitsault (Pedersen et al., 1995), or as a retrofit. At other existing or closed mines, there is obvious potential for STD. This article reviews five cases of actual or potential STD retrofitting, so as to demonstrate factors involved in planning and designing retrofit.

The one case of achieved retrofitting is the system at Atlas Copper Mines in the Philippines. This was undertaken in the early years of STD development (1971). It was provoked by the loss of agricultural land downstream of the original tailings river discharge points and by the tailings creating navigation hazards for the concentrate-loading freighters in the downriver harbor. At the Toquepala and Cuajone (copper) mines (Peru) and the Marcopper Mine (the Philippines), STD was explored after river or shore disposal created a number of environmental and social problems. Sites for STD were identifiable for both mines. At Bougainville Copper Mine (Papua New Guinea), STD, apparently, was not considered as an alternative to the adopted river disposal. The mine is now closed, but if it ever reopens STD is an option that can be considered. There is a deep-water slope within technically accessible distance of the mine site. At Jordan River (copper) Mine (Canada) the selected STD system did not work, and the system reverted to beach disposal. The case provides an illustration of the submarine constraints on STD systems, as opposed to such on-land constraints as coastal accessibility.

The case histories illustrate the nature of technical screening criteria for STD that can be applied to new and retrofitting developments. Screening criteria drafted by Ellis et al. (1994) include:

(1) Coastal accessibility—tailings transport practical
(2) Suitable bathymetry—slope and physical oceanography appropriate for generating a tailings density current and accommodating the tailings deposit below the euphotic zone
(3) Outfall site—a secure site, appropriate for generation of tailings density current
(4) Toxins release—minimal potential through appropriate ore and reagent chemistry and receiving area geochemistry
(5) Tailings resuspension and upwelling—minimal potential
(6) Other resources uses—minimal potential for impact.

The Jordan River case is an example of a site where application of such screening criteria shows the risks of selecting STD for tailings disposal. Another example is the Ok Tedi Mine (copper and gold) in Papua New Guinea (Ellis et al., 1994; Pintz, 1984). Although the coastline has suitable bathymetry, the closest access is about 300 km from the mine site, with a mountain range barrier between.

A Little-Known Early Case History: Atlas Copper Mines, the Philippines

The Atlas mines retrofitted STD to discharge their tailings to the sea in 1971. By 1981, 100,000 tonnes per day were being discharged. A description of the engineering was published soon after operation commenced (Salazar & Gonzales, 1973). Thus, Atlas vies with Island Copper Mine for being the first to adopt STD. Its system and engineering were somewhat different from Island Copper's, in part through the mines being located a few kilometers inland.

Atlas also differs from Island Copper in that the mines' follow-up environmental monitoring has had limited documentation. We have seen articles by only Salazar and Gonzales, (1973); Dira and Canete, (1980); Salazar and Dira, (1977); and Alino (1984). In addition, Guevara (1981) provided responses to a questionnaire.

The intent of the retrofit in 1971 was to prevent further losses of agricultural land in the original valley receiving the tailings and the downstream coastal plain and further siltation around the mines' loading dock.

The Mines and Their STD System

The mines are located in the central part of Cebu Island, about 7 km inland. Reserves were estimated in 1973 at 700 million tons, with 30 years of mining anticipated for tailings discharge.

The major gangue minerals of the ore body are silica and silicates, with residual copper, pyrite, gold, silver, molybdenite, and magnetite.

When STD was initiated in 1971, there were two concentrators serving two pits, Lutopan and Biga. There were four lines collecting the tailings from the concentrators. The pipelines were merged, passed through a 850-m tunnel and onto a 500-m causeway and pipe pier at Ibo Point (Figure 1). Considerable attention was given to grind characteristics, flow hydraulics, and engineering to ensure minimum sanding of the pipelines. Energy dissipation was achieved by pipeline orifices, rather than by drop-boxes. Sanding nevertheless occurred to the extent that by 1973 drop-boxes and flumes were being installed and more tunnels (with open launders) built to shorten the route to the sea. A third concentrator (Carmen) within 5 km of the others was added to the system in 1977, bringing the total length of pipelines and launders to 47 km.

Discharge is at Ibo Point, selected from bathymetric surveys showing the presence of a trench with −15% slope near shore, leading offshore with depths of 350 m (Figure 2) only 1.5 km from shore. A strong southeasterly shoreline current

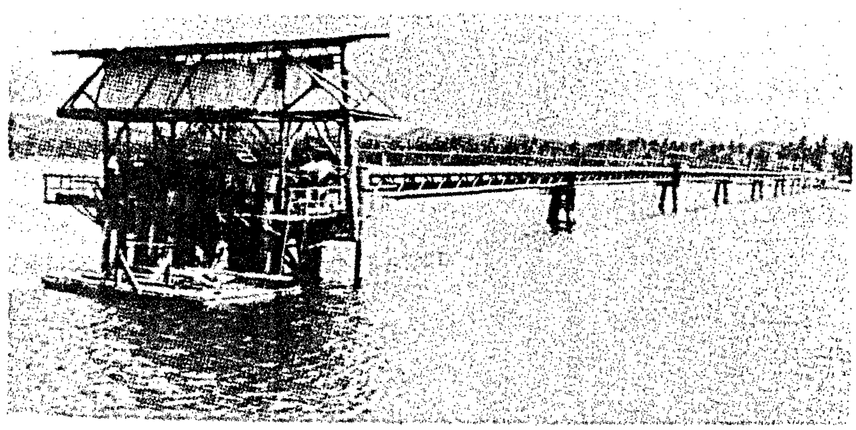

Figure 1. The tailings causeway and discharge point for the Atlas Mines (rephotographed from Salazar & Gonzales, 1973).

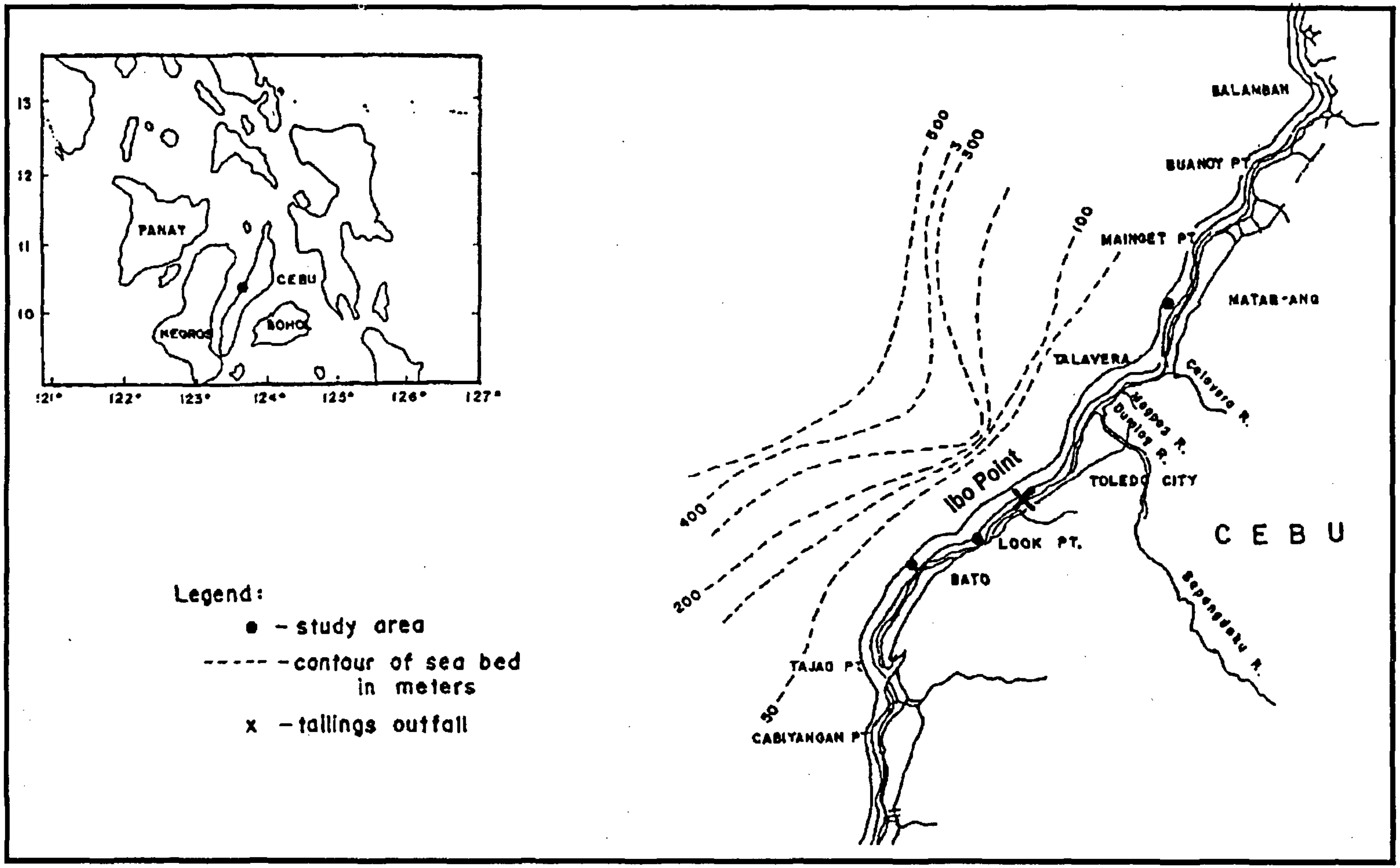

Figure 2. Bathymetry offshore from the Atlas outfall location at Ibo Point (reprinted and modified from Alino, 1984).

was expected to disperse suspended slimes. Depth at the discharge point was 30 m. Drop pipes with "90 degree bend nozzles" extend 10 m below mean low seawater level.

Quarterly hydrographic surveys showed by 1973 that some nearshore tailings deposition had occurred (0.02% of total discharged), and "stabilised at 12 meters below sea level in the area immediately below the discharge point" with slope approximately −20% (Salazar & Gonzales, 1973). It is implicit in this and the other reports that the density current maintained the flow toward the targeted incised channel. There was some deposition back of the discharge point, but there was no evidence of tailings surfacing along the beaches. Also, surface turbidity was confined to within 5 m of the discharge point.

Salazar and Gonzales (1973) also report, but without supporting documentation, that "the disposal of Atlas plant tailings at Ibo has no adverse effects on marine life in the area. In fact, the discharge point at Ibo has become a favourite fishing ground of fishermen in small native boats (bancas)."

However, Salazar and Dira (1977) and Dira and Canete (1980) refer to government marine environmental surveys from 1972 to 1973. The reports stated essentially that there was no significant effect on plankton. Benthos were absent in an area extending 3.5 km from the shoreline and extending 6 km on both sides of the discharge point parallel to the shoreline. Tested physical and chemical conditions were within ambient levels. Acute bioassays with *Tilapia* gave 100% survival at tailings concentrations from 10% to 56%. Interviews with local fishermen established that catches had not been affected.

Nevertheless, by 1981 Alino (1984) found, during university thesis studies (Alino, 1983), evidence for some elevated sedimentation, metal contamination, and reduced coral cover around the outfall. Elevated copper levels in sediments in traps, with highest values closest to Ibo Point, indicated that some tailings were surfacing. Coral cover was reduced close to Ibo Point. The scarcity of local references in Alino (1984) indicates that there was little environmental data available during the time of his investigations, or if there were such data in government or industry files it was not publicly available.

In summary, the STD system installed appears to have achieved its design function of directing the major part of the tailings stream to depth. The outfall design adopted allows some minor secondary plumes of fines to upwell and drift behind the drop-box toward shore and then disperse in the surface currents.

The major environmental impact reported is absence of benthos over an area 3.5 × 12 km. Results from Island Copper Mine (Ellis et al., 1995), Kitsault (Pedersen et al., 1995), and the Toquepala and Cuajone mines in Peru (below) contrast with this. They establish that substantial amounts of benthos can occur on stabilized tailings. Details of the sampling gear used in the single survey at the Atlas STD site are not available, but if a fisheries trawl was used, it would not collect the type of benthos reported in abundance from Canada and Peru.

Toquepala and Cuajone Mines (Peru)

The importance of these mines located in southern Peru (Figure 3) is that the STD retrofit was designed for an existing system discharging tailings to a river (from two adjacent large open pit mines).

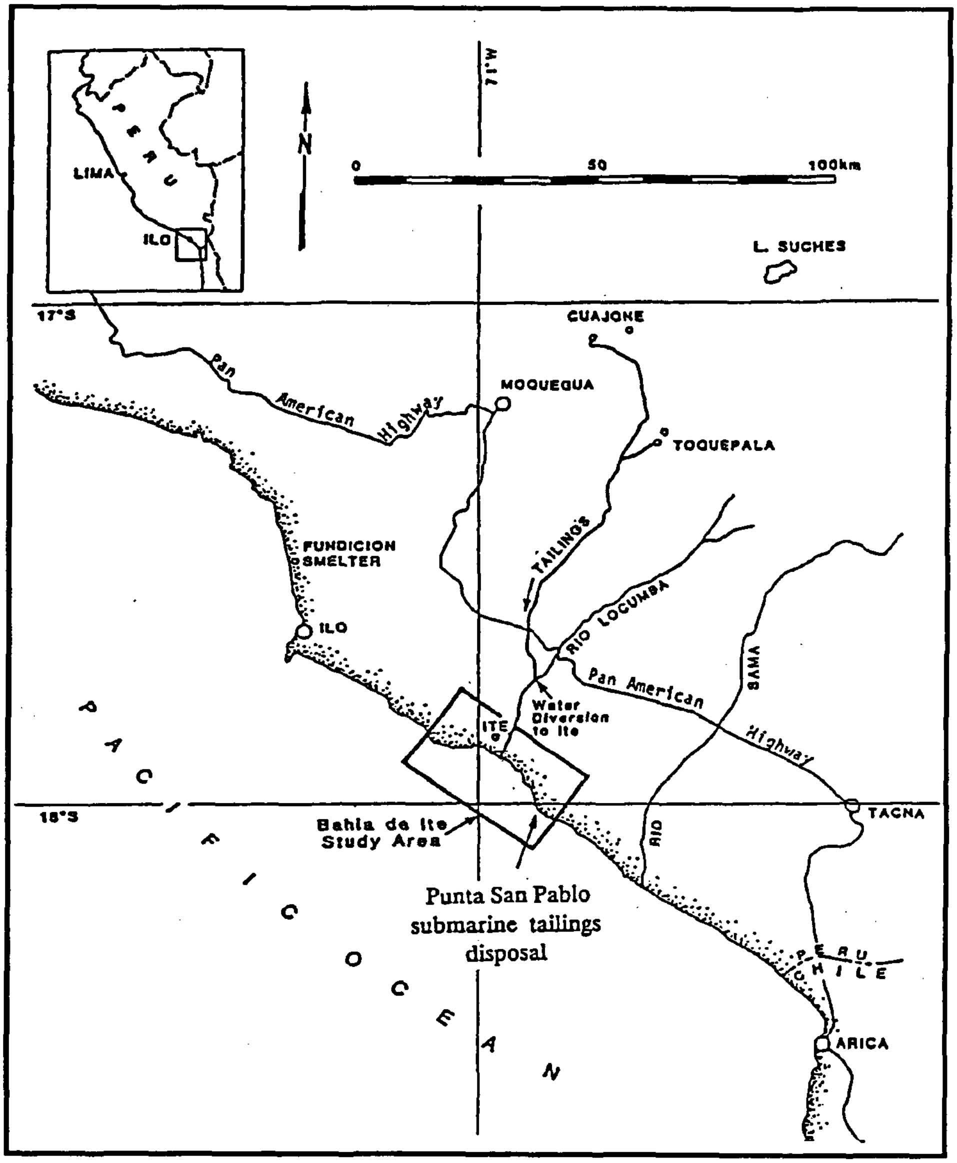

Figure 3. Map of southern Peru showing location of the Toquepala and Cuajone mines and the on-land tailings transport system (reprinted and modified from Rescan, 1992).

The lower River Locumbo and some of its headwaters had been in effect turned into open tailings flumes, eliminating fish and other biological resources. A 10-km long tailings beach had formed, prograding 1.2 km seaward. The proposed STD was designed to control acid mine drainage that had developed on the tailings beach. For this circumstance the proposed STD at 20-m depth to a high-energy wave-swept coastline with low-oxygen seawater was practical.

A land disposal alternative has now been selected, and the STD system will not be implemented.

The Mine and Its Proposed STD System

The mines are located approximately 100 km inland (Figure 3), and are large open-pit operations generating approximately 100,000 tonnes per day of tailings from the two mills. Southern Peru Copper Corporation (SPCC) is the operator. Ore composition is primarily sericite at 35%, quartz 25%, chlorite 12%, biotite 8%, kaolinite + montmorillonite 8%, sulfides 7%, and tourmaline 3%.

The mill process is shown in Figure 4. Tailings were being transported by a mix of launders and dry creek beds to the channel of the Locumba River. The input point to the river channel was just below where the river had been diverted as an irrigation source for the Ite area. From there the tailings flowed down the dry river bed to a beach, the Playa Inglesa, within Ite Bay (Bahia de Ite).

Longshore currents and strong surf had worked the depositing tailings into a 10-km-long beach 1.2 km wide at low time. There had been a persistent surface plume of tailings extending several kilometers alongshore.

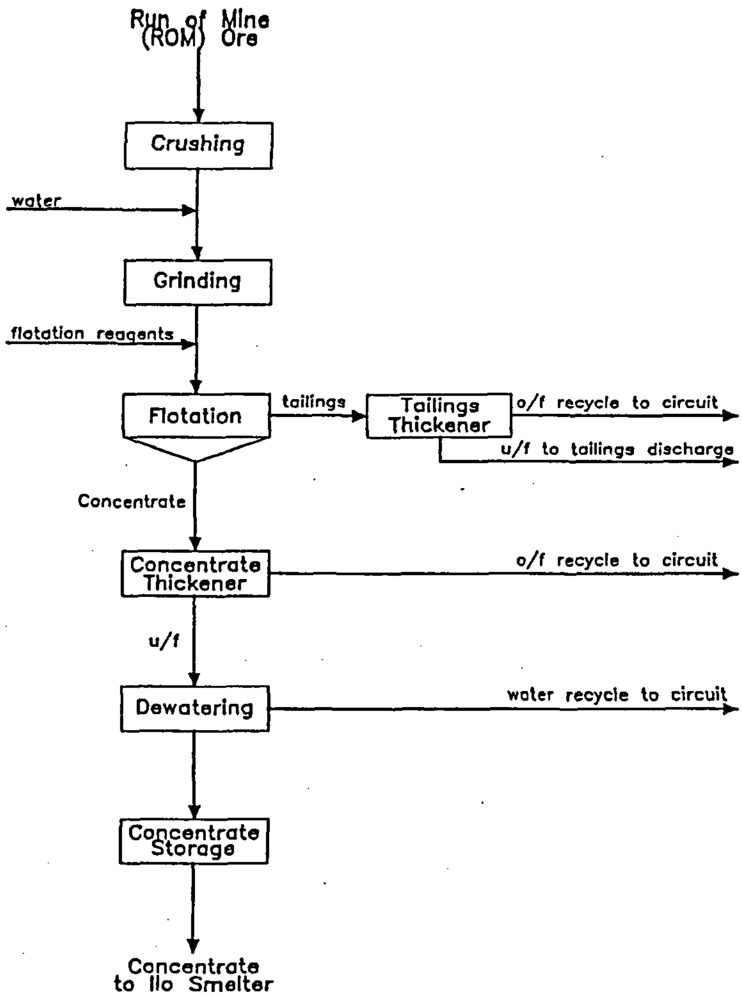

Figure 4. Simplified process diagram for the Toquepala and Cuajone mines (reprinted and modified from Rescan, 1992).

Near high-water mark, within 2 km of the River Locumbo channel, segregation of light and heavy minerals had produced in places a 1.5-m thick banded deposit of pyritic sands. Chemical oxidation of the high sulfitic tailings had resulted in acid generation and concomitant heavy metal solubilization. This was a source of contamination to seawater and marine organisms.

In contrast, more distant from the tailings outflow, freshwater seeps from irrigation of adjacent farmland terraces have generated a series of backshore coastal wetlands. These serve as wildlife habitat and are used for pasture by tended goat herds (SPCC, 1992) (Figure 5).

There has been very substantial physical degradation of the intertidal environment, with productive rocky shores replaced by a barren tailings beach. The impoverishment undoubtedly continues offshore, but by 36-m depth a benthic fauna occurs similar to that elsewhere (Rescan, 1992).

Rescan (1992) identified a needed comprehensive environmental impact assessment (EIA) and subsequent monitoring program. This encompassed physical oceanography, sedimentology, water quality, the fishery resources, and marine ecosystem structure and dynamics.

There was some community action responding to SPCC's proposal for STD. This was incorporated within a generalized reaction against SPCC developments and management, culminating in a complaint by *Associacion Civil Labor* to the Second International Water Tribunal (IWT, 1992; Diaz et al., 1991). The complaint refers to mine, water intake, and smelter environmental management as well as to tailings disposal.

The Second International Water Tribunal, a nongovernmental organization, was held for open discussions of water management in third-world countries and to make recommendations (IWT, 1991). The tribunal basically accepted the complaints of Labor and recommended that SPCC "invest sufficient amounts for the

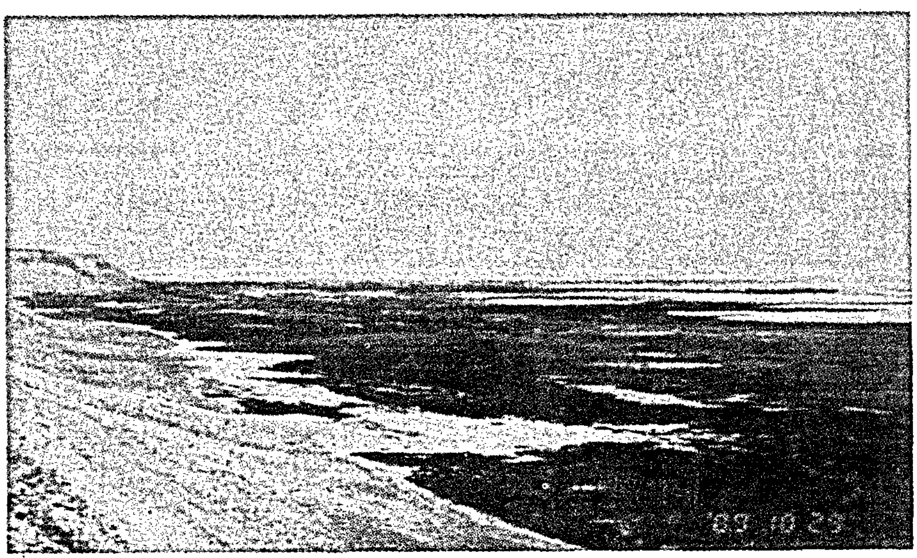

Figure 5. The development of freshwater wetlands on the backshore of the beach formed by tailings from the Toquepala and Cuajone mines (reprinted from a color photograph in Rescan, 1992).

improvement of its environmental performance, including installation of secondary treatment, introducing more modern copper processing technology, minimizing environmental impact and remediating existing impacts." (IWT, 1992).

At the IWT, one of the authors (D. E., who was a member of a committee of experts appointed to assist the IWT jury) discussed STD with the Labor delegates there. It became apparent that there was a consistent hositility to STD in principle. It appears that this is based on the conventional wisdom that (1) tailings in seawater must leach their toxins, and (2) coastal upwelling of deep offshore water must continue into shore and sweep back to shore the tailings deposited at depth.

In the context of toxin leaching, low-oxygen conditions below 20–30-m depth (see below) add to the ambient reducing conditions, and the risk of such leaching is negligible (Perry, 1995). In the context of surface upwelling of tailings, the consistent oxygen stratification shows that the well-known deep-water upwelling (low-oxygen water) from the Peru Coastal Undercurrent rarely if ever comes inshore to impact on the beaches (see below). The major threat for resuspension and surfacing of tailings comes from extreme storm-generated wave action and temporary destratification of the water column.

The STD concept proposed by SPCC was to pipe tailings from an intake point on the River Locumbo some 6 km inland and transport them by gravity flow in a 25-km pipeline to Punta (Point) San Pablo (Figure 6, marked E). At the Point, tailings would pass through a deaeration chamber and be mixed with seawater taken from 5-m depth. The tailings would then be discharged at a depth of 20 m about 170 m offshore. The tailings would then flow by density current to deposit deeper than 20-m depth on the sloping shelf.

A temporary offshore pipe by the River Locumbo would have brought some immediate amelioration of the existing beach impact during construction.

The STD system proposed was relatively shallow compared with others built, under construction, or being considered. Rescan (1992) reported on the site-specific physical oceanographic surveys and plume dispersal modeling studies undertaken for prediction of the deposition pattern in this currently novel situation. Below 20-m depth, predominant currents averaged 12 cm/s to the southeast, in contrast to stronger surface currents setting to the northwest. There was no evidence for seasonal upwelling returning suspended fines to the surface nor resuspending fines once deposited.

In addition, at about 20-m depth there was a marked oxycline. Below that depth, low oxygen levels were generally less than 2.0 mg/L. This was derived from upwelling deep water. This would have facilitated the development of reducing conditions within the tailings by sulfate-reducing bacteria (SRB) (Perry, 1995).

An extensive EIA was undertaken to determine physical, chemical, and biological oceanography (Rescan, 1992). Initial objectives were to establish (1) the potential for tailings suspension, resuspension, and upwelling; (2) the chemical potential for contaminant bioactivation; and (3) the extent and productivity of the biological resources, i.e., the fishery resources and their benthic feedstock ecosystem.

In summary, the STD system proposed by SPCC was novel in that it would have discharged tailings to a platform extending broadly offshore from 20-m depth. This is shallow relative to existing use of STD. The system was considered practical and with low environmental risks at this site for two reasons. Unusually low oxygen levels derived from deep-water upwelling would have facilitated formation of a

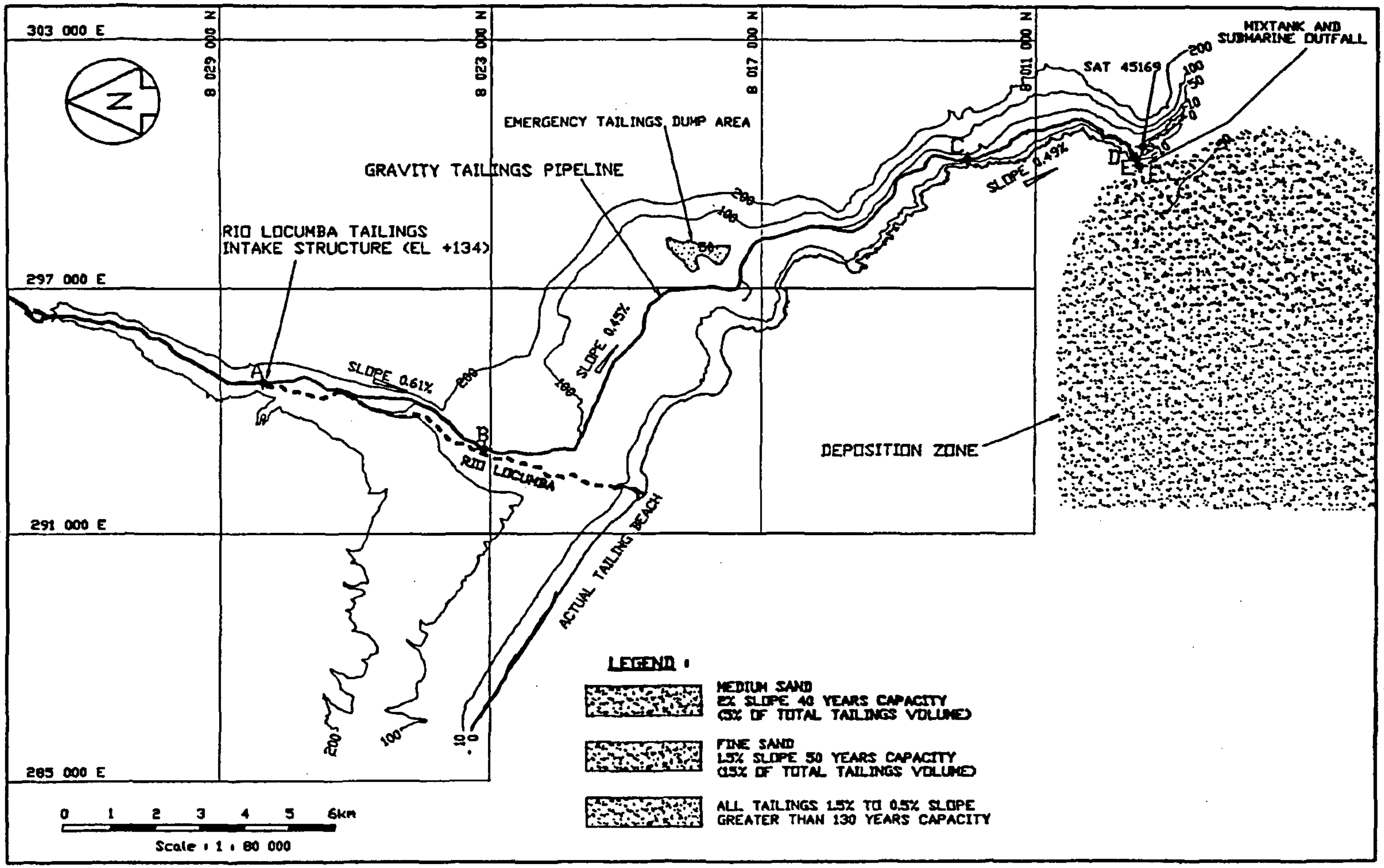

Figure 6. Tailings pipeline route developed for the proposed STD for the Toquepala and Cuajone mines (reprinted and modified from Rescan, 1992).

reducing ambient environment within the deposits. This in turn would have eliminated oxidation of sulfitic tailings releasing toxic metals. Upwelling of discharged tailings before or after deposition was of low risk, and dependent on extreme temporary storm events. The deep-water upwelling from the Peruvian Coastal Undercurrent was considered to have too little energy for tailing resuspension.

Marcopper Mine, the Tapian and San Antonio Developments (the Philippines)

Marcopper is yet another low-grade (0.4–0.5% Cu), high-tonnage (approximately 30,000 tonnes of tailings per day), open-pit copper mine, developed in the late 1960s. It is located on Marinduque Island about 10 km from tidewater, with nearshore deep water being 15–20 km distant (Figures 7 and 8) by other routes.

The mine opted initially to discharge its tailings from the Tapian pit to an on-land tailings dump. Then in the early 1970s there was an unusual development in that a second ore body (the San Antonio) was found under the on-land dump. Consequently a start was made (in the mid 70s) on dredging the tailings and discharging to the coast.

Rescan (1989) restated that originally an STD system was proposed for discharge at Trapichihan Point with suitable nearshore slopes. However a nearshore STD system was installed instead with discharge at 6-m depth to a 20-m-deep basin. The shallow slope caused the system to plug and fail within a few weeks of start-up in 1972. The response was to build a causeway by progressively extending beach discharge out to deeper water (Ellis, 1989a; Ellis et al., 1981) (Figures 9 and 10).

A review by outside consultants of the environmental information gathered by the mine staff was commissioned by the mine in 1981. The consultants concluded that tailings directly from the Tapian Pit, from the on-land dump over the San Antonio ore body, and eventually from the San Antonio development should be considered as a single continuing waste stream for the 20-30-year lifetime of the twin mines. They recommended a new feasibility investigation for deep submarine disposal of the finest tailings fraction (slimes). These should be separated in the milling process from the coarse fraction, which would be backfilled to the Tapian pit. The STD site recommended was again Trapichihan point. The consultants emphasized that an alternative plan for a shoreline tailings dump should be dropped, due to its risk of acid waste generation, catastrophic collapse during earthquakes, and social impact.

Local objections to the Marcopper Mine, supported by international environmental groups (McAllister, 1987; Velasquez, 1987), publicly surfaced during the political upheavals surrounding President Marcos in the late 1980s. The mine was closed for a few months in 1988.

An environmental impact statement (EIS) for the second pit, the San Antonio development, was prepared in 1989 (Rescan, 1989). This was based on the concept of STD for the fine fraction tailings (< 50 μm).

The Mine and Its Environmental Impact

The mine is located in north central Marinduque Island (Figure 8), 8–12 km from the nearest shoreline, in Calancan Bay. The Tapian pit lies about 4 km south of the

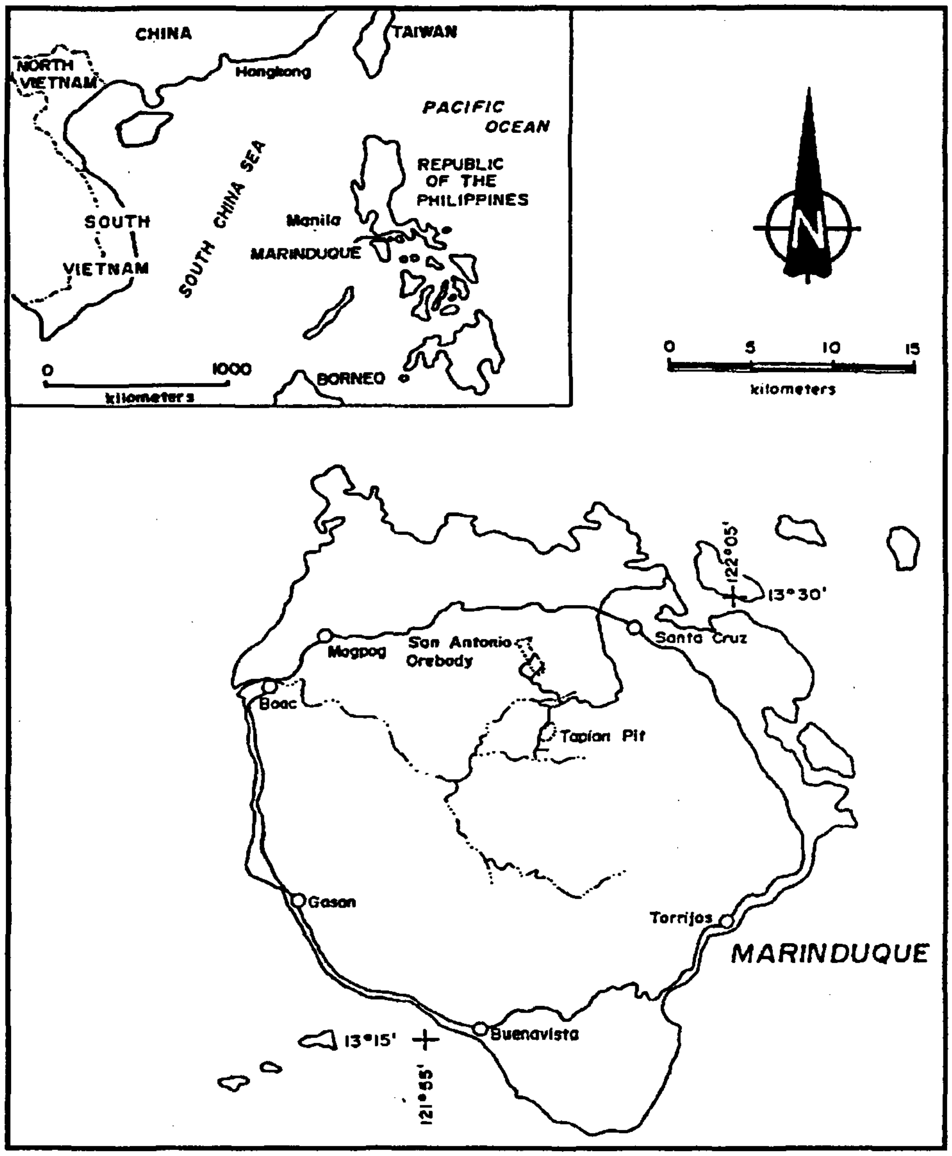

Figure 7. Map showing location of the Marcopper Mines (reprinted and modified from Rescan, 1989).

San Antonio development. Geological ore reserve studies indicate reserves of approximately 200 million tons at 0.44% copper with subsidiary gold and silver. "Copper mineralization at the San Antonio development is hosted in a medium-grained porphyritic hornblende diorite, located within the northwesterly-trending tectonically-active Philippine Mobile Rift Zone. The primary copper sulfide mineralization, consisting of chalcopyrite and minor amounts of bornite, occurs mainly as fracture-filling and disseminations within the medium-grained host rock, a near-surface supergene-enriched chalcocite zone is locally developed" (Rescan, 1989).

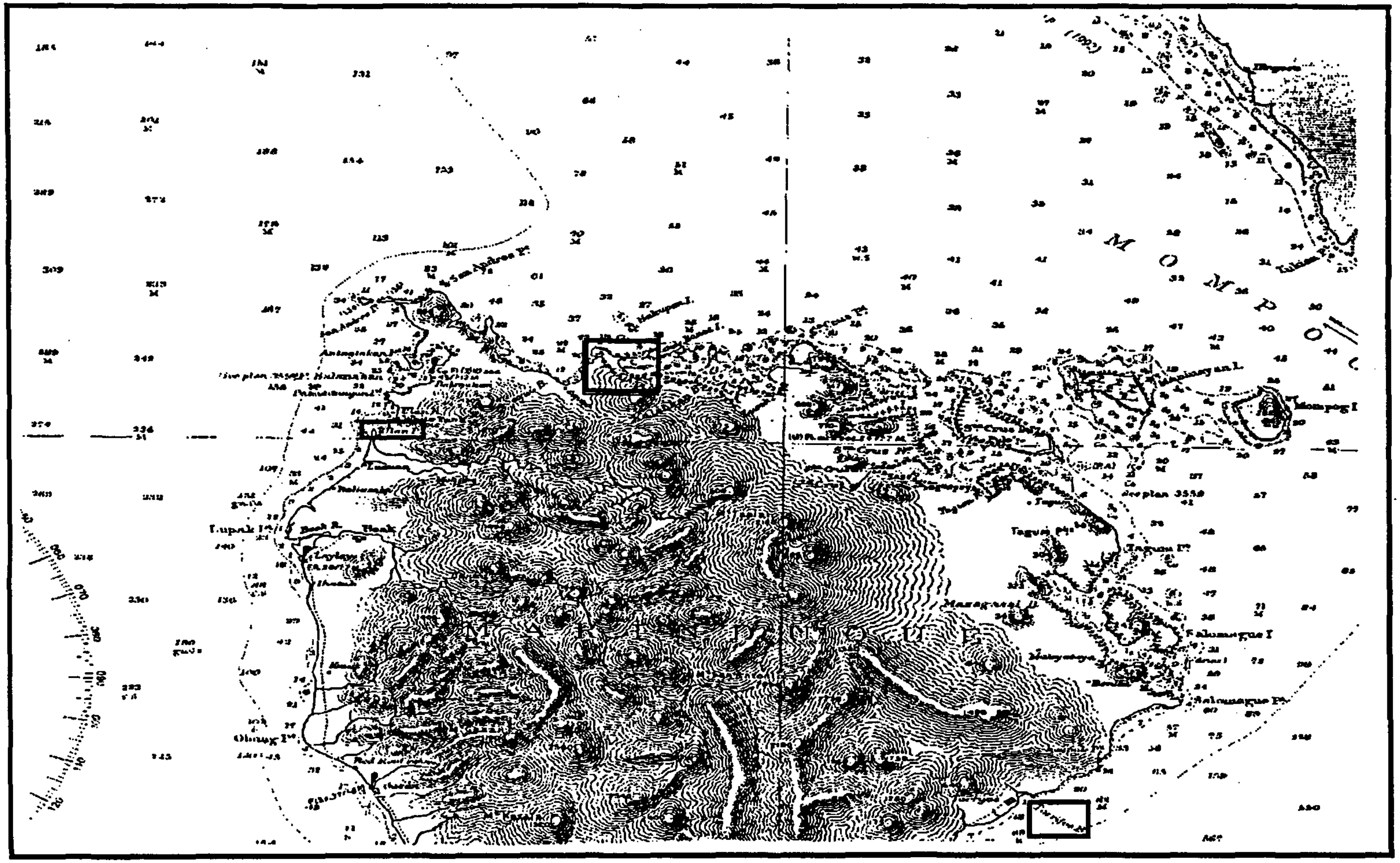

Figure 8. Coastal bathymetry for Marinduque Island (modified from Chart 3817). The 3 boxed areas are potential STD sites.

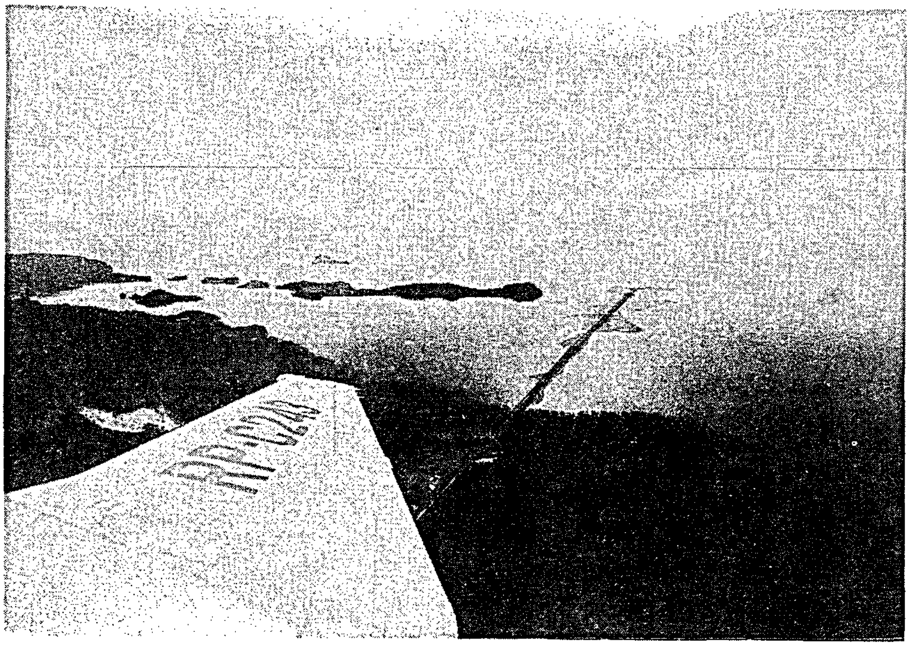

Figure 9. The tailings causeway for the Marcopper Mines and surface turbidity in 1981.

The proposed beneficiation process as described by Rescan (1989) consisted of a "primary crushing facility, a semiautogenous grinding (SAG) circuit, sand and slime flotation circuits, conventional three-stage cleaning, dewatering and combined land and marine disposal." Ore would be processed at a maximum rate of 30,000 t/d. A simplified process flowsheet is shown in Figure 11.

Bathymetry and tailings deposition to 1987 are shown in Figure 10. Monitoring routinely covered tailings deposition, plus some biological/fishery surveys by scuba diver, and surveys of trace metal contamination.

There appears to have been no formal community involvement initially, although there has been growing informal action, assisted by international agencies (McAllister, 1987; Velasquez, 1987). The latter document clearly shows local hostility generated to that time.

By 1989, Marcopper had commissioned a detailed EIA (Rescan, 1989) for the San Antonio development and STD (Figure 12). The recommendation supported previous concepts of backfilling the coarse tailing fraction to the Tapian pit, and STD for the fine fractions (< 50 μm). The proposal called for a deaeration chamber 4.2 km offshore (at the end of the causeway pipeline) with a submarine pipeline to 40-m depth 1 km further offshore. The discharge would be to a slope of at least 5% for 300 m distance. This slope was needed to prevent blockage from settling of the coarsest fraction. An incised channel would receive the finer-fraction density current and conduct the tailings to a broad area below 100-m depth approximately 5 km westward (Figures 12 and 13).

The environmental impact of the shallow-water tailings discharge to Calancan Bay was summarized by Rescan (1989). The causeway creates a major block to natural current flows. There is surface turbidity and deposition of tailings. The latter will have had substantial effects on coral and mud-bottom ecosystems, only the former of which had been documented to any extent (by scuba surveys). There has been some documentation of the recovering nearshore ecosystems in recent years (e.g., Trono, 1988) as the causeway has been progressively extended, and more of the tailings are swept offshore. Impact on fisheries cannot be determined, due to heavy fishing (some with destructive methods such as dynamite and cyanide) in the area, including close by the tailings plume. Trace metal contamination was generally slight, although oysters nearby have been detected with copper and zinc at levels of concern for human consumption; e.g., copper, 1950 ppm and zinc, 1310 ppm dry weight. There has been a reclamation program implemented on the causeway to control fugitive dust.

Rescan (1989) also noted the development of environmental monitoring. At that time monitoring had been extended from initial occasional marine biological surveys by scuba diver to a routine program. This consisted of monitoring chemistry of the tailings discharge and seawater, surveying local fisheries for yields and trace metals, monitoring tailings deposition by grab samples of the seabed, surveying the biodiversity of intertidal and subtidal biota, and bioassaying the effluent with *Tilapia* and milkfish.

In summary, the Marcopper Mine was developed initially with little environmental information and community involvement. Gradually the scope of EIA was widened and tailings disposal adjustments made. In the 1980s political conditions and social responses to the mine culminated in a temporary closure. By that time

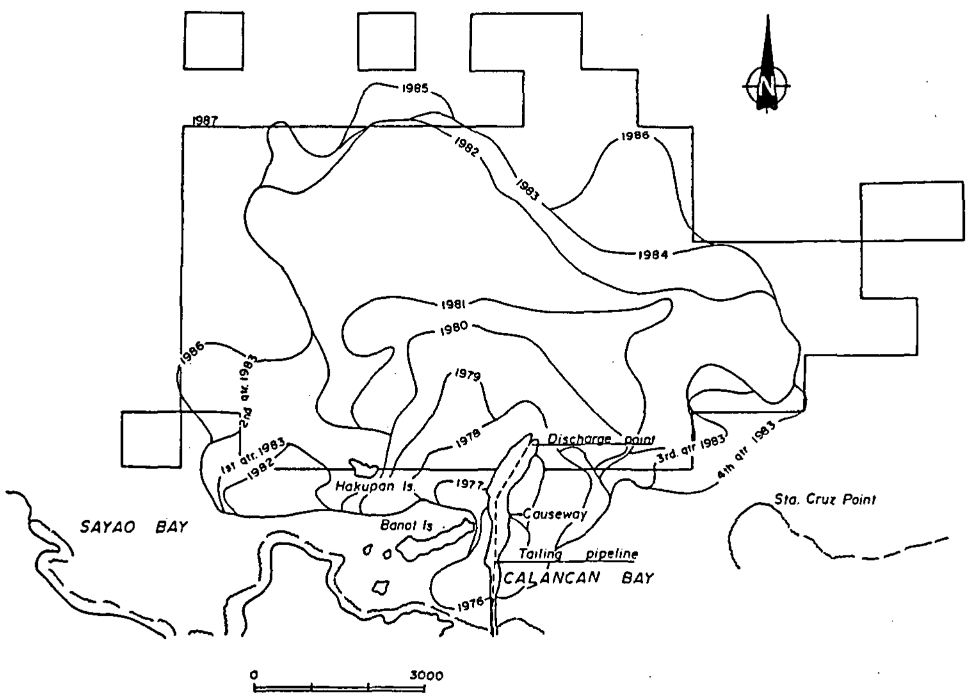

Figure 10. Extent of tailings coverage yearly from 1976 to 1987 from the Marcopper Mines (reprinted and modified from Rescan, 1989).

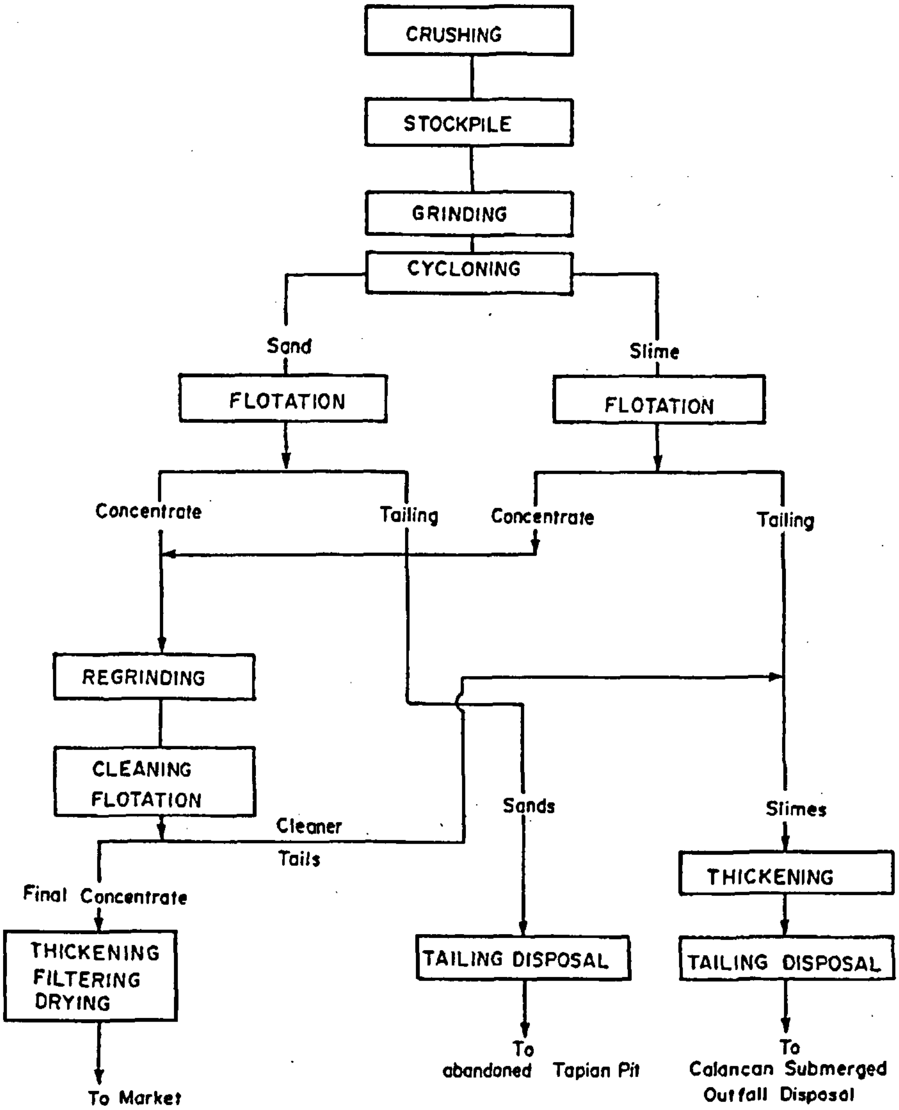

Figure 11. Simplified process flow sheet for the Marcopper Mines (reprinted and modified from Rescan, 1989).

the mine had twice sought engineering and environmental recommendations for tailings disposal by STD, but had not implemented the recommendations received.

The Potential for STD

STD has been identified for the Marcopper operations based on extension of the existing surface tailings disposal system. The causeway has already been extended to a distance offshore where it is sufficiently close to a potential STD site that engineering is practical. Environmental consequences if STD were implemented

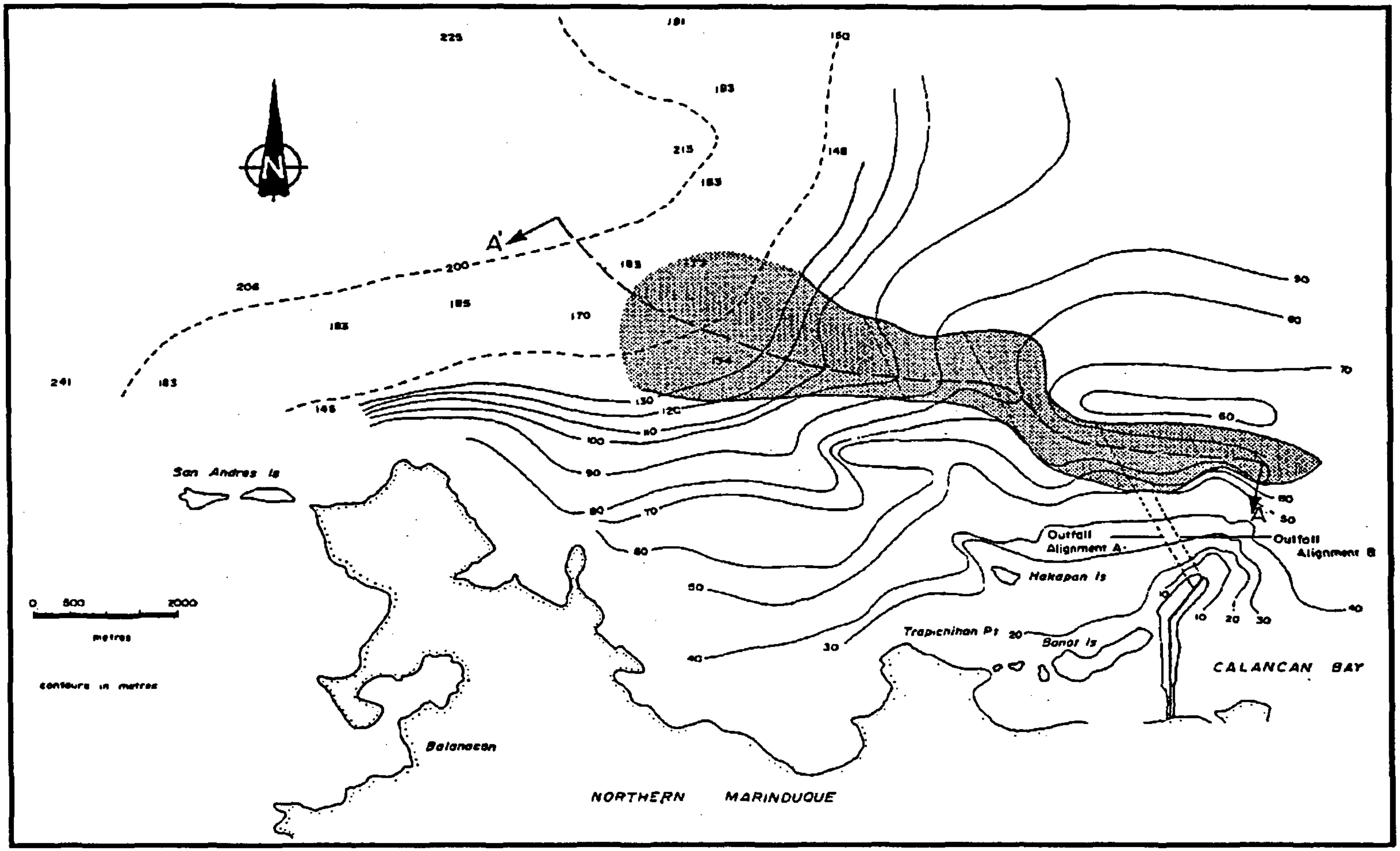

Figure 12. Predicted deposition of tailings slimes for the proposed STD from Marcopper Mines (reprinted and modified from Rescan, 1989). A′–A represents the thalweg.

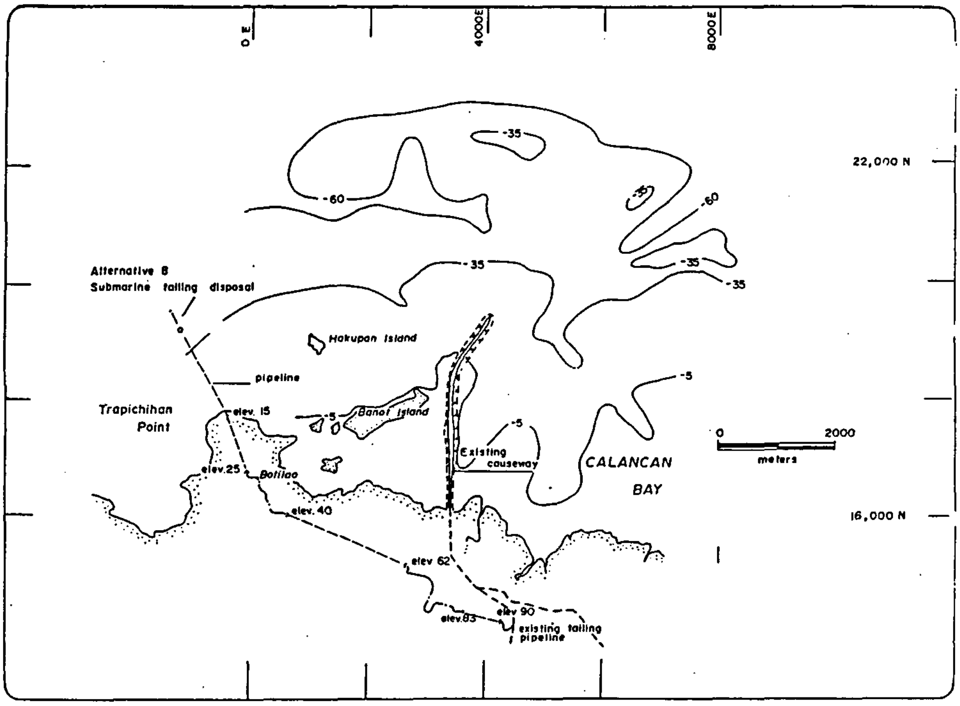

Figure 13. Potential site for STD from Marcopper Mines at Trapichihan Point (reprinted and modified from Rescan, 1989).

would be an improvement over those generated from the surface tailings disposal through the 1970s and 1980s.

Although the site for STD has been identified based on the prior disposal system, there are alternative sites available.

The existing on-land tailings line could have been extended a further 2 km westward to Trapichihan Point, where a steep gradient exists at the shore (Figures 12 and 13). The slope descends steeply to about 45 m and then becomes gentler. Use of this site would have required negotiations with owners and users of land over a further 2 km.

Marinduque is an island of maximum dimension only about 50 km. Any nearshore deep-water site is likely to be suitable for STD. Rescan (1989) identified one at Torrijos Bay 20 km distant on the east coast with 50-m depth water within 1 km of shore (Figure 8). Similar depths and distances would be involved to the west down the Ulan River to Ulan Point. Both sites would have required negotiations with land owners and users over an even longer distance than for Trapichihan Point as well as having substantially greater costs.

Bougainville Copper Mine (Papua New Guinea)

Bougainville Copper Mine (BCM) provides a case where a very large (and initially very profitable) open-pit operation, with river disposal of tailings, coincided (1970s through the 1980s) with social disruption, eventual regional anarchy and loss of central-government control, mine closure (in part because of danger to personnel), and write-off by the multinational involved.

There is continuing discussion about the cause and effect relationships among mining, social impact, and political instability, especially in the nearby nations of the Solomon Islands and Fiji with mining potential (e.g., Kabutaulaka, 1993; Wasi, 1993). No one wants another Bougainville.

The Mine and Its Environmental Impact

The mine is located inland, about 20 km from the east coast and 25 km from the west coast (Figure 14) of the island. It is at 670-m elevation, within 3 km of the watershed divide between east- and west-flowing rivers. It is approached by road from the east coast (Figure 15). This was built specifically for mine access and

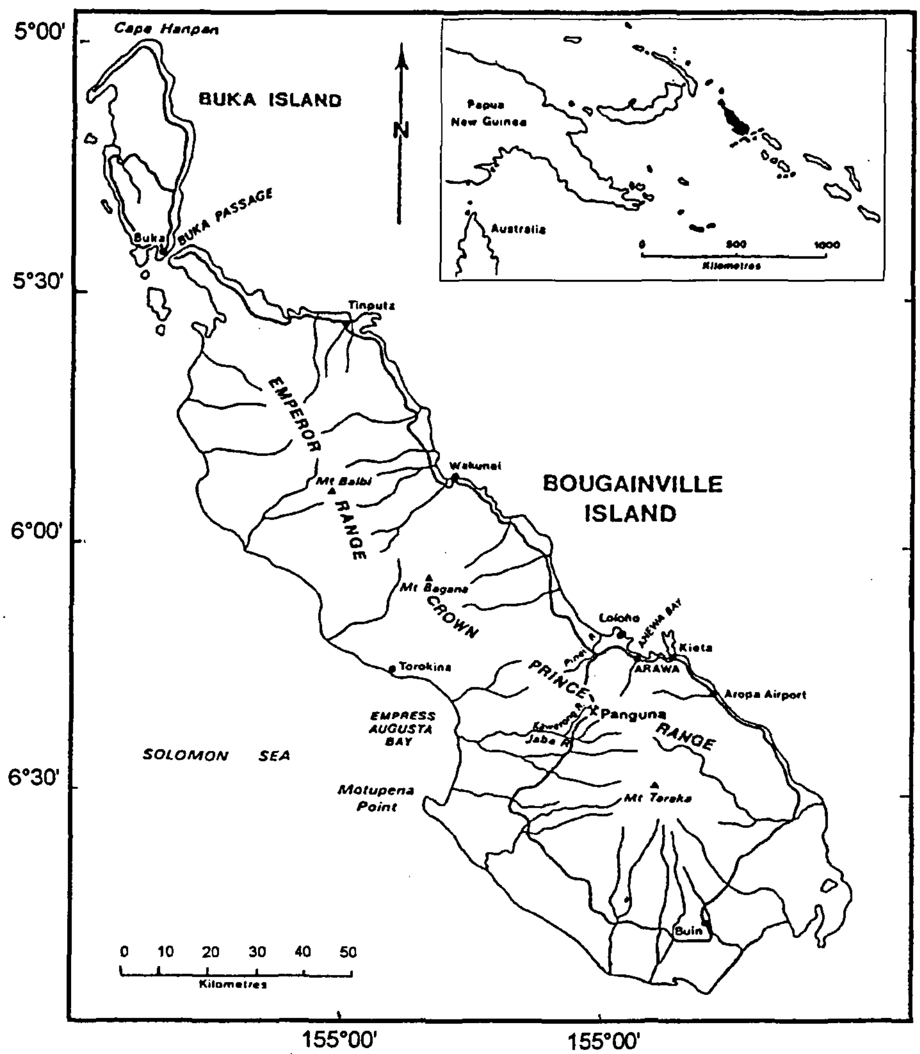

Figure 14. Map of Bougainville Island showing location of the mine (reprinted and modified from AGA, 1989).

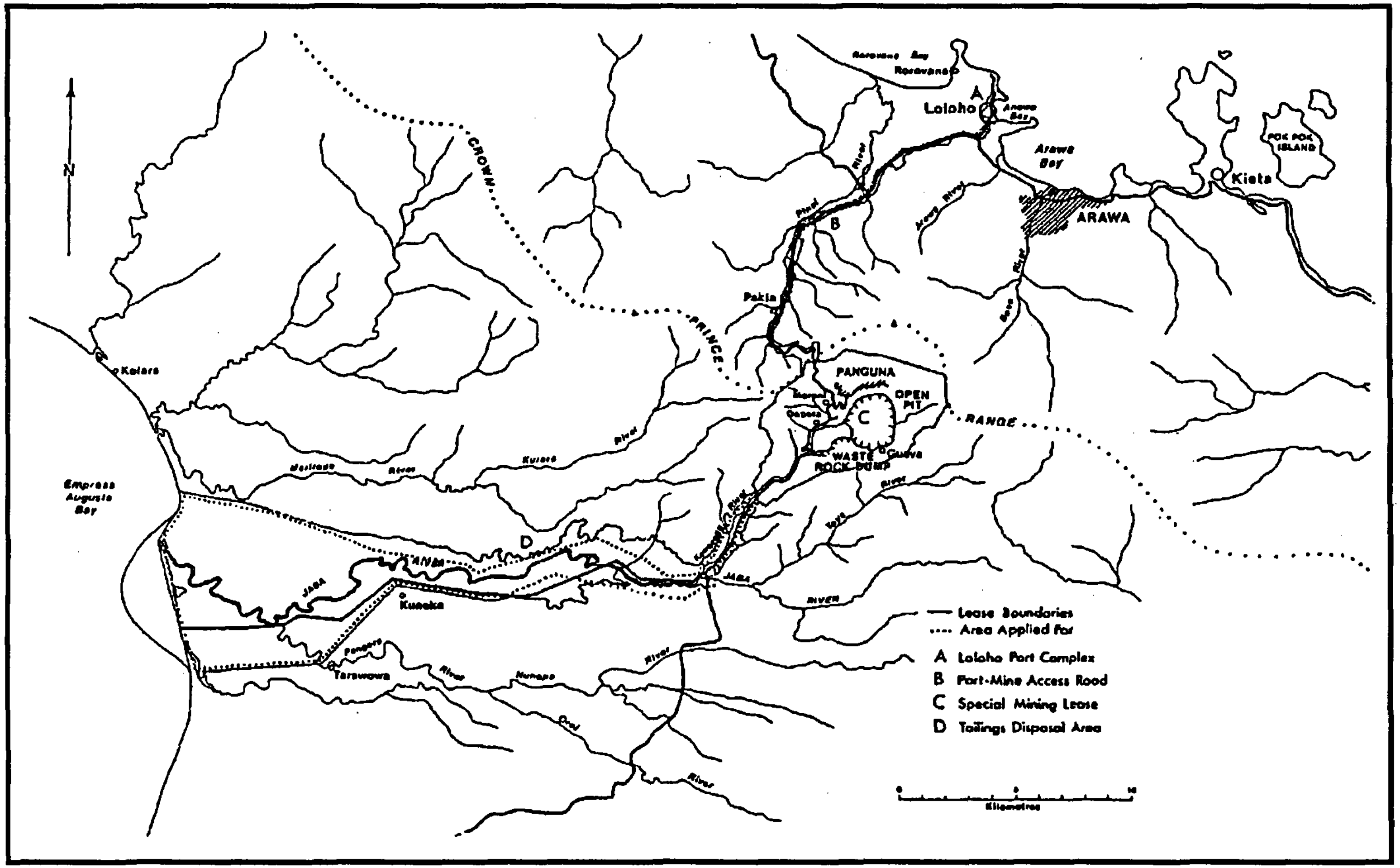

Figure 15. Arrangement of Bougainville copper mining operations (reprinted and modified from AGA, 1989).

required its own set of land use negotiations (Applied Geology Associates, 1989) independent of those for the mine area and the tailings route. The access road allowance also accommodated a concentrator slurry pipeline to the coast.

The mine is in steep, rugged highlands, supporting tropical rain forest with 4400 mm rain a year. There were some tribal people inhabiting the area and denser populations on both the eastern and western coastal strips. Residents have strong traditional rights over land ownership, use, and, inheritance. Even the initial prospecting generated some social conflict over land access.

The mine is described in a report from Applied Geology Associates (AGA) (1989).

> The Panguna ore body is roughly elliptical in shape and occupies an area approximately 2500 m by 1000 m to a depth of 300 m beneath the Kawerong Valley near its source. The deposit as originally defined comprised 950 million tonnes of ore grading 0.48% copper and 0.55 grams per tonne gold, about 3 grams per tonne silver and a trace of molybdenum.... The mine is a roughly symmetrical, cone-shaped excavation or open pit with benches stepping down from the lip... [it] is approximately 2.5 km across and 350 m deep.... Each day approximately 300,000 tonnes of ore and waste are blasted, excavated and trucked from the pit....
>
> The ore is selectively mined. Ore with disseminated copper is crushed for direct delivery to the mill and ore with copper in joints and fractures is upgraded in the preconcentration and screening plants (PCS). The ore at this stage contains 3% copper sulphides and 0.5 to 10% iron sulphides.... Flotation cells...stimulate frothing which selectively removes the copper sulphides on bubble surfaces. Gold and molybdenum are collected with the copper sulphides and are not separately removed.

Tailings (130,000 tons per day) were discharged to the Kawerong River, by pipeline terminating below the waste rock dump. The tailings then flowed into the Jaba River (Figure 16) and across the coastal plain where they partially silted out in two major basins (Figure 17). The remaining tailings eventually reached the sea in the shallow Empress Augusta Bay, whose maximum depth is about 60 m (Ellis, 1984, 1989b) (Figures 18 and 19) and formed an extensive delta. The two rivers had been effectively converted into a tailings flume, unconfined and flooding over the coastal plain during and after the frequent storms.

An extensive environmental monitoring program was developed during the mine's lifetime (Ellis, 1989b), although initially monitoring appeared to be directed at establishing compensation values for lost resources, largely river fisheries. There had been little marine environmental information available prior to operations. By 1989 AGA was able to report that monitoring encompassed hydrometeorology, sediment transport, chemical and biological monitoring, and revegetation investigations. Monitoring extended into the marine ecosystems on both coasts.

BCM environmental staff and consultants developed a number of predictive models concerning sediment deposition and trace metal leaching. These allowed selection, in the late 1980s, of an upgraded tailings disposal system from several possible options. By 1989 a tailings pipeline from the mine to the west coast at the existing tailings-derived delta on the west coast was under construction. It had

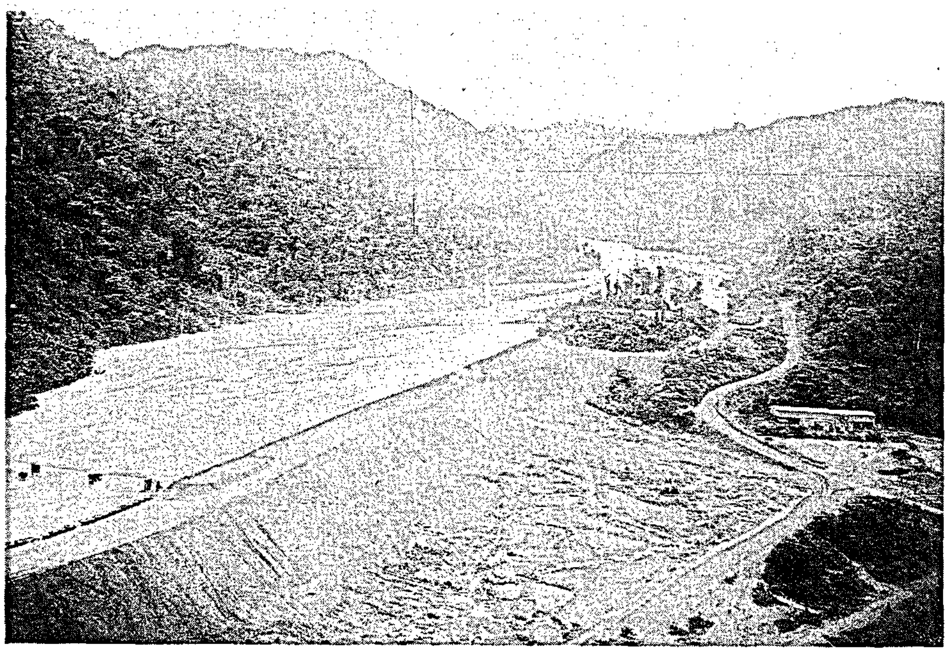

Figure 16. Tailings stream filling the Kawerong Valley downstream from the Bougainville Mine and depositing at the junction with the Jaba River.

Figure 17. Tailings from the Bougainville Mine filling the channel of the Jaba River and flowing to the west coast. Tailings deposition from flooding is being reclaimed.

Figure 18. Tailings from the Bougainville Mine form a delta in Empess Augusta Bay after flowing down the Jaba River.

been recognized that the tailings already deposited on land caused severe, and lasting, environmental problems—600 years was one estimate for continued leaching from the waste rock dump. AGA (1989) stated, "Stabilisation of the area may take tens of years, rehabilitation much longer."

There is an unremarked possible consequence of the upgraded tailings system extending the existing delta into Empress Augusta Bay. The extended delta, with substantial air and aerated shallow water exposure, would largely transfer the risk of trace toxin leaching from the land to the coast.

Initial community hostility to the original prospecting gave way to formal local community involvement as subsistance residents realised that their livelihood from vegetable gardens and fisheries in the Kawerang, Jaba, Pangara, and other rivers had been destroyed. There have been substantial relocation and compensation payments made during the mine lifetime (AGA, 1989). AGA lists stated concerns ranging from inadequate forewarning of substantial environmental losses and inadequate compensation to corruption in administration of a trust fund and health problems.

There is also an underlying belief in "kago,... the efficacy of supernatural assistance for the acquisition of material goods" (Oliver, 1981). In short there were substantial differences in perceptions and understanding between the mining company and land owners and users. These misunderstandings encompassed land use, the meaning of land alienation for mining, the value of compensation, and the eventual return of land.

On 7 January 1990 the mine started a retrenchment program. By 24 March 1990, BCM had withdrawn its employees from the mine site. Although it was able to protect its resources in the coastal towns at that time, the mine site was abandoned "as a result of militant activity" (RTZ, 1990). It is difficult to keep track of the political situation, but there is a secessionist movement on Bougainville Island that is being constrained by the PNG government (Kabutaulaka, 1993; Wasi, 1993).

In summáry, BCM originally discharged its tailings to a river system some 25 km from the sea. Tailings deposited *en route* and at the coast. There was considerable social disruption and growing local demand to compensate residents for lost subsistance livelihood. By 1990 BCM was developing an on-land pipeline to transport tailings onto the delta already formed. The delta would then prograde

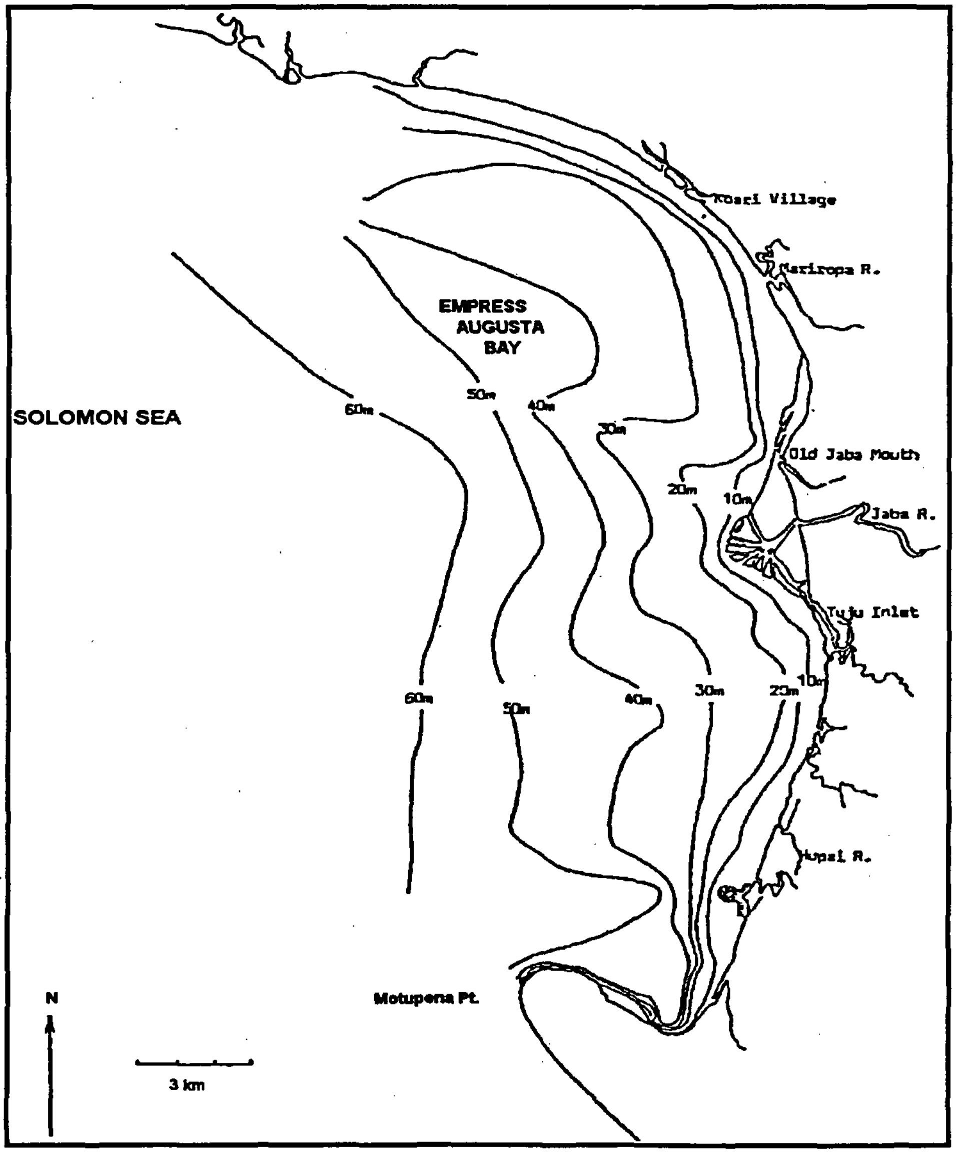

Figure 19. Bathymetry of Empress Augusta Bay, which receives the tailings from the Bougainville Mine (reprinted and modified from Powell, 1984).

out to sea within the shallow, silled Empress Augusta Bay. The mine was abandoned in 1990, due to "militant activity."

The Potential for STD

Figure 14 shows that the closest available area for STD is on the east coast near Kieta. Along this coast a fringing reef 1–5 km offshore marks the line of steep drop-off to several hundred meters depth. The concentrator slurry pipeline is within the road allowance, so potentially a tailings line could be installed there also. The slurry line uses a pump to pass the watershed divide, whereas the larger flow tailings line would need a tunnel. These requirements for on-land tailings transport are within those accepted at other mines, e.g., Atlas Copper Mine.

The west coast to which much of the tailings were discharged by river transport is more distant than the east coast (40 km down the Kawerong/Jaba River), and the deep eventual dropoff also more distant offshore (approximately 15 nautical miles) than on the east coast.

Empress Augusta Bay is a basin with limited, even if large, capacity for a tailings deposit. Also, the gentle slope of Empress Augusta Bay, i.e., 1 km for each 10 m out to 60 m (Figure 19), might be suitable for STD, but in principle is less attractive than the nearshore steep drop off to great depth on the east coast.

Adopting east coast STD at the time of mine development would have meant that the eastward impact would have been accentuated to some extent by adding construction of a second pipeline to that of the slurry line and the road. Negotiations would also have been needed with landowners and land users at the coast for an outfall site, with some preemption of land. However, the environmentally and socially far-reaching impact on the west coast could have been reduced to negligible levels and could have been constrained to the upper area of the Kawerong River. On the east coast, in contrast, design and construction of an STD outfall would not have imposed significant impact in the shallow water of the lagoon.

An environmentally sound STD system is dependent on there being adequate environmental knowledge and the potential to make appropriate social arrangements. It would have been very difficult to obtain these from the technical and social procedures available in the late 1960s and early 1970s. Misima mine (Jones & Ellis, 1995) shows that they are now possible.

In principle, the Bougainville Mine meets requirements for STD in terms of proximity to a coast with suitable bathymetry.

Jordan River Copper Mine, Canada

The small underground Jordan River Copper Mine is set back about 2 km from the coast in south Vancouver Island (Figure 20). Its quoted discharge rate of 100,000 IGPD of tailings per day converts to approximately 450 m^3/day. The mine was permitted to discharge its tailings by shallow discharge to a wave-exposed, high-energy, gently sloping nearshore shelf. The outfall was poorly located, designed, and constructed. It broke at least twice (Figure 21), and apparently other breaks went unreported (Elder, 1973). The causes for failures of outfall systems need to be considered in planning new STD systems.

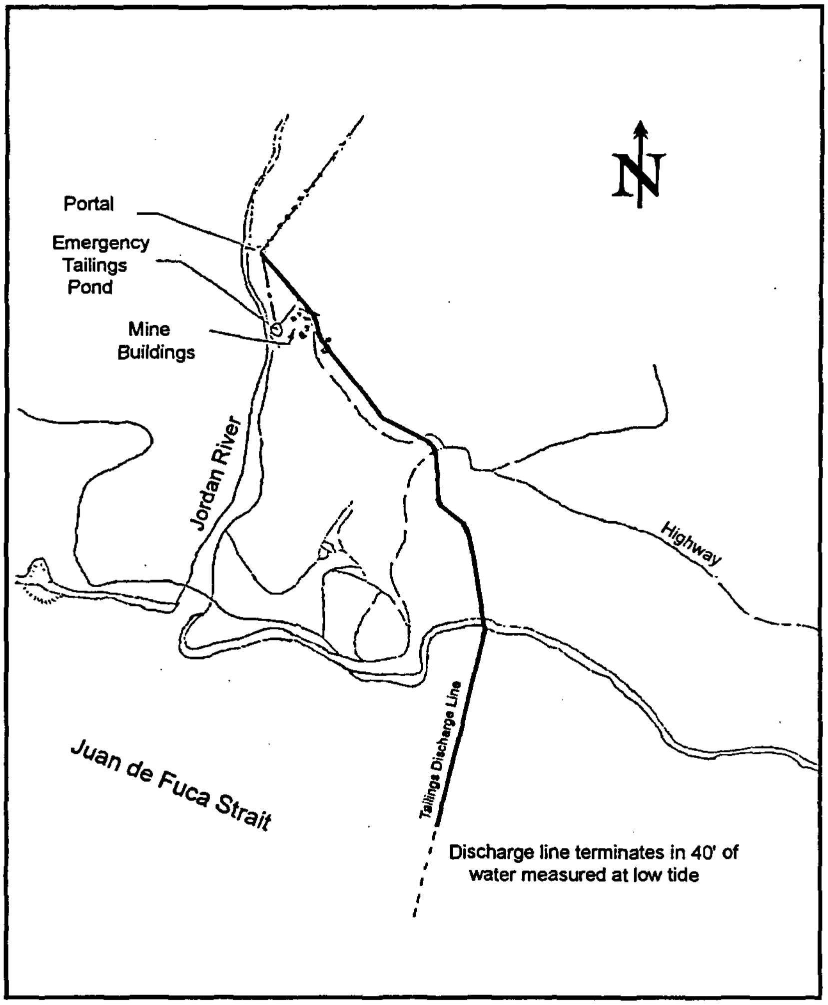

Figure 20. Map of the mine layout at Jordan River (reprinted and modified from Venables, 1973).

The Mine and Its Environmental Impact

The mine was last reopened in April 1972 after three prior short periods of operation, starting in 1962, by different operating companies and funding sources. Marine tailings disposal was terminated in December 1974 when the funding company placed the mine in receivership with an accumulated $2,000,000 debt (Bridges, 1978).

In 1962 reserves were evaluated as approximately 1 million tons of 1.54% copper and approximately 750,000 tons of 1.14% copper. The mill was placed underground and the tailings were pumped through a 15-cm line to tidewater, presumably at Outfall Point (Figure 22). Initially the tailings were the consistency of very fine sand, with 79.4% particles < 0.074 mm (minus-200 mesh), 11.2% $>$ 0.074 mm (minus-200 mesh), and < 0.10 mm (plus-200 mesh); and 8.5% > 0.10 mm (plus-200 mesh) and < 0.15 mm (plus-100 mesh) (Kilby, 1991).

Mine flooding was a constant problem during operations. It was the cause of several temporary interruptions and the first closure (1963). In part flooding was the result of insufficient geological knowledge or insufficient perception of risk by the operator in charge (Titus, 1978).

In 1972 a new 20-cm, high-density polyethylene pipe tailings line was installed to meet a 12-m discharge depth requirement set by the regulatory agency. The terminus, approximately 1 km offshore, was intended to discharge to a depression within Juan de Fuca Strait (Figure 21). After the failure of several attempts to bury the pipeline in a backhoe-excavated trench, the pipe was simply laid over the high-energy beach and subtidal shelf, anchored by concrete blocks.

The tailings line suffered one crisis after another, as there were engineering difficulties in installing the tailings line across the high-energy shelf. The line plugged and broke for the first time after only a few days of operation. A temporary permit allowed near-beach discharge while a new tailings disposal system was designed. Meanwhile the mine was brought to court (and fined) on a charge of releasing tailings to the river (the emergency tailings pond overflowed during a rainstorm). The final closure of the mine in 1974 was in part brought about by the cost implications of maintaining the discharge point initially required by the regulatory agency and later confirmed after application for a change.

The 1972 mill grind was also a very fine sand with 9.5% coarser than 100-mesh, 46.4% between 100- and 230-mesh, with the balance finer. Only 50–75% of the

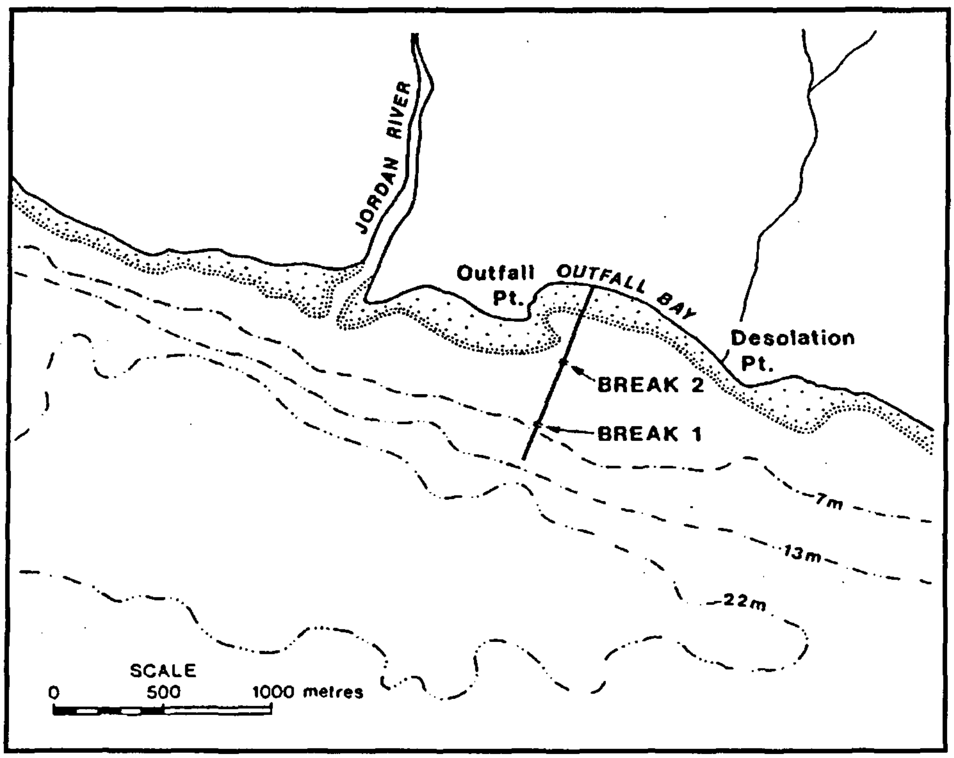

Figure 21. Positions of two documented breaks in the shallow water tailings outfall of the Jordan River Mine (reprinted and modified from Ellis, 1980).

Figure 22. A surface plume of tailings from the Jordan River Mine close to the intended discharge point.

tailings were estimated to deposit, with the balance suspended and dispersing (Littlepage, 1973). Figure 22 shows a surface plume from the original terminus, and Figure 23 an onshore drifting plume from a nearer-shore breakpoint. The latter was the discharge point from soon after operations started to closure, i.e., for about a year and a half.

A marine monitoring program had been designed, but the sampling stations based on the original discharge point became irrelevant after the first break (Ellis, 1975a, b). Progressive postponement of monitoring while waiting for the outfall to be replaced meant that little monitoring was achieved during the first year of operations. Finally, by the time of the mine's closure, it was determined that copper levels were higher near the outfall (250–1510 ppm) than at a reference site (15–16 ppm) 25 km down the longshore current to the east but no higher than prior to discharge in 1972 (Ellis, 1977; Ellis & Popham, 1983). The high levels appeared to be from prior operations. Nevertheless, by 1978 sediment copper levels had increased (70–100 ppm) at the reference station (Meidinger, 1978), presumably from longshore drift of the beach tailings deposits.

A similar conclusion was developed by Kilby (1991) in a detailed geomorphological analysis of nearshore sediments along the north shore of the Strait of Juan de Fuca (Figure 24). Longshore drift and wave action had formed a nearshore placer deposit (out to 800 m) with high heavy mineral concentrations (> 15% by weight), including titaniferous magnetite and ilmenite, which contributed anomalous values for Cu, Ti, Cr, V, and Mn and elevated values for Fe, Co, and Ni. The latter was apparently derived from the ball mill, and the others from the ore body. The placer extended from east of Desolation Point (Figure 21) along the length of Sandcut Beach (Figure 24).

After the tailings line broke and discharged, in effect, on shore, the breakpoint with discharge upwelling through the surrounding tailings was exposed at very low spring tides and created a safety hazard.

The extended smothering effect on local algal beds and rocky-shore organisms had, however, recovered by 1975. These are species that naturally are adapted to frequent high turbidities from storm river runoff.

At the time of mine development in the early 1970s, local attitudes toward the mine were mixed. There was formal opposition by environmentally concerned citizens (Elder, 1973), but a subsequent survey (Titus, 1978) stated that the main complaint about previous mining operations was that miners left without paying their bar bills.

In summary, Jordan River Mine was permitted to discharge its tailings at 12-m depth over a high-energy beach and wave-swept platform. The 20-cm pipeline,

Figure 23. Surface plume of tailings from the Jordan River Mine at the final break point drifts back onto shore.

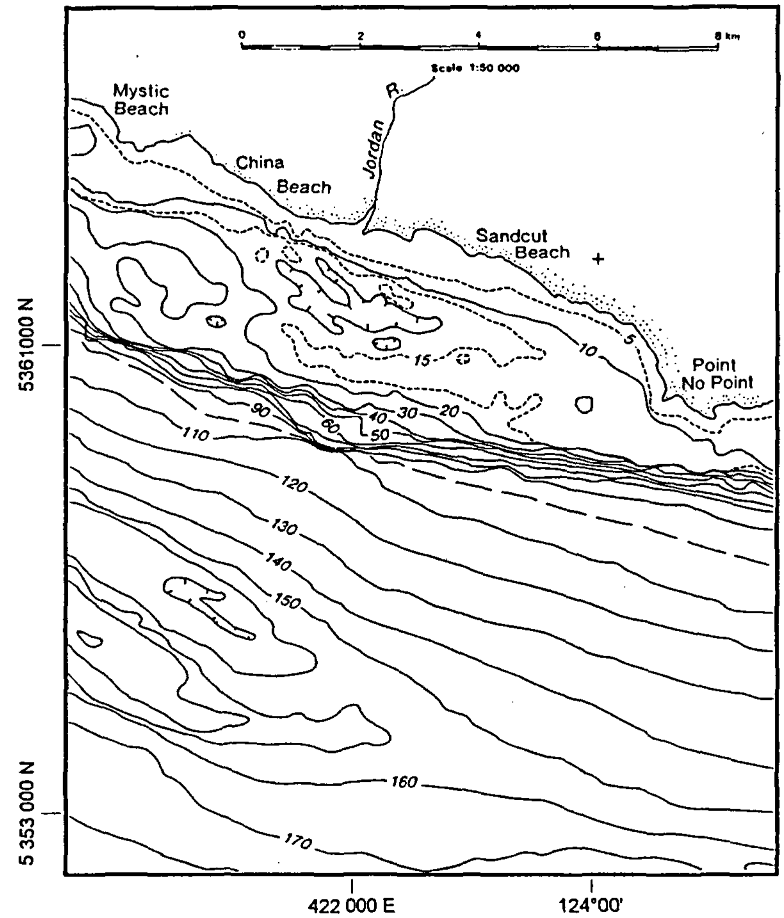

Figure 24. Offshore bathymetry in Juan de Fuca Strait near the Jordan River Mine (reprinted and modified from Kilby, 1991).

anchored with concrete blocks, was inadequate and broke several times. For most of the 1972–74 operational period tailings were discharged from the broken end at low tide level. There was consequent copper contamination of the beach and temporary biological impact.

The Potential for STD

The bathymetry in Figures 24 and 21 shows that there is no steep dropoff nearshore. There is a depression within accessible distance, but calculations using 1973 procedures indicated only 50–75% deposition potential with the fine grind used in the mill. New formulas for modeling tailings density current behavior (as developed at other mines) would provide better predictions than were available then. These would need to be used if the mine were to reopen and STD was considered an option for tailings disposal.

This modeling in turn would require considerable physical and sedimentological oceanographic surveys for input data. The state of such modeling appears now able to give reasonable predictions for slope gradients required to generate density current flow away from the end of the pipe, thus preventing blocking.

STD is a possible option for tailings disposal at this site, but considerable data gathering and analysis is needed to verify whether a proposal for STD should be adopted or rejected.

Conclusion

STD systems can be retrofitted in the sense of being designable and attachable to existing tailing disposal systems. Several of the screening criteria listed at the beginning of this article can be quickly applied as simple tests for retrofitting capability.

These screening criteria can be summarised as follows:

(1) A coastline with slope leading toward a final deposition site for the tailings.
(2) Accessibility of the coastline. Tailings lines more than 100-km long have been constructed and even longer may be technically possible. With increasing distance, however, engineering problems may escalate, especially if topography imposes need for tunneling. Social problems of conflicting land use and security may also escalate.
(3) A set of interacting technical and environmental criteria. It must be technically possible at the site to generate a tailings density current that will flow coherently to the final deposition site without suspension or resuspension and without upwelling to surface waters.

If such screening criteria indicate site suitability for STD in principle, then a retrofit conceptual design can be developed (Ellis et al., 1994).

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