A review of risks presented by

The Ramu Nickel Project

to the ecology of Astrolabe Bay, Papua New Guinea

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A review of the risks presented by the **Ramu Nickel Project** to the ecology of **Astrolabe Bay** in Papua New Guinea

A research paper commissioned by the Evangelical Lutheran Church of Papua New Guinea

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Sotpela Ripot

Dispela ripot i lukluk long sampela bagarap i ken kamap long solwara na ol samtin i stap long em, sapos Highlands Pacific Limited (HPL) i go het long pamim pipia bilong faktori i go insait long solwara, long Astrolabe Bay, long yusim Sabmarin Teilings Disposal (STD) sistem. Dispela ripot igat fea tokuat long painim aut bilong wanpela indipenden saentis tim husait igat bikpela save long we bilong STD sistem, na ol wankain sistem ol narapela kantri i yusim pinis.

Klostu long pinis bilong yia 2000, Evangelical Lutheran Sios insait long Papua Niugini (PNG), i givim tok orait long Australian Mineral Policy Institute (MPI) long wokim independent reviu long Envaironmen Plen bilong Ramu Nickel Mine. As tingting bilong dispela em bikos sios i kisim strongpela tingting long kamapim gutpela sindaun bilong ol pipel insait long Madang, na laikim tru bai behain taim projek i kamap, i mas gat gutpela developmen na envaironmen i noken bagarap tumas long Madang Provins.

Dispela wok bilong STD sistem i save kamapim bikpela bagarap long solwara na ol samtin save stap long em. Sapos dispela projek i kamap, ol mas skelim gut ol hevi o bagarap dispela kain wok bai kamapim, wantaim ol narapela we bilong putim pipia bilong faktori we bai envaironmen i ken stap gut na noken bagarap tumas. Gavaman bilong PNG ino bin skelim gut dispela as tingting long wanem, Envaironmen Plen bilong Ramu Nikel Projek ino mekim klia ol hevi STD wok bai kamapim, na tu Envaironmen Plen ino bin autim klia long ol narapela we blong putim pipia blong faktori.

Natural Systems Research i bungim na kamapim gutpela ripot na i lukluk klia. Tasol planti samtin ol i bin raitim i no bin stret long wok bilong Sabmarin Teilings Disposal. Ripot long Envaironmen Plen i laik soim olsem, STD em wanpela we tasol bilong rausim pipia bilong faktori, na bai ino inap bagarapim or kamapim hevi long solwara na ol samtin i stap long em.

As luk save long riviu bilong ol saientis i soim olsem Envaironmen Plen ino tok klia long wanem rot ol pipia igo insait long Astrolabe Bay. Long Envaironmen Plen, Natural System Research i bin usim wok save bilong ol yet long soim olsem pipia long faktori i pundaun na stap tasol klostu long Vitiaz Basin, tasol dispela ino tru. Olsem na igat bikpela askim long wok Natural Systems Research i mekim long hevi dispela STD sistem bai kamapim long ol pis na laip i stap long solwara long Astrolabe Bay.

Painim aut bilong ol dispela indipenden saientis i stap insait long dispela ripot i sekim wok bilong Natural Research System long Ramu Nickel Envaironmen plen. Ol saientific pepa long dispela ripot na ol samari long main ripot, long tingting bilong ol man i raitim, i soim olsem ino gat ol planti samting insait dispela eria:

- Wok ino inap,
- We bilong painim tinting bilong ol ino stret,
- Tok save i soim narapela sait piksa long wanem samting tru bai kamap,
- Ripot i sapotim wan sait aidia tasol,
- Igat sampela wari long sampela piksa long Envaironmen Plan

Executive Summary

Ol indipenden saientis husat it tok insait dispela ripot, em i gat bikpela wari bilong em i tingting Natural Systems Research i no lukluk gut long ol planti wok bilong em yet. Long wanen taim ol hevi bilong dispela wok i stap insait as tingting bilong saientis, em i tok, ol hevi bilong dispela project i no kamap long ples klia. Sampela kain hevi i kan kamap long hap we ol i putim pipia bilong faktori i kan bagarupim nambis, solwara, rip na kaikai long ol pis.

Long pinisim toktok bilong ol saientis ol i tok olsem, Natural System Research i no kamapim klia piksa long wanem samting rabis bilong faktori bai i wokim long solwara long Astrolabe Bay. Ol i tok olsem dispela kain samting ol luksave i hat long ol man long save long wanem samting ino kamap yet long ol long lukim na toktok long en.

This report examines the potential for ecological damage resulting from the Ramu Nickel Mine's preferred waste disposal option - the discharge of mill tailings through a submarine pipeline into Astrolabe Bay. Through the expert analysis of a team of independent scientists this document presents an impartial assessment of these risks, considered in the wider context of world-wide experience at Submarine Tailings Discharge sites.

In late 2000, the Evangelical Lutheran Church of Papua New Guinea commissioned the Mineral Policy Institute to undertake an independent review of aspects of the Ramu Nickel Mine Environmental Plan. This was motivated by concerns for the well-being of the Madang community and an underlying desire for both development and environmental protection in Madang Province.

There can be no doubt that disturbance on the scale of a Submarine Tailings Disposal operation will have significant biological impacts. If such a mining operation is to proceed, the potential consequences should be weighed against the environmental degradation which could result from both Submarine Tailings Disposal and other tailings disposal methods. The Government of Papua New Guinea did not have this option in regard to the Ramu Nickel Project as the Environmental Plan prepared by Natural Systems Research gave no indication of the likely impacts or risks associated with the proposal and did not thoroughly examine alternatives to marine discharge.

Natural Systems Research compiled a well presented but fatally flawed case for the discharge of mine tailings via a submarine pipe into Astrolabe Bay. The Natural Systems Research Environmental Plan attempts to show that Submarine Tailings Disposal is not only the best solution for tailings disposal from the Ramu mine, but that it is to the utmost degree, environmentally responsible.

The fundamental finding of this review is that the behaviour of tailings discharged into Astrolabe Bay is not adequately explained in the Environmental Plan. While NSR claim that tailings will be deposited safely on the deep-water floor of Vitiaz Basin, on the basis of their own data, this is extremely improbable. Overall, this deficiency sheds significant doubt on Natural Systems Research's predictions about the biological impacts of Submarine Tailings Disposal in Astrolabe Bay.

The independent review and scientific analysis contained in this report has examined the work of Natural Systems Research in the Ramu Nickel Environmental Plan. The scientific papers in the appendices to this report and the summaries in the body of the report argue that, in the authors' opinions, there may be deficiencies in that work, in the areas of:

- Inadequate data collection,
- Faulty methodology,
- Models that are contradictory,
- Highly optimistic scenario development, and
- Problems in the presentation of the evidence in the Environmental Plan.

The independent scientists are also of the opinion that Natural Systems Research may have overlooked numerous factors, including some of the field evidence upon which their reports were based. When these factors are accounted for, the evidence in the report leads to a conclusion that the risks associated with Submarine Tailing Disposal in Astrolabe Bay may be significantly increased, including the likelihood of contaminating the local reef system and parts of Astrolabe Bay with mine-derived materials.

In conclusion, Natural Systems Research has not presented a convincing scenario for the fate and impact of the tailings material. While it is remotely possible that the discharge of 100 million tonnes of mine tailings into Astrolabe Bay may have no impact at all, this is exceedingly unlikely. Neither Natural Systems Research nor Highlands Pacific can have any certainty as to the short and long term effects of Submarine Tailings Disposal on the ecology, fish, animal and plant life of Astrolabe Bay.

Introduction

The Ramu Nickel Cobalt Mine

A lateritic nickel deposit was discovered at Kurumbukari, a site south of the Ramu River, in the early 1960s and was owned by a succession of interests before management of the project was secured by Highlands Gold in 1992. In 1997 Highlands Pacific was established as a new company to manage the Ramu Nickel project on behalf of Ramu Nickel Pty Ltd (wholly owned by Highlands Pacific Limited) and Nord Australex. In November 1999 Nord sold their share of the project to Highlands Pacific. The Ramu Project, which is expected to cost US$838 million, is now 68.5% owned by Highlands Pacific and 31.5% owned by Orogen Minerals Limited.

Highlands Pacific Ltd (HPL) as manager of the Ramu Nickel Joint Venture (RNJV) is currently seeking funding and a joint-venture partner for the development of the Ramu Nickel Project. Components of the Ramu Nickel Project include:

- A series of open-cut mine pits and a benefication plant to produce ore slurry at Kurumbukari
- A slurry pipeline approximately 134km long to transport the ore slurry from the Kurumbukari mine site eastwards to the refinery plant at Basamuk Bay on the Rai Coast
- At Basamuk Bay, a refinery to produce nickel metal and a cobalt salt product using acid pressure leaching technology. An acid plant, a lime plant, a power station, a wharf, a limestone quarry and an accommodation area will be integral components of the Basamuk refinery complex
- A Submarine Tailings Discharge (STD) facility at Basamuk Bay for the disposal of tailings into the ocean at a depth of 150m.

Acknowledgement: A number of illustrations in this report have been taken from NSR's Environmental Plan.

- **Field Experience:** Ten research cruises in the Gulf of Alaska, three in the Coral Sea, and two in Indonesian waters, plus numerous minor field trips throughout the region.

2) Dr Gregg Brunskill – marine geochemist

- **Research Fellow** at the Australian Institute of Marine Science (AIMS) in Townsville, Australia.
- **Research Interests:** Marine geochemistry
  Chemical oceanography
  Coastal sedimentation

Australian Coordinator of Project TROPICS (Tropical River-Ocean Processes in Coastal Settings), which is a consortium of coastal oceanographers and marine geologists from Australia, Indonesia, Papua New Guinea, USA, and Japan. The goals of Project TROPICS are to describe and model the fate of wet tropical river inputs of water and sediment to the estuaries, continental shelf, slope, and abyss of New Guinea. Project TROPICS partners have had 7 research cruises (1996-2000) to the Sepik River estuary and Bismarck Sea, and two Indonesian cruises to the Mamberamo River estuary & coastal sea.

3) Dr Marcus Sheaves – marine ecologist

- **Lecturer** at James Cook University, Townsville, Australia.
- **Research Interests:** Ecology and biology of tropical mangrove, seagrass, estuarine fishes and invertebrates
  Coastal ecosystem health and conservation
  Ecology of stressed coastal ecosystems
  Trophic organisation of tropical mangrove seagrass and estuarine ecosystems patterns of biodiversity in tropical mangrove, seagrass and estuarine ecosystems
  The larval and juvenile ecology of tropical mangrove, seagrass and estuarine organisms

Terms of reference

The team was provided with a complete copy of the NSR Environmental Plan (1999) including all the research appendices as well as the reports produced by the University of Papua New Guinea and NGOs. This was exactly the same information that was available to the Government of PNG at the time of their approval of the Environmental Plan.

The team was tasked with the assessment of this material in relation to their own research and the scientific literature. Specifically, they were asked to provide reports on:

1) The confidence of the predictions made by the Environmental Plan itself in relation to the quality of the information used by NSR,

2) The risk posed to the ecology of Astrolabe Bay by the STD proposal.

This project was undertaken between November 2000 and February 2001 and the results were presented orally at a meeting for interested parties at the Gateway Hotel in Port Moresby on 8th February 2001.

Chapter 1

A **review of risks** presented by The Ramu Nickel Project to the **ecology of Astrolabe Bay**, Papua New Guinea

Note: This section consists of a synthesis of the consultant reports. While it is founded entirely on the findings of the scientists themselves, it does not purport to represent their views, or the views of the organisations to which they belong. The individual scientists' reports are presented in full at the end of this report.

Summary of findings:

The scientific conclusions of our experts suggest that Natural Systems Research (NSR) compiled a well-presented but fatally flawed case for the discharge of mine tailings via a submarine pipe into Astrolabe Bay.

The NSR Environmental Plan concludes that STD is the only feasible option for tailings disposal from the Ramu mine and that it is to the utmost degree, environmentally responsible. The NSR Environmental Plan suggests that tailings will uniformly travel from the outfall pipe to the abyssal plains of Vitiaz Strait where they will be safely deposited across 150km^2 of sea-floor. The Plan claims that heavy metals and other toxins will be immobilised by sulphide-producing chemical reactions and diluted by the addition of river sediment. It claims that the biota in the deep sea floor is biologically poor and therefore unimportant and that the deep-sea fish fauna is not utilised and will avoid contaminated areas anyway. Lastly it purports to show that the currents of the region cannot carry the tailings to the surface layers of the ocean, or for that matter a long way away from the discharge site. Unfortunately, on the basis of NSR's own data, the majority of these claims are either open to serious question or not supported by NSR's research.

Set out below is a summary of the independent review and scientific analysis that lead those experts to argue that there may be deficiencies in NSR's work in the Ramu Environmental Plan. Those deficiencies appear to be in the areas of:

- Inadequate data collection,
- Faulty methodology,
- Models that are contradictory,
- Highly optimistic scenario development, and
- Problems in the presentation of the evidence in the Environmental Plan.

The independent scientists are also of the opinion that Natural Systems Research may have overlooked numerous factors, including some of the field evidence upon which their reports were based. When these factors are accounted for, the evidence in the report leads to a conclusion that the risks associated with Submarine Tailing Disposal in Astrolabe Bay may be significantly increased, including the likelihood of contaminating the local reef system and parts of Astrolabe Bay with mine-derived materials

The **potential impact** of the **STD operation** in Astrolabe Bay:

The review was able to come to the following conclusions in relation to key subject areas.

The fate of tailings material

The proponents of STD acknowledge that a successful operation requires that tailings are permanently deposited in a deep-water environment. After deposition, physical oceanographic forces such as upwelling or lateral currents must be so slight that tailing fines are not resuspended or upwelled into the euphotic zone. Neither of these requirements are present in Astrolabe Bay.

Overall, the Environmental Plan does not contain adequate information to assess the feasibility of environmentally responsible deep-sea tailings disposal in the Basamuk Bay and Vitiaz Basin. This is exemplified by the several major inconsistencies in the Environmental Plan. The Environmental Plan makes the following predictions and conclusions;

1) The refinery tailings will flow along the bottom to deep water in the Vitiaz Basin with little mixing or upward movement to the euphotic zone, will be trapped in the sediment as sulfide minerals, and will be diluted and covered by natural river sediment,

2) Seawater mixing will dilute the refinery waste to acceptable water quality standards within several kilometres of the pipeline orifice,

3) Deep water Vitiaz Basin sediments are non-sulfidic, oxidizing, and of marine origin,

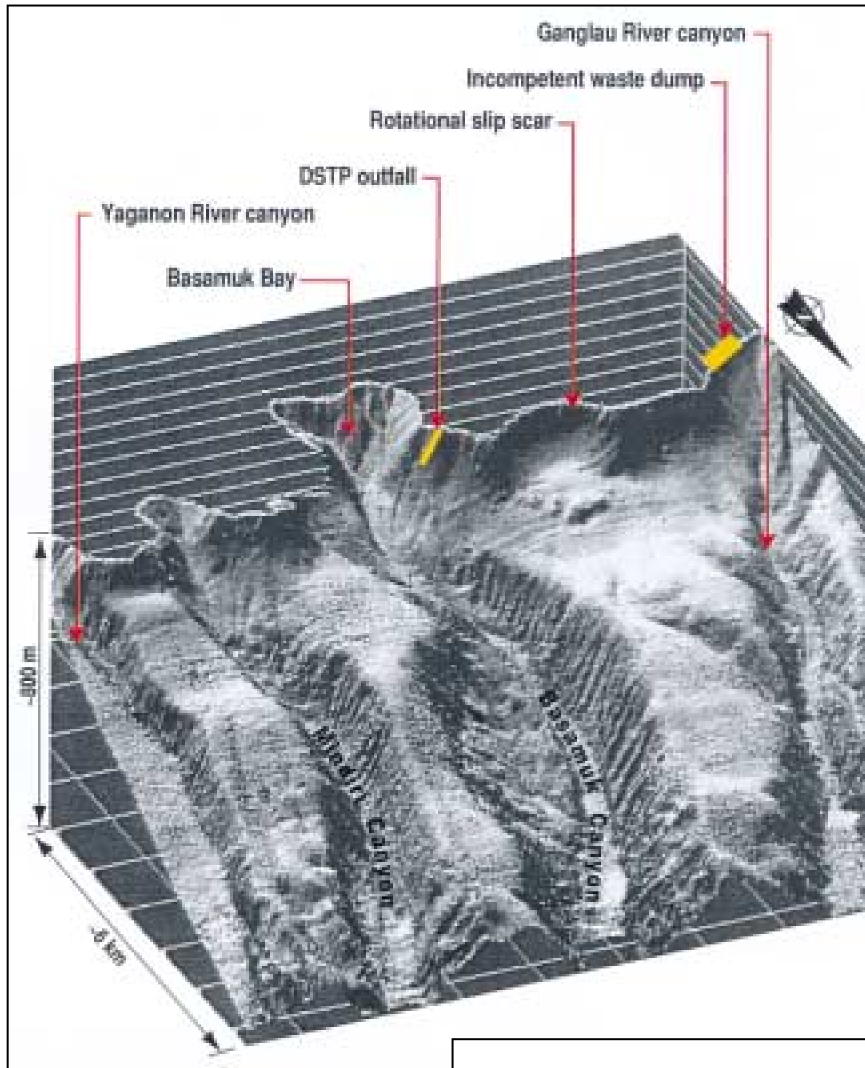
4) Deep water currents in the Vitiaz Basin are flowing at a speed that will erode fine sediments faster than expected deposition rates, and

5) The natural Astrolabe Bay river sediment is not deposited in the Vitiaz Basin.

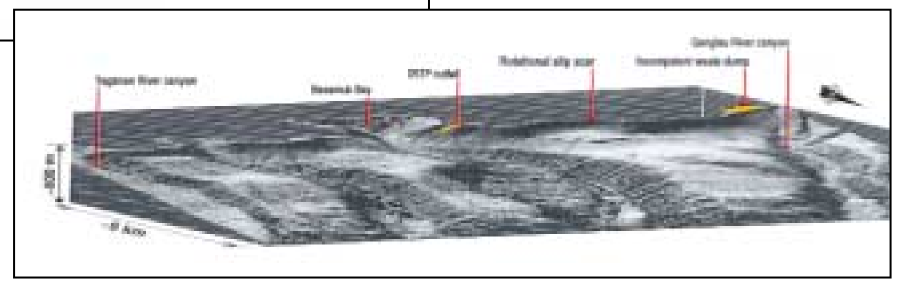
These predictions are contradictory. Point 1 is not consistent with any of the other points and in parts of the Environmental Plan, points 1 & 2 are used interchangeably. When the NSR Environmental Plan suggests that the tailings will be safely deposited on the sea floor the conclusions in point one are used. Point 2 is used when NSR wants to demonstrate that tailings will be rapidly diluted on discharge and therefore toxic concentrations will not occur at a certain distance from the outfall. Of course it is not possible for the tailings to be deposited on the sea floor and diluted in the water column. Based upon this information, it is unlikely that the Ramu tailings disposal plan will function as described by NSR

The Environmental Plan contains no useful information on sedimentation rates and sources of sediments in the Vitiaz Basin. The information provided, which is based on very few samples for such a large area, suggests that most of the deep basin sediments are not from the local rivers of Astrolabe or Basamuk Bay, but are largely volcanic glass, diatom frustrules, iron oxide gels, carbonate skeletal remains, and small proportions of terrestrial clay minerals. Based upon this, there is little evidence to suggest that mine tailings from the Basamuk Bay tailings outfall will reach the Vitiaz Basin and there is no evidence whatsoever that natural sediment will dilute tailings thereby reducing their bulk toxicity. Even if tailings were deposited on the floor of Vitiaz basin and not carried immediately to the north-west, it may take centuries for the tailings to be diluted by natural sediments.

The scientific consultants reports contained in this publication conclude that it seems more likely that the majority of tailings will accumulate in the nearshore canyons and inter-canyon platforms, and be transported to the west towards Madang in the New Guinea Under Current at about 1 metre per second. A proportion of the tailings will probably be re-suspended and enter the surface levels of the ocean in the vicinity of Basamuk Bay and the wider Rai Coast. An additional quantity will separate from the main tailings flow and form plumes that will travel away from the outfall at the different levels in the water column.



In the Environmental Plan, NSR uses three-dimensional images to show the submarine topography. In the graph to the left, it is easy to be impressed by the depth and steep walls of this canyon. However if the horizontal and vertical scales are made comparable, a very different picture is presented. The picture below shows the Basamuk Bay area with equal x and y scales.



[12] Ramu Nickel Environmental Plan, 1999. Volume 3, Appendix 9.

[13] The sedimentation rate was estimated at <0.1kg m-2 yr-1.

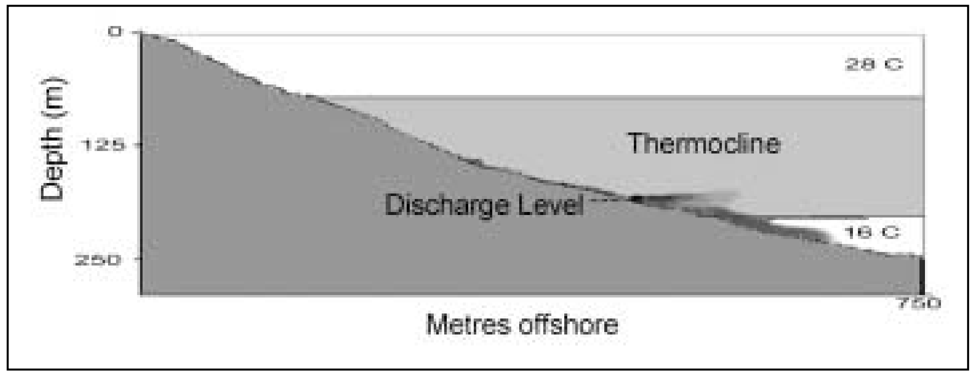
Current speeds in deep water of Vitiaz Basin were estimated by the NSR environmental plan to be in the range 20 – 40 centimetres per second. Their flume study on tailing sediment indicated that the threshold for current erosion of particles was 17-40 centimetres per second, and the seabed erosion rate is estimated to be approximately 160kg m-2 yr-1 at this current speed[12]. This erosion rate is about 1000 times faster than the expected sedimentation rate[13]. Based upon this information, it is unlikely that all the fine-grained tailings will stay in place on the Vitiaz Basin seafloor. Hence even if tailings were to reach Vitiaz basin, itself an unlikely proposition, they would be rapidly resuspended and carried to the north-west.

Of critical importance, there exist convincing data in NSR's own research showing mechanisms that could transport tailings into the surface waters. **NSR's data strongly suggests that upwelling occurs in the vicinity of Basamuk Bay.** There exists a substantial current onshore from the depth of the STD outfall that has the potential to carry tailings material rapidly to the surface regions of the sea. This upcanyon current, moving directly onshore near the seabed at the out fall site was observed but not commented upon in the Main Report of the Environmental Plan. This current was observed by NSR to move at 0.9cm/sec, or 0.8km per day. If this current brings STD material to the surface, the potential for ecological damage will be greatly increased. Despite this evidence, NSR concluded that upwelling did not occur near Basamuk Bay. This was partly due to their reliance on satellite imagery. Unfortunately the pixel size of these images was too large to observe upwelling between the outfall site and the coast even if it was occurring. Further, their analysis was highly skewed towards the months of the SE Trade winds when upwelling is least likely.

Even in a 'best-case scenario', STD material will not simply be deposited over a clearly demarcated area of the seabed. Instead some fraction will enter the ocean over a range of depths and will be transported as patches of turbid water well out of the source area.

These 'turbidity plumes' will spread out horizontally from the descending tailings plume and are likely to be more extensive in this project than at the Misima mine where as the tailings are denser. Turbidity plumes are likely to form small scale eddies that could maintain their chemical identity (hence high concentrations of tailings) over tens if not hundreds of kilometres. These patches will be anything from tens of metres to tens of kilometres in diameter. When this occurs, the potential for ecological damage over the wider Astrolabe Bay region will greatly be increased.

Aside from STD impacts, the dumping of waste rock and soils directly into the coastal bay will probably generate turbidity in the surface mixed layer near shore, as was found at the Misima mine[14]. This deliberate addition of waste material to the surface mixed layer of coastal waters seems totally unnecessary and environmentally irresponsible.



Diagrammatical representation of a hypothetical tailings plume. Note the turbulent cloud at the discharge level and the thin layer separating at the base of the thermocline.

[14] NSR Environmental Consultants (1999). Review of the Coral Reef and Nearshore Environment, Misima Mine PNG, NSR, CR 206/22/v6

The toxicity of tailings

The annual addition of 5 million tonnes of hot tailings slurry to the 150 m depth zone of the Basamuk Bay slope for over 20 years will create a shelf-edge zone of very unusual seawater chemistry within a radius of about 1km (landward and seaward) of the pipeline orifice. In this mixing zone there will be very high concentrations of ammonia (being oxidized by bacteria to nitrate), sulfate, manganese, and enhanced metal concentrations (nickel, chromium, cobalt, mercury, and cadmium) in the dissolved phase. As previously discussed, this turbid water mass will be moving west or north west at about 1 m/sec and will probably be distributed over several of the coastal canyons.

Very high concentrations of ammonia, iron and manganese will likely occur in the pore water of the tailing plume and seabed deposits. While NSR believes that deposited tailings will be anoxic and that metals will be immobilised through their conversion to sulphides, there is no evidence to support this proposition. The redox status of the fluid mud current and deposited tailings pile will be very complex over a 20+ year period of additions, with very large oxidation power from the high concentrations of manganese and iron hydroxides. Some release of all varieties of trace metals in tailings to oxic and anoxic pore water and oxic overlying sea-water can be expected. **Consequently benthic organisms in the vicinity of the seafloor tailings will accumulate excess metals from tailings pore water solution and by ingestion of sediment particles.**

Biological impacts

In regard to marine biology, the NSR Environmental Plan suffers from two major problems; a lack of detailed biological assessment of deep-water fauna and tendency to base evaluations on best-case situations. When the deep water environment is intended to be the site for the repository and impact of some 100 million-tonnes of tailings, the acquisition of clear, strongly supported, accurate base-line information on deep water systems is critical. Given the lack of worst-case evaluation and the poor quality of the biological data, it is not possible to make accurate predictions of the likely effects of toxins that are specific to the Ramu mine project. **This means that the EIA predictions are probably over optimistic, and, in the case of the deep-sea fauna, without substantive foundation.**

The high likelihood of entrainment of tailings into the water column and their movement both on shore and north-westward by the prevailing currents means that it is inevitable that they will have an impact on the ecology of Astrolabe Bay – but in the absence of the necessary oceanographic and biological data, the extent and severity of this impact is completely unknown.

Shallow water fisheries:

Sampling of fish in the shallow water region was sub-optimal, especially for those species that are seasonally abundant, nocturnal, or those that are active predators. For this reason, NSR's shallow water impact predictions need to be treated with caution. The fish fauna of the shallow waters off Basamuk are largely those characteristic of clear water areas. If sediment levels in coastal waters were to increase substantially there could well be serious consequences for the fisheries stocks in the area. Even without considering the presence of toxic materials, a substantial increase in turbidity, especially if it was maintained for an extended period, would be likely to exclude many of the species that rely on clear water conditions from the area. This is likely to be the case for a large proportion of the species recorded by NSR. Given the intention of the developers to dump waste rock and soil directly into Basamuk Bay and the likelihood of upwelling bringing tailings to the surface, significant impacts on the shallow-water fish fauna should be expected. In the case of Misima, coastal impacts occurred for a distance of 5km on either side of the mine. This should be expected at a minimum to the east and west of Basamuk Bay.

Deep water fisheries:

For numerous reasons NSR's sampling was totally inadequate to represent the deep water fish community and as a consequence the fish fauna of Astrolabe and Basamuk Bays remain undescribed. The fact that only 42 fish of 12 species were caught over a total period of 24 hours, over 10 days, does not support NSR's claim that it possesses an adequate base-line data set.

What types of fish live in the area? Do they occur in large numbers? Are there major unidentified deep-water fisheries resources in the area? Is the area an important spawning ground for any species? These are vital questions that remain unanswered. Their importance clearly illustrates that an extensive spatial and temporal evaluation of the fish fauna should have been conducted as a basis for determining the suitability of the area as a tailings discharge site.

It is inevitable that plumes of tailings will develop along density interfaces allowing substantial quantities of tailings to separate from the primary flow and spread out horizontally. It is also probable that tailings will enter the surface waters through their interaction with shoreward currents, and it is almost certain that deep-sea currents will carry tailings rapidly to the north west. Each of these scenarios present separate mechanisms whereby mid-water fish and invertebrates will come into direct contact with tailings material. In the Environmental Plan, NSR makes no evaluation of this impact on the fishery or other marine organisms.

As in many of their reports[15]**,** NSR claims that the impact on the local fisheries will be minimised because fish exhibit 'Avoidance Behaviour' – that they detect pollutants in the water and swim away from them. To support this claim, NSR regularly cites a paper titled "Avoidance behaviour by fish: a literature review"[16]. Whether or not fish can detect and respond to tailings plumes is important because of the assumption that fish will move away from the tailings plume, so limiting the adverse effects on fishes to displacement rather than direct mortality. Despite numerous citations in NSR Environmental Impact Assessments, NSR has declined to release the document for public perusal or discussion.

Through an assessment of the science of 'avoidance behaviour', this report concludes that there are no clear data available on the ability of particular species to avoid tailings plumes. Although fish do seem to avoid mine-derived settled sediments, there appears little hard evidence that fish actively avoid tailings plumes. Consequently, it seems that rather than assuming that fish will actively avoid plumes, it would be better to take a precautionary approach and assume that fish will come into contact with tailing plume sediment. Again this seems a situation where some attention could have been paid to a "worst-case" assessment. A "worst-case" assessment would also need to consider the possibility that if a plume developed at the tailings outfall, numerous shallow water fish would be impacted, including some current and/or potential fisheries species.

[15] See for example their work on Misima and Lihir in PNG.

[16] Prepared by NSR for Placer Pacific. CR206/15/v3

It must be stated that even the avoidance of tailings plumes may cause ecological problems. As has been discussed, turbidity plumes are likely to form as sediment breaks away from the tailings stream at discontinuities in the water column and/or onshore currents may transport turbid water to shallow depths. Oceanic fish, such as tuna and billfish, are sensitive to turbid waters and actively avoid them. Tuna is a very important commercial species in Papua New Guinea, supporting a large harvest by distant water fishing nations and a developing local fishing industry. Tuna are highly migratory, regularly covering large distances, often along predictable migratory routes. Consequently, given their tendency to avoid turbid waters, the potential exists for turbidity plumes to disrupt migrations or impact on spawning aggregations or nursery grounds. The potential for human activities to adversely affect bluewater fishes, particularly during their early life stages is already of concern in the western Atlantic Ocean.

In regard to the poisonous components of the tailings, it is known that ammonia, together with a variety of nitrogenous chemicals and metals in the dissolved and particulate forms, can also be acutely and chronically toxic to fish. Estimating the exact concentration of ammonia that will produce toxic effects is difficult because different species of fish show different tolerance levels. Even at concentrations below those producing acute toxic effects,ammonia can produce sublethal effects such as reduced growth and gill damage. Sublethal effects, such as reduced growth, have the potential to reduce the health of fish including their reproductive success and fecundity. Such effects are likely to occur within a kilometre of the tailings outfall and have the potential to occur at much greater distances depending upon which scenario(s) for tailings dispersion are in operation.

Sea-floor biota:

According to NSR, it is the benthic biota that is most at risk from the STD operation. They predict that it will be smothered and subject to tailings toxicity over an area of 150km_. One would therefore expect that this biota was well sampled, especially given that it is one of the few types of deep water fauna that "can be sampled with anything approaching statistical rigor"[17].

Unfortunately NSR's sampling of the deep sea floor was extremely poor. In the words of the experts used by NSR to identify the collected benthic fauna, the sampling gear used was *"...an inefficient collecting method for benthic invertebrates"*[18]. Further, the samples were sieved resulting in the loss of very small organisms (nematodes etc) from the samples. Lastly, so little sampling was undertaken that there was no likelihood that the effort could adequately represent the deep-water benthic fauna. In total, only 8 sub-samples were taken, from 5 separate samples. Of these, only one was taken at a depth greater than 800m even although the NSR environmental plan expects most of the sediment to settle at between 1000m and 1,600m water depth.

Taken together, these two factors (inefficient sampling gear and insufficient sampling intensity) suggest that the conclusions drawn about the benthic fauna of these regions (e.g. that they are biologically poor) and their trophic roles (e.g. that they are dominated by deposit-feeding polychaete worms) are without any substantive basis. In fact the sampling gear and sampling intensity were never likely to be sufficient to lead to accurate estimates of abundance. Further, simply identifying the trophic groups of benthic

[17] Gwyther, D., 1998. Ecological aspects of deepwater submarine tailings placement - a risk weighted perspective. Presented for Dames & Moore, Workshop on Submarine tailings placement, Bandung, Indonesia, 5-6 August, 1998.

[18] Ramu Nickel Environmental Plan, 1999. Volume 3, Appendix 3.

organisms could shed little light on their role in the food chain because no attempt was made to sample their potential predators. Consequently NSR does not have sufficient data to come to firm conclusions about the composition of the benthic community and is therefore not in a position to determine the role of this community in the ecosystem of Astrolabe Bay.

The extent to which sediment dwelling organisms are at risk from the ingestion of tailings particles remains a concern. As NSR itself admits *"...benthic organisms on the periphery of the depositional zone and recolonising organisms after tailing deposition ceases will be exposed to tailing solids containing elevated concentrations of metals ...chromium, nickel and mercury..."*[19] not to mention extremely high levels of ammonia. While NSR argues that this is unimportant as the tailings will be diluted by other sediments, there is no evidence to support this conclusion.

Overall there remains little doubt that benthic organisms in the vicinity of the seafloor tailings will accumulate excess metals from tailings pore water solution and by ingestion of sediment particles. However the implications of the contamination of sea floor organisms for the health and viability of the local and regional ecosystem remain unknown.

[19] NSR (1999) Ramu Nickel Project, Environmental Plan. Prepared by NSR Environmental Consultants Pty Ltd, Victoria, Australia.

Oceanography

1) The near shore zone (from shoreline out to the outfall) was ignored in field work and upwelling analyses. This was partly due to the use of satellite imagery with a pixel size greater than this area of interest. This factor, amongst others, meant that NSR's research could not have shown upwelling occurring in this region.

2) During the NW Monsoon, the time of year when upwelling is at a maximum, only one satellite picture was obtained and it is likely that the interpretation of this was flawed because of afternoon heating of the sea surface.

3) No cross-sectional plots of water properties were provided in the Environmental Plan. These would have been a key to understanding upwelling and the onshore currents found during the deployment of the current profiler.

4) The CSIRO oceanographer employed by NSR[20] deduced the presence of 100m amplitude internal waves oscillating around 100m depth. The implications of these waves were not commented upon by NSR. They could easily act as periodic pumps to bring a fraction of the STD slurry to much higher levels, where other identified processes could bring it higher yet.

5) The numerical model for tailings deposition did not include an assessment of probable accumulation thickness or a slump failure analysis. Importantly, this numerical model ignored tides, which are significant to particle trajectories and the potential for tailings to be re-suspended and transported into shallow water.

6) The consultants employed by NSR to determine the erodability of deposited tailings used freshwater in their experiments. The validity or basis for extrapolation of their results to the saltwater environment is unclear.

Marine Chemistry

1) The proposal contains almost no chemical oceanographic information about Astrolabe Bay and the Vitiaz Basin.

2) Primary productivity (and respiration) of the surface mixed layer (euphotic zone) is not known, despite this being the major source of metabolisable organic matter to deep-water benthic animals and bacteria.

3) Estimates of the annual flux of organic matter from the upper water layers, and the lateral transport of terrestrial organic matter in the water layer near the bottom, would have been useful to generate important models of the chemical transformations in the tailings sediments. To immobilize reactive metals in the tailings sediment on the slope and basin, the formation of anaerobic conditions and iron sulfide minerals is required. This requires an abundant supply of organic matter to fuel the microbial processes that consume oxygen and make hydrogen sulfide from seawater sulfate. If the supply rate of organic matter is very small, then aerobic conditions (and deeper biological mixing)

[20] Cresswell, G.C. (1998) Ramu Nickel Project, Environmental Plan, Volume C: Appendix 2. Currents and water properties off northern PNG as they may relate to development in Astrolabe Bay and off the Rai Coast. 36 pp.

in surface sediments will persist, and metal mobility will be greater. As has been discussed it is likely that deep water in the Vitiaz Basin is well oxygenated. Metal release and bio-uptake are generally accelerated with higher temperatures, lower salinity and higher dissolved oxygen concentrations.

4) Little mention is made of the sewage disposal plan for 1000 to 2500 people for 30 months. This is equivalent to half a tonne of phosphorus and 4.1 tonnes of nitrogen being added per year to a nutrient deficient coastal water mass. Inputs of ammonia in the tailing pipe are also large, equivalent to 8 tonnes of nitrogen per year. These are powerful fertilisers. Misima Mines's efforts with sewage disposal were not impressive, as the shallow (12m) pipeline was broken during storms, and they exceeded their compliance levels on several occasions.[21]

5) The sediment sampling methods employed by NSR are about a century old, and not very effective. A pipe dredge is not a suitable tool to sample the sediment surface, and is certainly not appropriate for pore water studies. These were the same samples that were used for biological analysis.

Marine Biology

It would appear that there are a number of gaps in NSR's reporting of the biology of Astrolabe Bay, and a complete list of these deficiencies can be found in the report of Dr Marcus Sheaves titled *"An Analysis Of The Ecology Of Astrolabe Bay In Relation To The Ramu Nickel Cobalt Mine"*. This is presented in Chapter 5. In summary, the sampling of deep water benthos and fish was inadequate, with the result that the data cannot be relied upon to provide any basis for the evaluation of impacts. The data provides no basis for the report's biological conclusions and no information that would allow anyone else to make an authoritative estimation of the likely outcome of the deep-water tailings disposal.

[21] NSR Environmental Consultants (1999). Review of the Coral Reef and Nearshore Environment, Misima Mine PNG, NSR, CR 206/22/v6. NSR Environmental Consultants Pty Ltd, 1996. Review of the effects on the marine environment, Misima Mine PNG. April 1996, CR 206/19/v5.

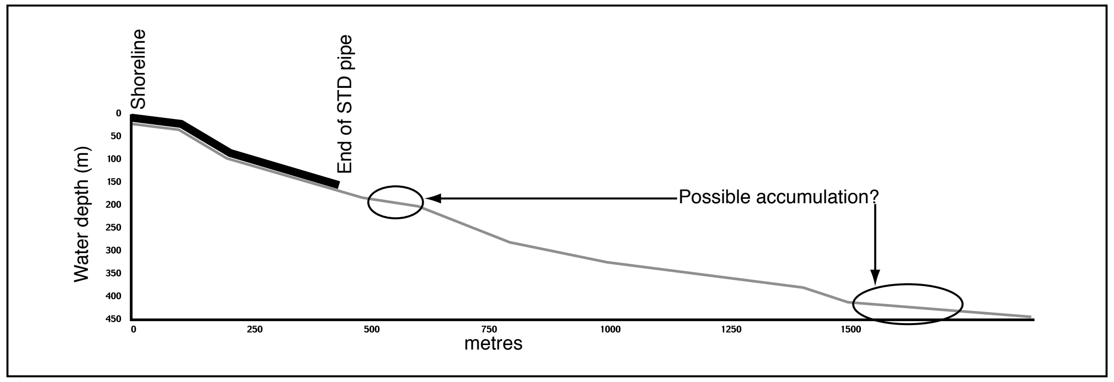
Risks associated with the **NSR Environmental Plan**

A key deficiency in NSR's work is a refusal to consider uncertainty. The assessment of risk is a vital component of professional environmental impact assessments. Without fail, NSR entertains only best case scenarios. NSR consistently rules out any chance of low-probability events, errors in their data, errors in their predictions, data that does not conform with their low-impact model or the possibility that parameters important to the success of the STD may change over time.

A responsible risk assessment requires an understanding of worst-case, as well as best-case scenarios. The Environmental Plan limits the assessment of most risks and impacts to the best case scenario: where the assumptions underlying the assessments are all justified and no accidents occur. The following points summarise some of the more important risks that have not been considered in the NSR Environmental Plan.

General Risks

1) Scientists involved in the production of the MPI report draw attention to the NSR report not giving sufficient consideration to the consequences of tailings slumping and the possible generation of a tsunami. Based on the depth cross-section of Basamuk Bay, the alternative scientific view is that it is more plausible that tailings material will accumulate near the discharge point and at around the 450m depth contour, where the slope abruptly flattens from 16º to 7º. If this scenario is correct, then massive build-up will be significant because of the potential for subsequent slumping, which in turn has the potential to generate a tsunami. This latter scenario cannot be discounted without additional study.



Sites of potential accumulation and slumping

2) Terrestrial and seabed landslides, tsunamis, volcanic eruptions, and earthquakes are a threat to the land and seabed pipeline and the refinery site. The run of the pipeline along the coast between Erima Harbour and Basamuk Bay appears to be especially dangerous, as all small river estuaries will be funneling channels for tsunami waves. There appears to be no contingency plans or safety margin for these shore waves which would likely be 6-15 m tall and of unknown time scale frequencies.

3) No consideration is given to consequences of incomplete de-aeration or pipeline rupture, even although these events have occurred at other STD sites.

Risks to shallow waters

There is a clear possibility that the inputs to shallow waters may be greater than expected, with the consequence that damage to the biota could be more extensive than expected. For example:

1) There are a number of potential sources of additional sediments and pollutants from the refinery site that may enter shallow waters. Some of these are not identified by NSR, and others are mentioned but not treated in detail. This includes the dumping of waste rock and soil from refinery construction directly into the coastal bay.

2) There is no assessment of the risk of additional sediments not flowing to the deep ocean floor as NSR predict, or the effects on the biota of the repeated resuspension of such sediment if it was retained in shallow waters.

3) Some issues do not seem to be followed through to their logical conclusion. For example, NSR rate the risk of rupture to the slurry pipeline carrying ore to the refinery as unlikely. This seems somewhat over optimistic in such a seismically active area. By NSR's own assessment a pipeline rupture is most likely at a low point and would release up to 2,000 tonnes of ore slurry. If this occurred where the slurry could be washed into the sea, 2,000 tonnes of ore slurry could be deposited into shallow water habitats. Any events like these would lead to greater than estimated inputs of sediments to shallow marine systems.

Deep water impacts

As with shallow water impacts, projected effects of STD seem to be based almost entirely on best case scenarios. Consequently, the same uncertainty exists as discussed for shallow water impacts. This doubt is exemplified by concerns regarding the toxicity of the tailings and the fact that it is uncertain if pollutants such as mercury, that are known to bioaccumulate and biomagnify, will really be diluted to background levels.

In addition, if the tailings fail to deposit on the floor of Vitiaz Basin as hoped, a range of unpredicted biological effects are likely, none of which have been considered by NSR:

1) a different (shallow water) fauna would be influenced by the tailings than that predicted by NSR,

2) large build-ups of sediment at shallow depths may provide the opportunity for catastrophic slumping leading to scouring of existing sediments, producing unexpected habitat changes,

3) large accumulations of tailings would cause much deeper and more rapid burial of fauna leading to increased mortality. It may even influence mobile fauna able to deal with slow burial by burrowing upwards,

4) build ups close to shore would mean that much less natural river sediment would be available to mix with the tailings, because few streams enter Basamuk Canyon itself. This would lead to increased danger of toxic effects due to failure of assumptions about dilution,

5) large repositories of sediment in relatively shallow water increase the danger of resuspension of sediments due to upwelling, abyssal storms and turbulence, and turbidity plumes generated by catastrophic slumping.

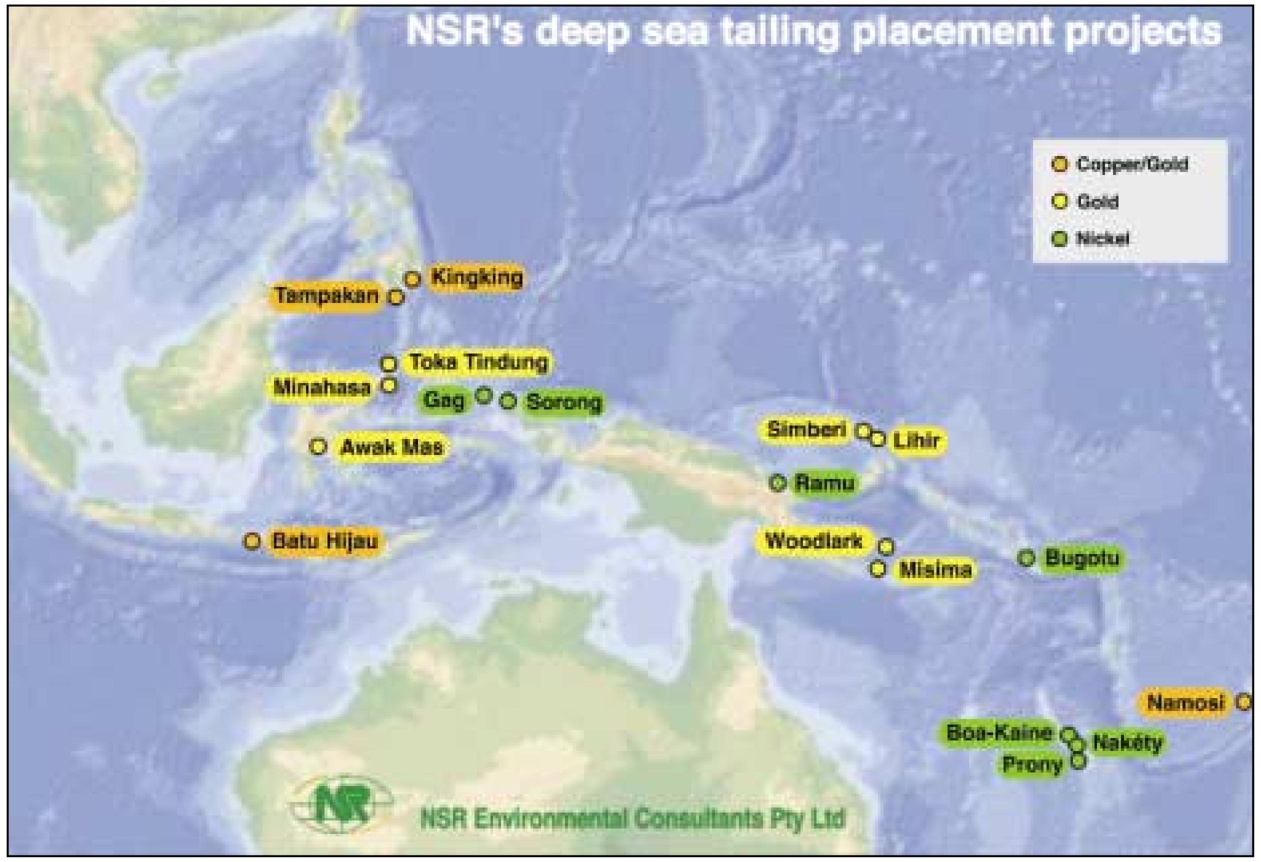
6) retention of sediments in shallow waters transfers the impact of tailings disposal into the 100-400m depth range preferred by the Goldband Snapper (*Pristopomoides multidens*) and the Ruby Snapper (*Etelis carbunculus*), thereby impacting the potential fishery identified in the Environmental Plan.

Chapter 2

Natural Systems Research – An analysis

An understanding of Natural Systems Research (NSR) in terms of its history and strategic direction is vital to understanding the turbulent ride of the Ramu Nickel Mine environmental approvals.

Over a period of 26 years NSR has worked on more than 400 projects, advising clients on projects as diverse as a woodchip plant, the Tasmanian Hydro Electric Commission's proposed Franklin River dam, BHP's Ok Tedi mine, a gas project in Burma and on the impacts of the Esmeralda disaster in Romania. But in particular, NSR has carved out a niche working on mining projects involving the dumping of tailings into rivers and oceans. Since 1982, NSR has advised companies on 24 ocean disposal projects which have been clustered in nine countries – Indonesia (6), Papua New Guinea (5), New Caledonia (5), the Philippines (3), Chile (1), Fiji (1) , the Solomon Islands (1), Cuba (1) and Canada (1).



[22] Natural Systems Resources Environmental Consultants Ltd (NSR), Oil and Gas Project Listing, www.nsrenv.com.au, 15 November 1999, page 3.

NSR goes beyond scientific advice to engage in corporate public relations work. In a promotional brochure NSR advertises that it "provides advocacy support and strategic advice to clients and offers environmental services for the planning and permitting of new resource development projects, principally for the mining and petroleum industries"[22]. This includes education of stakeholders with an introductory video on DSTP, strategic advice on stakeholder involvement and the negotiation of regulatory/permit conditions. The type of NSR's work can be seen in the following portfolio of recent contracts:

- When BHP was desperately seeking to defeat legal action by PNG landowners over the impact of tailings dumped in the Fly River, NSR was hired to provide assistance.
- NSR advised Placer Pacific on river dumping of tailings in the Strickland River from the Porgera mine in Papua New Guinea[23].
- When NSR was contracted by Minorco Services to advise on the proposed Weda Bay Nickel Project on Halmahera Island in Indonesia's Maluku province in 1998 it advised on the ocean disposal of mine wastes as well as on "non-technical issues i.e., permitting/public opinion/NGOs"[24].
- While the international community was working to isolate the Burmese military regime, in 1994 NSR was working for US oil giant Unocal to prepare a "pipeline route analysis" on the controversial Yandana gas project pipeline[25].
- When Placer Pacific was seeking Fijian government approval for the Namosi project, NSR was brought in to do presentations on ocean disposal of mine wastes to government officials[26].
- NSR was also hired in 1999 by the Philippine Department of Environment and Natural Resources to provide advice "to the Mines and Geosciences Bureau on the formulation of a DSTP policy for the Philippines"[27].
- Two years earlier, Western Mining Corporation (WMC) had hired NSR to advise it of the prospects of ocean disposal of mine wastes being used at WMC's controversial Tampakan project and the implications on this of the 1972 London Dumping Convention[28].
- NSR was hired by the US-based Kennecott Corporation to advise on ocean disposal of tailings for the Simberi Gold Project on Simberi Island, New Ireland Province in PNG. Between 1988-91 and again in 1996-97 NSR advisedthe joint venture on ocean disposal of mine wastes and other environmental and social issues[29].
- In 1998 Rio Tinto hired NSR to evaluate environmental issues in reopening the Bougainville copper mine[30].

[23] NSR, Mining in High Rainfall Tropical environments: Project Listing, www.nsrenv.com.au, 15 November 1999, page 9.
[24] NSR , Mining: Deep Sea Tailing Placement (DSTP) Project Listing, www.nsrenv.com.au, undated
[25] NSR, Oil and Gas: Project Listing, op cit, page 3.
[26] NSR, Deep Sea Tailing Placement: Project Listing, op cit, page 1.
[27] NSR, Deep Sea Tailing Placement: Project Listing, op cit, page 5.
[28] NSR, Deep Sea Tailing Placement: Project Listing, op cit, page 5.
[29] Burton, B. Mining Monitor p.7 Vol. 5. No. 3 Sept 2000.
[30] Natural Systems Research Environmental Consultants, Mining in High Rainfall Tropical Environments: Project Listing, www.nsrnv.co.au, 15 November, 1999, page 9.

NSR is actively involved in the promotion of STD to the mining industry. In a letter from the Director of NSR, Stuart Jones, to the Senior Vice President of the giant mining house Anglo American Plc in June 2000, this point is made clear:

"You mentioned that there is resistance to the concept of DSTP (STD) from your CEO. In my experience we find the same reaction in just about every person who has had no prior exposure to the concept. The senior management and the Board of Directors of two of NSR's new clients (Falconbridge and Sherrit International) had similar concerns. The approach adopted in both cases was for NSR to prepare a short briefing paper and then make a detailed presentation to senior management (two hours) and a short presentation to the Board of Directors (one hour). I did the presentation to Sherritt in February this year and both myself and our senior marine biologist (Dr David Gwyther) made the presentations to Falconbridge in March of this year (both in Toronto). We were told that the effect of the presentation was in both cases, that senior management and the Board of Directors felt comfortable with the concept of DSTP and were happy for DSTP to be considered...If you think it would help we would be pleased make a presentation to your CEO on the subject." [31]

It is interesting to note that Dr David Gwyther is mentioned as NSR's senior marine biologist in this letter dated June 2000. It was in late 1999 that Dr Gwyther was engaged as a consultant for Dames & Moore as the marine biologist in the independent review of the NSR Environmental Plan for the Highlands Pacific Nickel Cobalt Mine. In fact Dr Gwthyer has done consultancy work for both Dames & Moore and NSR since the early 1980s. In 1985 Dr Gwyther carried out an assessment of the utilisation of the Strickland River by local people on behalf of NSR. This was used by NSR and Placer Pacific in the approval process for the direct discharge of mine tailings into the river system.[32]

Although it cannot be suggested that Dr Gwyther is not an experienced and expert consultant in this field, it might have been preferable for Dames & Moore to have retained another marine biologist to advise it on the review of the NSR Environmental Plan. This would have avoided any perception of a possible conflict of interest on the part of Dr Gwyther in these circumstances.

[31] Letter from Stuart Jones, Director, NSR to Dr John Groom, Senior Vice President, Safety, Health and Environment, Anglo American plc, London, UK; dated 7 June, 2000.

[32] Gwyther concluded after a brief period travelling from village to village that local people "displayed an unexpected lack of interest in fishing". It could be construed that this was used by Placer to argue that the discharge of tailings into the river system was the most sensible solution to the tailings problem. (Gwyther, D., 1985. Population, settlement and aquatic resource investigation of the Porgera, Lagaip and Strickland Rivers. In; Natural Systems Research Pty, Ltd, 1988. Porgera Gold Project Environmental Plan, Volume B and C. Porgera Joint Venture. Port Moresby.)

Other work of Dr Gwyther includes:

1) Work with Dames and Moore in 1998 when he presented a paper titled "Ecological aspects of deepwater submarine tailings placement - a risk weighted perspective" at a workshop on Submarine tailings placement, Bandung, Indonesia, 5-6 August, 1998.
2) When the Australian Mining company Esmerelda had a major accident in February, 2000, causing the pollution of a river system in Hungary, it was Dr Gwyther who was flown in to work for Esmerelda to probe what caused the spill. "Our role is to try to understand the circumstances of the spill and the events that followed it," David Gwyther of Esmeralda told state television.
3) Dr Gwyther is currently employed as a specialist consultant to NSR assessing the potential effect on marine life of electrical and magnetic fields (EMF) associated with the Basslink Tasmania-Victoria undersea cable project.

It is also an issue of legitimate public concern to ensure that scientific consultancy firms engaged to provide analysis in the mining industry continue to maintain an independence and detachment from their clients in the mining industry. It is only when these conditions are met that governments, stakeholders and the community generally can have complete confidence that scientific analysis and reports are provided on a truly independent basis. There will always be room for legitimate scientific argument, not only about the relevant facts, but also about the interpretations and conclusions in relation to those facts. But when commercial interests of the stakeholders may affect the nature of the scientific and environment evaluation of a proposed project, this could lead to a loss of confidence in the integrity and rigour of the environmental impact assessment process

In conclusion, it should be noted that in excess of US$5 million was spent on the Environmental Plan.[33] It could be argued that for this sum of money it should have been feasible to carry out a thorough assessment of the STD option as well as commission a proper assessment of alternatives. These are all activities for which expertise and scientific equipment exist in the region.

[33] 21 March 2000, Highlands World Class Ramu Nickel project gains environmental approval. Media Release, Highlands Pacific.

Chapter 3

A review of the physical oceanography of Astrolabe Bay and coastal northeast PNG with reference to proposed submarine discharge of mine wastes

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Introduction

This report is a review of available physical oceanographic reports and publications. Its intent is to assess the probability of significant environmental impacts arising as a consequence of proposed development in Astrolabe Bay, PNG – in particular, a Submarine Tailings Discharge (STD) to be built in order to dispose of mine waste products.

The major question considered here is: **will tailings slurry find its way into the surface ocean, in particular shallow reefy areas where they are likely to cause immediate and substantial harm?** The processes considered include oceanographic upwelling, vertical mixing (via internal waves and tides), and buoyancy of some fraction of the slurry with respect to the ambient ocean waters.

Previous reports, in particular a major Environmental Plan, have asked essentially the same question, and have concluded that the planned development is unlikely to cause harm to the environment. However, as we shall see, these reports overlooked a number of factors, including some of the field evidence on which they were based. When these additional factors are accounted for, the risks are significantly increased. It is not the purpose of the report to advise whether or not to proceed. Rather, it aims to provide a more realistic assessment of the risks – and in the event that development occurs, suggests certain strategies which should be adopted to minimise the likelihood of negative impacts.

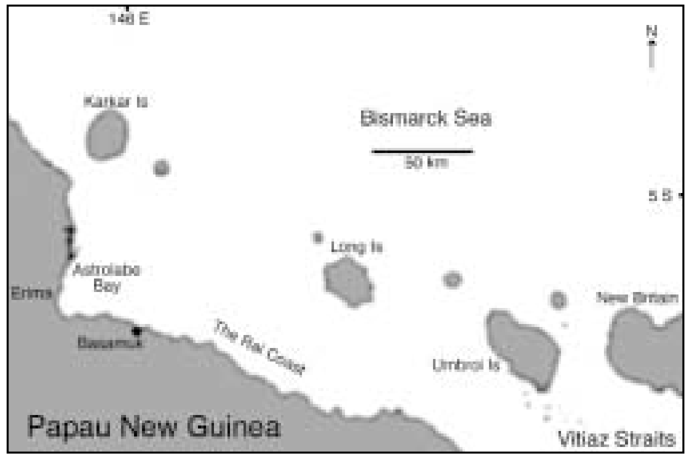

Fig. 1. Map showing Basamuk, site of proposed STD pipe.

The report begins by reviewing some oceanographic principles that may assist the reader to understand what follows. It then considers the physical oceanography of Astrolabe Bay, mainly on the basis of data and plots included in the Environmental Plan. A critique of the Environmental Plan then follows, pointing out a number of deficiencies, and finally, an assessment is made of the likelihood of negative impacts to the environment, with recommendations for minimising the risk.

The proposed mineral processing plant is to be sited in northwestern Papua New Guinea, at Basamuk (Figure 1), with an STD (Submarine Tailings Discharge) pipe discharging into the local Basamuk Bay (a sub-embayment of Astrolabe Bay). Basamuk Bay is located at the head of a submarine canyon which slopes down more steeply than Astrolabe Bay as a whole, and it is this relief which makes the STD concept a potentially viable option – if it can be done without harming the local environment.

Cresswell (1998) (hereafter "GC98") and NSR (1998) (hereafter "NSR98") describe aspects of the local (Astrolabe Bay) oceanography. GC98 draws on earlier regional studies and contains a reference list for those studies. NSR98 is Appendix 1 of an Environmental Plan. Two computer model studies were done in support of the Environmental Plan: Fluor/Daniel Simons (1998) and Jenkins (1999). These reports form the basis for this study.

Oceanographic background

The upper coastal ocean normally consists of a surface layer of fairly uniform temperature, underlain by a layer where the temperature decreases rapidly. Below these two layers the temperature falls off more slowly. The layer in which the temperature decreases rapidly is called the thermocline (Figure 2), and it is important to this discussion because vertical motions are suppressed within the thermocline. In order to lift a cooler (that is, denser) parcel of water through the thermocline, work must be done. For this, there must be a source of energy (for example, wind or tidal forcing).

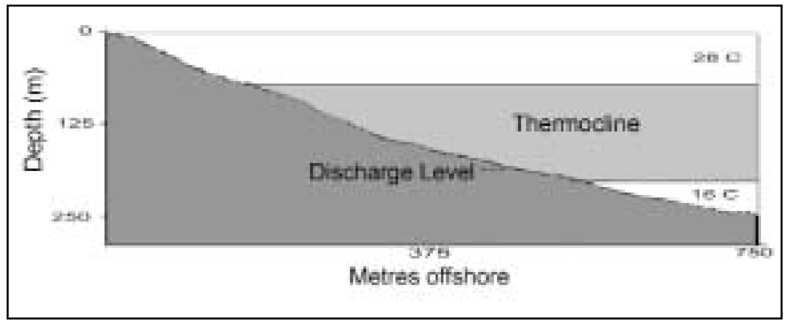

Fig. 2. A highly simplified vertical section of the coastal ocean. The temperature values and thermocline shown here are typical of Astrolabe Bay in August (NSR98).

It is something of a misnomer to call the surface layer "uniform". For example, as the day warms up, the upper metre or two (the "skin") may become quite warm. The uniformity might then be restored overnight by re-radiation and wind-mixing. The uniform temperature of the upper layer is therefore maintained by a combination of solar heating and wind mixing. The thickness of the uniform upper layer is generally determined by the vigor with which it is mixed by the wind.

Biological "primary productivity" (algal growth) occurs almost exclusively within the surface layer, to the depth that sunlight penetrates (the "euphotic zone") – typically around 60 metres throughout the year at Astrolabe Bay (NSR98). The reason for concern over tailings slurry making its way up into the surface layer is that this greatly enhances the probable ecological consequences.

The overall pattern of currents near Astrolabe Bay was reviewed in GC98. There is a coastal current, confined to the surface layer, and subject to seasonally-reversing monsoonal winds. A second current of note has been given a name, the "New Guinea Coastal Undercurrent" (NGUC) with a core at 200 m that flows at perhaps one knot. The NGUC flows persistently westward, and since it extends to at least 800 m (Tsuchiya, 1991), it basically dictates that the STD discharge – as long as it does not rise vertically after discharge – will find itself in a westward flow regime over most of its flow path.

Astrolabe Bay region can not (contrary to assumptions behind the numerical models supporting the Environmental Plan) be characterised as a "microtidal" regime. Using the values listed for Madang in NSR98 (and from the Australian National Tide Tables), the tidal range (an estimate of the maximum height difference between high and low tide) is 1.1 m. Tides approaching this value can be expected on a fortnightly basis. The tides recorded during the SRD bathymetric survey (reported in NSR98) show a range of about 0.7 m, with no indication given as to whether this was during the spring (maximum fluctuation) or neap (minimum fluctuation) part of the fortnightly cycle. Tides of this magnitude can be expected to be accompanied by significant tidal currents.

Upwelling, nearshore currents, and mixing in Astrolabe Bay

Shelf-width-scale coastal upwelling

A fair amount of consideration has been given to upwelling in GC98, NSR98, and elsewhere, and with good reason – in some areas of the world ocean wind-driven upwelling brings huge volumes of water to the surface, and if this were found to be such a region, it would be of great concern. Although those reports concluded the outfall depth was sufficient to negate those concerns, the issue is important enough that the evidence is reviewed again here.

In the Southern Hemisphere, an alongshore wind with the coast to the right of the wind direction will tend to blow the surface water offshore. (Contrary to Fluor/Daniel Simons (1998), this is true for northern PNG, despite its proximity to the equator.) The surface water will be replaced by deeper (cooler) water, which can often be detected from "heat-sensitive" images taken by satellite, as a distinct colour band running parallel and adjacent to the coast. These photographs are widely-used to detect upwelling zones. By comparing them with temperature profiles of the coastal ocean, obtained by lowering a thermistor probe, it is possible to estimate the depth from which the upwelled water originated.

GC98 examined numerous satellite-based sea surface temperature (SST) images of the region. In those images, cold upwelled water is coded as dark blue. A major upwelling zone was identified several hundred kilometres to the southeast of Astrolabe Bay, in Vitiaz Strait and along the southwest side of New Britain. Occasional patches of upwelled water also appeared along the Rai Coast east of Astrolabe Bay.

Initial comparisons with temperature profiles indicated that the upwelled water came from only 100 metres depth, a figure which was widely quoted in subsequent reports. It is of interest, therefore, to confirm this estimate. The first question is whether the colour scaling on the satellite photo is representative of the surface layer. In two instances, temperature profiles in NSR98 correspond to dates for satellite photos, and can therefore be compared.

- On 2 August 1995, the profile "OP2" (Figure 3.2) shows an surface layer temperature of about 28°C. In the SST imagery shown in NSR98, a photo taken on 1 August 1995 shows surface temperature in Astrolabe Bay (site of OP2), is close to 29°C according to the colour scaling.
- On 14 February 1995, the profile "OP5" (Figure 3.4) shows an surface layer temperature of about 26°C. In the SST imagery shown in NSR98, a photo taken on 6 February 1995 shows surface temperature in Astrolabe Bay (site of OP5), is nearly 30°C according to the colour scaling.

The SST images are normally considered to be reliable to within .5°C as a measure of the *skin temperature* of the surface ocean.

From the two comparisons, it would appear that the colour scaling in the SST images is only representative of the uppermost skin and not the upper layer as a whole. The "afternoon effect" can mask cold upwelled water below. Both SST images were taken at about 0500Z, which is late afternoon at Astrolabe Bay. To achieve a scaling appropriate for the surface layer (as opposed to the "skin"), one must subtract 1° and 4°, respectively, from the scales on the two photos.

Even aside from the problem of afternoon heating of the skin layer, there is a strong caveat on estimates of the source depth of upwelled water made by comparing SST images with temperature profiles. The reason for this is that the isotherms in upwelling zones slope upwards towards the coast, so that the "source depth" is highly dependent on the offshore position of the profile. There is a simple and reliable way to make this estimate, which could have been done from the NSR data. This is by drawing cross-sections of temperature and salinity leading out from the coast. Unfortunately, these cross-sections do not appear in NSR98.

SST images are an important tool for identifying upwelling zones, but to determine the source level of the upwelling can be difficult when subsurface data is limited. GC98 estimated 50-100m during the NW monsoon, based on data published in Colin et. al. 1974, and 100m depth during the SE monsoon, based on NSR data.

GC98 examined NSR water property data from station OP5, located at about 400 m depth, and 10 kilometres offshore. He found that the S=35 isohaline could be found below 100 m during the SE monsoon, but virtually outcropped during the NW monsoon. This is a clear indication that the maximum upwelling occurs during the NW monsoon (a period during which almost no SST images were available). The apparent contradiction to the preceding paragraph may be explained by interannual variability.

Upwelling in the Vitiaz Straits/New Britain area can be caused by wind blowing in virtually any direction, but the major upwelling, which is along southwest New Britain, is probably caused by wind blowing to the northwest. This is the prevailing wind direction during the southeast monsoon. A number of these same SST images also showed evidence of upwelling along the Rai Coast. The orientation of the Rai Coast makes this area unfavourable to upwelling under these wind conditions. As a possible explanation of this paradox, GC98 proposed a mechanism involving a westward alongshore current flowing offshore of the upwelling zone. The data is inadequate to test this concept, but the point remains that upwelling continues even during periods when the winds are evidently unfavourable.

During the northwest monsoon (January to March) season, when the wind-forcing is supposedly upwelling-favourable along the Rai Coast, it (the wind) would presumably reinforce the alongshore current mechanism, and water from greater depths could be drawn up. Unfortunately, only a single SST image was available for this period (cloud cover is a problem for obtaining clear images during the northeast monsoon). This image, already referred to above, was taken on 6 February, 1995, - did not indicate upwelling along the Rai Coast. That is, the colour was the same from the coast right out to deep water.

Nearshore Currents

In the preceding discussion of upwelling, we made an unspoken assumption concerning the scale of the motion. For example, the "pixel size" (essentially, the smallest detectable surface variation) of the SST images is 1.1 km, and the spacing of the hydrographic profiles of NSR98 is about one kilometre – and the closest the profiles come to the coastline is just offshore of the outfall site. This raises the question of whether nearshore processes have been overlooked in the field study.

Figure 4 (from Figure 4.9, NSR98), shows a net drift 9 m above the seabed near the outfall site of 0.9 cm/s at 202° - towards the southwest, or virtually directly onshore – or in other words, a bottom current flows straight up Basamuk Canyon. The speed, 0.9 cm/s, is about ? kilometre per day. Since there is no data inshore of the site, we can not say how far this current continues onshore. The angle suggests that it turns to the west and flows into Astrolabe Bay at some depth, probably feeding the seasonal coastal current. The data is from September to November, 1998. The net cross-shelf flow 49 m from the bottom is also onshore, but weaker. At 81 m from the seabed, the net cross-shelf flow is in the opposite direction – offshore to the northeast.

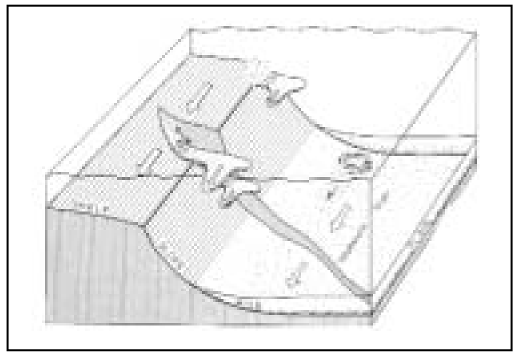

Fig. 3. Schematic of down-canyon flow. From Gardner (1989). Note two-ended arrow at top of canyon indicating reversing flow, and circular arrows in deep water indicating "abyssal storms".

The combination of a bottom current moving towards the shoreline, with mid-depth currents moving offshore, is suggestive of upwelling, and this can not be ruled out on the available evidence. However, there is another plausible explanation which relies on tidal currents as the driving force. Figure 4.8 (NSR98) shows that both the horizontal and vertical components of the bottom current in Basamuk Canyon undergo daily tidal oscillations. They are strongest (usually about half a knot) at around midday (the time zone is not indicated; if it is UTC, then the maximum actually occurs close to midnight). Of all the locations and depths shown in NSR98, this is the only site of strong tidal currents. Thus, the net onshore flow seen in Figure 4 may be the result of rectified tidal flow, amplified by the local topography, as described by Thompson and Golding (1981) in observations from the Great Barrier Reef. In that study, lines of constant density connected the shallow inner reef flat with deep offshore water below the thermocline, which was between 100 and 150 m. (Albeit this was in an area with a larger tidal range than Astrolabe Bay.) They suggested that this process drew nutrient-rich water from the deeper offshore zone up onto the relatively sterile coral reef, thereby fertilizing the coral.

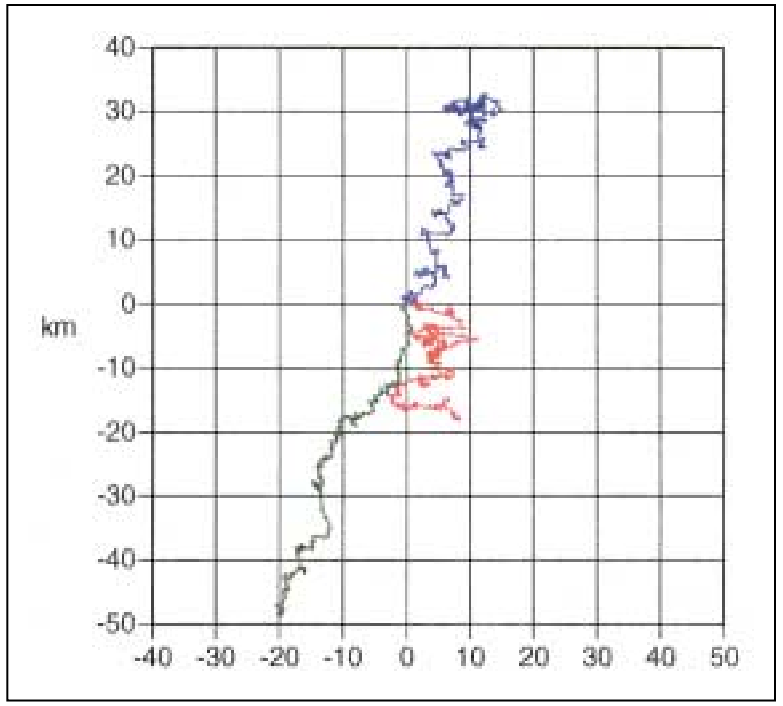

Fig. 4. Measured currents at the outfall site. Green: 9 m, red: 49 m, and blue: 81 m from the seabed, in water of total depth 160 m. Taken from Fig. 4.9 of NSR98. Solid and dashed circles have been drawn around the green and red lines, respectively, in case of B&W reproduction. (Note: this is a "progressive vector diagram". It shows currents at a single location only.)

Miscellaneous mixing processes

When a fluid enters into an ambient stratified flow it immediately attempts to seek its own level. According to Dames and Moore (1998), the density of the tailing slurry is 1030 kg/m3. Since the density of the seawater near the outfall site is slightly less (about 1025 kg/m3), the slurry will immediately begin to sink. The STD pipe is laid on the sloping seafloor. The slurry flows down the seafloor, fanning out over a widening area until stopped by friction, covering an area out to perhaps 25 kilometres from the discharge point (Jenkins, 1999).

Turbidity plumes have been reported in the outfall from the Misima mine (Dames and Moore (1999), quoting NSR) at discontinuities in the seawater. One such plume is illustrated in Figure 5, at the top of the 16°C layer. These are likely to be more extensive in the Basamuk STD, since the tailings slurry has a density of only 1030 kg/m3, as opposed to 1070 kg/m3 at Misima.

The downslope flow is subject to a variety of processes, such as quasi-steady undercurrents (such as the NGUC), oscillating tidal flows, internal waves, and episodic events of various sorts. It is difficult to estimate how energetic these processes are with the data available, and even the complex computer models presented in Fluor Daniel (1998) and Jenkins (1999) are unable to replicate them (for example, neither model includes tides, which are

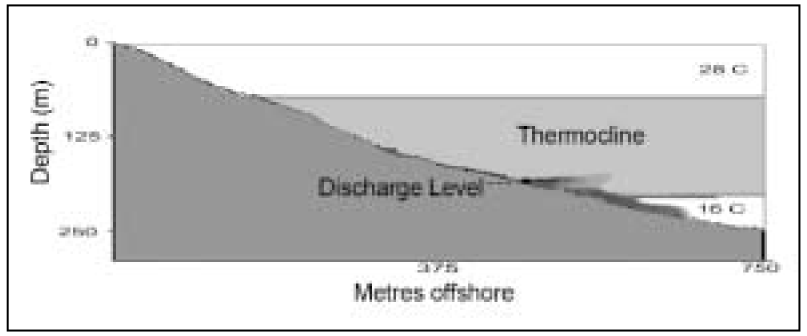

Fig. 5. Flow of discharged plume. Note turbulent cloud at discharge level and thin layer separating at base of thermocline.

the source of energy for substantial internal waves and bottom currents in Basamuk Canyon, and both models have cell sizes of 500 m, which allows only one to three cells to cover the width of the canyon).

Water at mid-depth can be brought nearer the surface by "internal waves". These occur in density-stratified water (usually thermoclines) when currents flow over an uneven seabed – places such as sills, canyons, underwater mounts, etc. If the current is tidal, the internal waves usually have the same semi-diurnal or diurnal period as the tide. The waves cause the thermocline to oscillate up and down or back and forth at some angle to the horizontal. Since the oscillations are not uniform, this causes shearing currents, which produces mixing and net vertical transport. Figures 3.5 and 3.9 of NSR98 show that the thermocline is generally 100 m or less thick, and is normally found between 45 m and 150 m below the surface. In this depth zone we can expect the strongest internal waves.

Although the tidally-driven internal waves are strongest within the thermocline, their effect extends well up into the surface layer. The largest vertical velocities reported in NSR98 occurred over the outfall site during October, at 57 m below the surface (Figure 4.10), at the diurnal (tidal) interval. The temperature at the recording instrument, which was moored 10 m below the oscillating layer, did not undergo diurnal fluctuations – hence, the large vertical velocities were in the surface mixed layer, at least 10 m above the top of the thermocline.

Internal waves can cause large vertical displacements. GC98 reported 100 metre displacements in the water column at the site of the proposed outfall. This was based on the rise and fall of the water temperature recorded by a thermistor on the ADCP, whose mean depth at the time was 138 m. A 100 m total displacement around a mean of 100 m depth would lift water from 150 m to 50 m. Thus, internal waves could act as periodic pumps to bring a fraction of the STD slurry to much higher levels, where other processes could bring it higher yet.

The planned system includes de-aeration of the tailing slurry, which should ensure that it is not positively buoyant when discharged. Should this fail, however, a buoyant plume could rise to the surface, and move horizontally on a path governed by the prevailing winds, coastal currents, and tides. Without a numerical model, the path is difficult to predict. However, consider a tidal current typical of those measured, say 0.25 knots flowing over a one hour period as the tide is rising. If we follow a single water parcel, in that time it will travel ? nautical mile (about 450 metres), that is, more than the distance to shore from the outfall site.

Our final example of a small-scale process, which could conceivably mix the slurry horizontally out into the ambient seawater, is "small-scale eddies". These are coherent rotating blobs of water that form wherever denser water enters the ocean (for example, in the Mediterranean outflow at the Straits of Gibraltar, and in the wintertime outflow at the eastern end of Bass Strait). Those formed in this manner are normally submerged at the depth at which their density matches that of their surroundings, and tend to maintain their identity over much greater distances (hundreds of kilometres) than non-rotating entrained patches.

The preceding mixing processes are likely to ensure that STD wastes are not simply deposited over a clearly demarcated area of the seabed - rather, some fraction will enter the ocean over a range of depths (concentrated at density discontinuities), and transported as patches of turbid water well out of the source area. Although the slurry is discharged at a density greater than that found at any depth, mixing and dilution will reduce the density as it flows downslope.

Comments and criticisms of the Environmental Plan

A physical oceanographic sampling program was undertaken as part of the Environmental Plan. The interpretation of this data in NSR98 was supported by the SST imagery and historical analysis of GC98, two numerical hydrodynamic models (Fluor/Daniel Simons, 1998, and Jenkins, 1999), and analyses carried out by GC98 and Fluor/Daniel Simons (1998).

The physical oceanographic sampling regime used good-quality instrumentation, and the data appear to be reliable. The report of GC98, in particular the analysis of SST imagery, provided a sound and thorough basis for the interpretation of the data. Numerical models provided important insights, but as usual, have inherent limitations which must be understood. Also, both the numerical models reported in the Environmental Plan ignored tides, which we have shown to be a significant source of energy in Astrolabe Bay. Including tides would probably increase the size of the "footprint" as predicted in Jenkins (1999).

The NSR98 interpretation (Appendix 1) falls short of fully exploiting the data, and ignores certain key issues. Also, at no point in the Appendix are the results of the field study combined with the consultant's reports and the models to assess the critical oceanographic factors which could lead to contamination of the local reef ecosystem.

Most importantly, only shelf-width-scale oceanographic processes were considered in the Environmental Plan. Particularly after the ADCP showed bottom currents flowing onshore at the outfall site, attention should have shifted to the zone between the outfall site and the shoreline.

Specifically,

- No attention[1] was paid to the fact that in Figure 4.9 in NSR98 (Figure 4 in this report), there is a net drift 9 m off the seabed near the outfall site of 0.9 cm/s at 202°. This angle takes it almost directly onshore (straight up the canyon). At this speed the turbid water from the outfall point would reach the surface layer in a matter of hours. This is a highly persistent net drift: does it continue up into the photic zone? what is the standard deviation of the speed? How often is there an onshore drift of twice this speed? What are the implications? None of this is discussed in NSR98.

  There is anecdotal evidence from fishermen in Astrolabe Bay, of the sudden appearance at the surface of sunken logs. Partly saturated, or naturally dense, logs can be neutrally buoyant. It is possible that a such log could have been carried at approximately 200 meters depth (depth of the Undercurrent) many kilometers along the coast of PNG, until it reached one of the Astrolabe Bay submarine canyons, where it got up in an upcanyon current, lifting it rapidly back to the surface. Such a scenario has obvious and disturbing implications for the proposed discharge, which appears to be directly into an upcanyon current.

- The ADCP was set to record in 4 m thick bins, and the bin nearest the seabed was centred about 10 m above the bottom. As a result, the true velocity of the critical bottom current is poorly resolved. Much better would have been to add a conventional rotor-type current meter to the mooring anchor, perhaps 2 metres off the seabed.
- The numerical model (Jenkins 1999) commissioned for NSR98 was used only to estimate the "footprint" or area covered by tailings. The model should also be able to determine massive buildup is likely to occur at bathymetric "perches" or abrupt changes in the seabed slope. Based on the depth cross-section (Figure 6) accumulation seems most likely near the discharge point and at around the 450 m ocean depth contour, where the slope abruptly flattens from 16° to 7°. Massive build-up is significant because of the potential for subsequent tsunamigenic slump. (Note: the maximum seabed slope at Basamuk Canyon is only 21°, as opposed to 45° at the Misima STD (USDI, 1994).)
- Cross-sectional plots of water properties (temperature and salinity) in a vertical plane, based on the CTD data on the BC section, may well have provided useful insight into the question of the depth and frequency of shelf-width-scale upwelling events.
- Fine-scale sampling along the BC section (say, at 100 metre intervals from 20 metre depth out to 520 metre depth) would have indicated whether water from the bottom at the outfall site is brought onshore into the photic zone (as indicated by the ADCP current data at the outfall site).
- The NSR98 report should have noted that the pixel size in a typical NOAA AVHRR SST image is 1.1 km. This is important because the distance from the shoreline to the outfall site is only about a third of a pixel, meaning that the images would not have detected small-scale upwelling close to the site.
- A tracer study, wherein dye or neutrally buoyant drifters are released at the outfall site at different depths (especially near seabed), different stages of the tide, and different times of the year, would have been economical and provided insight into the nearshore processes of concern.

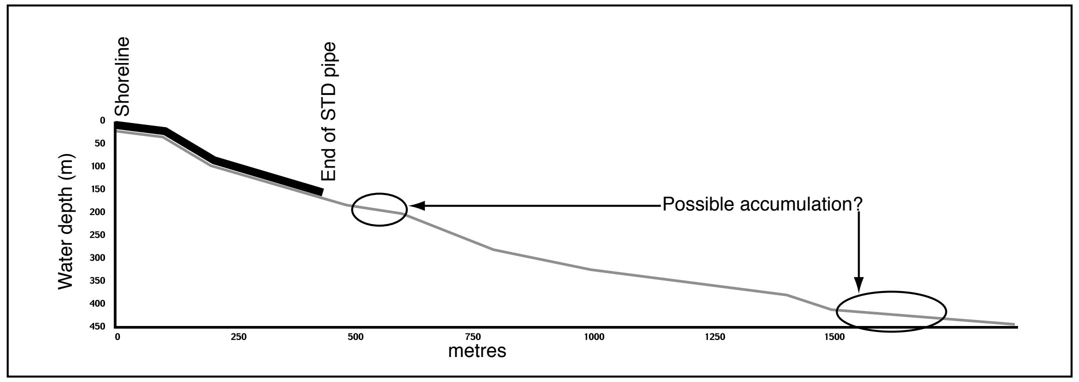

Fig. 6. Profile of seabed at Basamuk Canyon. Based on Fig. 2.5 of NSR98.

[1] *The Executive Summary of Appendix 1 states "Deep water current measurements revealed...offshore net drift near the seabed", ignoring the more critical onshore current at the outfall site.*

- The two oceanographic computer models ignored tides, although tidal currents near the seabed regularly reach 0.5 knots near the outfall site. One model had a "nested" 500 m grid, but even this was much too large to model the nearshore processes at the outfall site, which is 380 metres offshore. A second level of nesting at 50 metres gridsize, with tidal forcing, might have identified the onshore drift at the seabed at outfall site.
- No attempt was made to use the Seabird CTD to assess the amplitude of internal waves during the field phase. Internal waves are evident in the vertical component of the ADCP (notably in Figure 4.2 of NSR98, current level 57 metres) and also by comparing the temperature oscillations on the ADCP with the background profile. Using the latter technique, GC98 estimated internal wave oscillations of 100 metres.
- The erodability study (Jenkins and Golding, 1998) used fresh water to study the threshold velocity of resuspension of settled Ramu tailings. In the conclusions, the authors speculate that the threshold may be higher in salt water, but no specific guidance is provided for estimating the true (salt water) velocity. We therefore refer the freshwater figure in the following.

Likelihood of impacts, with recommendations for minimizing risk

***1.** Will wind-forced upwelling bring water from below 150 m to the surface layer, contaminating local reefs?*

During 1997/98, the maximum upwelling, which occurred during the NW monsoon, drew water from about 100 m (GC98). This happened to have been an El Niño year, during which one would expect a stronger-than-average NW monsoon. Without personally viewing the data, particularly the cross-sectional plots of temperature and salinity data of NSR, it is hard to improve on the GC98 estimate. Internal waves can move water over distances of 100 m, providing at least a hypothetical mechanism for transporting water up into the surface layer.

Recommendation 1: Cross-sectional plots of temperature and salinity should be examined for evidence of upwelling from below 100 m.

***2.** Will the prevailing current at the seabed carry turbid water onshore into shallow water?*

The prevailing current definitely appears to be shoreward at the seabed at the STD site. The possibility that this current continues up into the surface layer (euphotic zone) cannot be discounted, because no data has been collected in this zone.

Recommendation 2: **A.** Conduct a study of the bottom currents at the outfall site, using a conventional current meter mounted just above the seabed. A second meter at 10 m above the seabed will help evaluate the earlier ADCP data. **B.** Conduct high-resolution numerical modelling of the flow field including tides, winds, and baroclinic effects.

***3.** Will tidal or other currents resuspend the material after deposition?*

The reported velocity nearest to the seabed (about ten metres from bottom) at both the nearshore and deep ADCP deployments was frequently close to or above the threshold for resuspension (0.45 m/s according to Jenkins and Golding 1998).

Recommendation 3: Same as Recommendation 2.

4. Will the STD plume send turbid patches out into the surrounding ocean at various depths?

This seems almost inevitable. If the patches also take on a rotation, they will maintain their original character even after they have been carried hundreds of kilometers away. Such patches will be anything from tens of metres to tens of kilometres in diameter.

Recommendation 4: If contamination of the deep and mid-depth water is a concern, the waters near the plume should be monitored by nephelometer, beginning prior to commencement of STD.

5. What if the pipeline ruptures or tailings slurry floats to the surface (due to failure of de-aeration)?

If the pipeline ruptures, tailings slurry will pollute the local reefs to an extent dependent on the size of the spill, but potentially catastrophically. If the slurry floats (due to failure of de-aeration), it will appear as a dark stain on the water surface about 380 metres from shoreline. If allowed to continue for many hours (for example, if the alarm on the de-aeration tank fails, possibly at night) then many tonnes of tailings slurry could be driven onshore by wind of tidal currents.

Recommendation 5: **A.** Ensure that RNJV's rapid-response spill strategy is demonstrable and effective. **B.** To detect leaks, require also a monitoring program which includes visual surveillance of the HDPE pipeline by remotely-operated vehicle. **C.** Require RJNV to set aside funds for rehabilitation of the reef ecosystem in the event of a disaster.

6. Is there any chance STD sediments could slump during an earthquake, causing a tsunami?

This can not be discounted without additional study. A submarine slump triggered by an earthquake is thought by many to have caused the Aitape tsunami. In that case, the slump occurred about 15 km offshore, in water depth of about 1500 m. At Basamuk the potential problem seems most likely to be nearer to shore (in about 450 m water depth, about 1000 m offshore, where the depth gradient flattens from about 16° to 7°).

Recommendation 6: **A.** Repeat the model of Jenkins (1999), to determine whether tailings massively accumulate at bathymetric perches. If so, additional study (e.g., tsunami modelling) may be required to assess risk. **B.** Require periodic ROV swathe surveys to monitor accumulation.

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Chapter 4

Critique of geochemical & sedimentation aspects of the Ramu Nickel Joint Venture proposal for deep sea tailings disposal in Astrolabe Bay and the Vitiaz Basin, Papua New Guinea

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My expertise is in the area of marine geochemistry, chemical oceanography, and coastal sedimentation. I have been involved in studies of coastal geochemistry and sedimentation in northern Australia and New Guinea since 1992. I have led oceanographic research cruises along the northern and southern coasts of PNG, and I have worked out of Madang and in the estuary of the Sepik River in the Bismarck Sea.

Project TROPICS, Sepik River Canyon Studies

I am the Australian Coordinator of Project TROPICS (Tropical River-Ocean Processes in Coastal Settings), which is a consortium of coastal oceanographers and marine geologists from Australia, Indonesia, Papua New Guinea, USA, and Japan. The goals of Project TROPICS are to describe and model the fate of wet tropical river inputs of water and sediment to the estuaries, continental shelf, slope, and abyss of New Guinea. Project TROPICS partners have had 7 research cruises (1996-2000) to the Sepik River estuary and Bismarck Sea, and two Indonesian cruises to the Mamberamo River estuary & coastal sea. For more information about TROPICS, please see http://www.aims.gov.au/tropics. This work is of direct relevance to likely behaviour of the Ramu Submarine Discharge (STD).

The Sepik and Mamberamo River discharge very large volumes of water and sediment into coastal waters of the Bismarck Sea, and a significant fraction of the annual river sediment load is carried into the deep sea by fluid mud flows down steep canyons that bisect the narrow muddy shelf. As described by Cresswell et al. (1997, 2000) and Kineke et al. (2000), variable solute and particle fractions of this descending fluid mud flow are floated off into water layers of increasing density (isopycnal water masses). These isopycnal water layers are coastal currents that flow quickly NW and SE along the coast, often in opposite directions, similar to that found in Astrolabe Bay. TROPICS scientists have tried to sample these nutrient and iron rich turbid layers at the interfaces between water masses of different density, and have followed them to the NW along the coast and northward to the equator (Burns, unpublished, Szymczak, unpublished, Mackey et al, 1997, 1998, 2001).

Box cores and Kasten cores of sediment accumulated on the narrow shelf platform near the Sepik River mouth, within the Sepik River coastal canyon, on the continental slope, and in the trough at >1 km water depth have been obtained (Kuehl & Nittrouer, 2000, Brunskill, unpublished). A sediment budget for the annual input from the Sepik River (~80 MT/yr) indicates that we can account for only 20% of this sediment in the canyon and trough deposition fan to 1200 m water depth. The majority of the sediment probably moves NW along the coastal slope and trough (seaward of the canyon) towards Irian Jaya, but we have not yet found this large amount of sediment. Cores of sediment from the inter-canyon shelf platform, canyon floors, and slope indicate rapid modern accumulation at rates of 0.5-4 cm/yr (1-8 kg m-2 yr-1), with significant (probably transient) accumulation of fine and coarse-grained sediment within the canyon from 200-600 m water depth. These transient canyon sediment accumulations have 234Th and 210Pb depositional histories of duration months to years. Sediment deposition rates seaward of the 1000 m contour are much smaller (<0.2 cm/yr), and the sediment is either a stiff silty sand or volcanic glassy sand and gravel. We have found no fine-grained Sepik River sediment in deep (>1000 m) water of this region. Our work therefore suggests that the vast majority of Sepik sediment is being entrained by submarine currents and carried to the west.

General criticisms of the Ramu Proposal in regard to terrestrial impacts

If the environmental goals are to minimize the area of alienation of local ecosystems, then Option 2b (Appendix 6) would be the best choice. Retention and storage of all mine wastes at the mine site would alienate about 20 km2 and could be observed and contained into the future by the mining company. Disposal at sea would alienate over 150 km2 of biodiverse marine habitat in a region where the mining company and their consultants cannot observe or contain the waste.

If the proposal is to be taken seriously, then the applicant should begin monitoring the annual dissolved and sedimentary flux from these 128 catchments of Astrolabe Bay, to obtain a real estimate of the potential dilution rate of the tailings, and the rate at which natural sediments would bury the tailings in 2025-2100. The goal in this work should be to obtain annual fluxes of dissolved and particulate elements of concern (Ni, Cr, Co, Cd, Hg, N) to the sea, to compare with the same annual fluxes from the tailings pipe in Basamuk Bay.

Local people in the vicinity of Kurumbukari and the road to the coast will have problems with gravel extraction from river beds and altered fish habitat, reduced stream water flow and village water supply, and potential pipeline rupture events.

In relation to the impact of the mine site on the Ramu River, impact prediction is hindered by a lack of reliable data. Surface and groundwater from the Kurumbukari mine site is chemically unusual now, but will likely be more unusual during excavation of the ore body. Groundwater flow and chemical investigations on the mine site orebody would be useful to predict downstream changes in dissolved element chemistry. The reported chemical investigations on Banap Creek and the Ramu River (Appendix 13) are useful only for the major elements in water. Trace element data for water and suspended sediments would require much more careful work by qualified chemists with experience in the nM to pM concentration range. If these Appendix 13 results are accepted, then 73% of total Cr in unfiltered water is in the dissolved phase, and all Ni was in the ionic form (no ligand complexing capacity in local waters), which seems unlikely. These changes in local water quality should be of concern to the people who live near the Ramu River.

The chromite waste burial system at the mine site is poorly described, and we are not assured of stabilization of this relatively abundant and potentially soluble element (Abu-Saba and Flegal, 1997).

Project revenues (page 8, Main Report NSR) do not appear to include costs of environmental reclamation, pipeline rupture emergencies, decommissioning, and rehabilitation of the mine site and spill sites.

Tsunami, Seismic Quakes, Landslides, Submarine Slumps

According to Everingham (1977) and Davies (1998), tsunami coastal waves of 6-15 m height are known for the north coast of PNG and the Bismarck Sea islands. Speculations about the source and frequency of these events can only be estimated from historical records and the disciplines of physical oceanography and marine geology. Davies (1998) summarizes the disaster in Aitape in July 1998, NW of the Sepik River, where 2000 lives were lost from 10-15 m tsunami waves onshore. These events are not infrequent, as similar tsunami disasters occurred in Flores Island in 1992 (1700 killed), Okushiro, Japan in 1992 (239 killed), East Java in 1994 (230 killed), Biak, West Papua in 1996 (107 killed), and Vanuatu in 1999 (Caminade et al., 2000). In the local area around Madang, severe tsunamis have occurred along the Rai coast in 1855 (a village at the mouth of the Kabenau River was destroyed), on Ritter Island in 1888 (a wave generated by the collapse of Ritter Island was recorded at Alexishafen, north of Madang), and Bogia-Karkar Island in 1930. Hypotheses for the origin of the energy that causes tsunami waves include submarine volcanic eruptions or submarine landslides initiated by earthquakes (Tappin et al. 1999; Kawata et al., 1999).

As acknowledged in the proposal, terrestrial and seabed landslides, tsunamis, volcanic eruptions, and earthquakes are a threat to the land and seabed pipeline and the refinery site. The run of the pipeline along the coast between Erima Harbour and Basamuk Bay appears to be especially dangerous, as all small river estuaries will be funneling channels for tsunami waves. There appears to be no contingency plans or safety margin for these likely 6-15 m shore waves of unknown time scale frequencies.

Major eruptions of the Long Island volcano are known to have occurred 16,000 years ago, 4,000 years ago, and 300 years ago (Briffa et al., 1998). Another major eruption can be expected some time in the next several thousand years (Rabaul Volcanological Observatory, Chris McKee at Port Moresby Geophysical Observatory). Some idea of the multi-decadal hydrological consequences of a nearby volcanic eruption is given in Major et al. (2000).

Biogeochemical Oceanography

The proposal contains almost no chemical oceanographic information about Astrolabe Bay and the Vitiaz Basin. The marine chemistry review in Attachment A of Appendix 1 (Biogeochemical Behavior & Speciation of Metals) is very well done, but it does not relate to the local conditions of Astrolabe Bay and the Vitiaz Basin, nor to suspended or deposited tailings reactions over 20+ years. Several pieces of chemical information from the region are needed to evaluate the proposal assumptions:

1. Primary productivity (and respiration) of the surface mixed layer (euphotic zone) is not known, and this is the major source of metabolizable organic matter to deep water benthic animals and bacteria. The variations of the supply rate of organic matter to the slope and trough sediments will largely control the depth of bioturbation, sediment mixing, microbial metabolism, and the sediment depth horizon of deoxygenation resulting from decomposition of organic matter. Anaerobic conditions for sulfate reducing bacteria in the sediments are assumed to occur for the formation of iron sulfide minerals, which are possible sites of temporary fixation of tailings metals. It will probably be found (according to our work in the Sepik plume region) that surface waters have low productivity and high respiration rates, and the supply rate of organic matter to deep water sediments will be very small. These measurements need to be made by experienced scientists fine-tuned for low productivity waters, and the measurements should be made using daily and seasonal changes in both carbon dioxide and oxygen concentrations (to estimate photosynthetic production and respiration).
2. Sediment trap estimates of the annual flux of organic matter from the euphotic zone, and the lateral transport of terrestrial organic matter in the nepheloid layer near the bottom, will be useful for needed models of the chemical transformations in the tailings patch sediments. To immobilize reactive metals in the tailings sediment on the slope and basin, the formation of anaerobic conditions and iron sulfide minerals is required. This requires an abundant supply of organic matter to fuel the microbial processes that consume oxygen and make hydrogen sulfide from seawater sulfate. If the supply rate of organic matter is very small, then aerobic conditions (and deeper biological mixing) in surface sediments will persist, and metal mobility will be greater. It is likely that deep water in the Vitiaz Basin is well oxygenated (Wijffels et al, in Cresswell's report, Appendix 2).
3. Profiles of nutrients, particulate organic carbon, oxygen, chlorophyll, micronutrients (Fe), and indicators of natural and/or tailings upwelling (particulate and dissolved Al, Fe, Cd, DOC), along with CTD casts would help resolve the question of physical and chemical upwelling in Astrolabe Bay during the NW Monsoon. Such information would also provide data for models of the supply of organic matter fuel to the tailings patch on the slope and basin floor. This would have to be done carefully, with an eye toward the seasonal wind strength and shear events in the stack of different water masses from the inshore (canyon head) to offshore. It is especially critical to estimate oxygen concentrations in the deepest water currents, near the sediment surface.

These are all normal oceanographic activities that can be done on research vessels of the region, with existing equipment, and there are local experts in each of these fields.

Seawater Tailings Chemistry

The sustained addition of 5 MT/yr of hot tailings slurry to the 150 m depth zone of the Basamuk Bay slope for over 20 years will create a shelf-edge zone of very unusual seawater chemistry within a radius of about 1 km (landward and seaward) of the pipeline orifice. The tailings have no metabolizable organic matter or reduced sulfur, so the solution phase will be oxygenated and turbulent. This mixing zone could be min/max modelled, with some input from physical oceanographeric data on current speed and shear turbulence, to determine the sphere of influence of this mixing zone. There will be very high concentrations of ammonia (being oxidized by bacteria to nitrate), sulfate, Mn, and enhanced metal concentrations (Ni, Cr, Co, Hg, and Cd) in the dissolved phase (Appendix 5). This turbid water mass will be moving west or northwest at about 1 m/sec (Appendix 1), and will probably be distributed over several of the coastal canyons. Of the abundant trace metals in the sediment, Cr (6) may be the most soluble in oxygenated seawater. Ammonia and nitrate are powerful fertilizers in nutrient deficient tropical coastal waters (Vollenweider, 1992). The redox status of the fluid mud current and deposited tailings pile will be very complex over a 20+ year period of additions, with very large oxidation power from the high concentrations of MnOOH and FeOOH. Some release of all trace metals in tailings to oxic and anoxic pore water and oxic overlying sea water can be expected (Zachara et al., 2001; Abu-Saba et al., 1997; Florence et al., 1994; Lam et al., 1997; Trolard et al., 1995).

The seawater intake pipe orifice water depth will bring relatively warm water into the mixing tank. If part of the purpose is to cool the 55∞ C refinery tailings waste, the deeper water would be better. High temperatures will also speed oxidation and mineral dissolution reactions in seawater.

Other Waste Streams

Little mention is made of the sewage disposal plan for 1,000 to 2500 people for 30 months. This is equivalent to half a tonne of P and 4.1 tonne of N being added per year to a nutrient deficient coastal water mass. Inputs of ammonia in the tailing pipe are also large, equivalent to 8 tonnes of N per year. These are powerful fertilizers (Vollenweider, 1992). Misima's efforts (two NSR Reports, 1999) with sewage disposal were not impressive, as the shallow (12 m) pipeline was broken during storms, and they exceeded their compliance levels on several occasions.

Little mention is made of refinery waste products and reagents, oil and grease, and domestic rubbish. The dumping of waste rock and soils directly into the coastal bay will generate turbidity in the surface mixed layer nearshore, as was found in the Misima experience (NSR Report, 1999). This deliberate addition of waste material to the surface mixed layer of coastal waters seems totally unnecessary and environmentally irresponsible.

Nearshore Sedimentation, Inter-canyon Platforms

Most of the consultant's efforts on sediment dispersal are focused upon direct and downward flow from the pipeline orifice at 150 m water depth into the Basamuk Canyon. It seems possible that a large fraction of the dense tailings would move this way, but experience at Misima, and our experience in the Sepik River canyon mud flow, suggest that dissolved and particulate fractions of the dense mud flow are lifted off the near bottom plume into isopycnal water masses, and are transported along shore at high current speeds (1 m/sec). Some of this material may find a place of rest on the inter-canyon platforms that extend from the shoreline to many kilometers offshore. These inter-canyon platforms were not sampled in this proposal study, and we know little about their composition.

In the Sepik River shelf region, the canyon walls and adjacent narrow shelves are composed of mud and sand, and appear to be recently deposited from the Sepik River. 210Pb based estimates of accumulation rate are high (~1 cm/yr, 3-6 kg m-2 yr-1) on the top of these inter-canyon platforms, which suggests that some of the river sediment load is pushed back onto the narrow shelf by currents and waves. By extrapolation, I would expect the inter-canyon platforms in the Astrolabe and Basamuk Bay regions to be relatively soft mud that is accumulating from natural riverine sediment plumes that do not go down the canyons. This fraction of natural river sediment input in Astrolabe Bay will not be available for dilution of refinery tailings in the canyon and seaward.

The stability of these inter-canyon platforms may be of some importance to tailings flow down the canyon. If there are frequent massive slumps of inter-canyon platform and wall sediment into the base of the canyon, this might result in dams and obstructions to tailings flow for periods of months to years. Some shallow high resolution seismic transects through these platform deposits, and long cores, would reveal the history of accumulation, lateral migration, and slumping.

Fluid mud in canyons

As mentioned above, observations in the Sepik Canyon by Cresswell et al. (1997, 2000) and Kineke et al. (2000) indicate that small and light particles, and soluble fractions of the descending fluid mud flow are entrained into layers of water of increasing density, from 80->400 m water depth. These stacks of isopycnal water masses are flowing rapidly to the NW and SE, with considerable turbulent shear forces at the interfaces. The cartoon model from Gardner (1989) shown by Cresswell (Appendix 2) is a good representation of the likely downward fractionation of the fluid mud flow. In addition to this, our Sepik Canyon and slope sedimentation studies (Kuehl & Nittrouer, 2000, Brunskill, unpublished) can only find about 20% of the river sediment inputs in the canyon and on the slope face, and we think most of this missing large amount of sediment is transported along the slope face (200-1000 m) to the NW with the New Guinea Undercurrent. The implication is that the Basamuk Canyon tailings sediment will not flow to the Vitiaz Basin, but will move to the west along the coastal slope according to the speed and direction of the current. Similar arguments for California coast hyperpycnal plumes have been made by Imran & Syvitski (2000). Based upon the solution and solid phase composition of the tailings, useful tracer elements to track this NW transport in the water column would be B, Br, Cr, Li, Mn, Ni, P, Se, Sr, and ammonia.

Vitiaz Basin Sedimentation

No useful information on sedimentation rates and sources of sediments in the Vitiaz Basin are provided by the proposal. The provided information (very few samples for such a large area) suggests that most of the deep basin sediments are not from the local rivers of Astrolabe or Basamuk Bay, but are largely volcanic glass, diatom frustrules, iron oxide gels, carbonate skeletal remains, and small proportions of terrestrial clay minerals. Based upon this, there is little evidence to suggest that mine tailings from the Basamuk Bay tailing pipe will reach the Vitiaz Basin.

Kawahata et al. (2000) and Burns et al. (unpublished AIMS TROPICS data) have sediment trap bulk and organic matter fluxes for the Caroline Basin and Bismarck Sea respectively, indicating largely hemipelagic carbonate and opal composition, at bulk mass accumulation rates of 96-160 mg m-2 d-1. Euphotic zone primary production was estimated to be ~100 mg C m-2 d-1 near the equator directly north of PNG, and only 7-9 mg OC m-2 d-1 survives decomposition reactions en route to the bottom sediments. Further to the east, ENE of New Britain Island, trap fluxes were a factor of 10 smaller in the core of the Western Pacific Warm Pool. These fluxes of bulk sediment and organic matter indicate the very slow burial rate of the tailings over the century after mine cessation, and the rate of supply of organic matter to microbial communities (and sulfide generation rates) in the tailings pile.

Current speeds in deep water Vitiaz Basin were estimated to be in the range 20-40 cm/sec (Appendix 1). The flume study on tailing sediment (Appendix 9) indicated that the threshold for current erosion of particles was 17-40 cm/sec, and they further estimate the seabed erosion rate to be ~160 kg m-2 yr-1 at this current speed. This erosion rate is about 1000 times faster than the expected sedimentation rate (<0.1 kg m-2 yr-1). Based upon this information, it is unlikely that all the fine-grained tailings will stay in place on the Vitiaz Basin seafloor.

The sediment sampling methods are about a century old, and not very useful. A pipe dredge is not a suitable tool to sample the sediment surface, and is certainly not appropriate for pore water studies. The critical parameters needed to evaluate the metal trapping ability of these natural sediments appears to be lacking and counter-indicated. There was no smell of hydrogen sulfide, and no evidence of sulfate reduction. The description of the iron oxide gels in the sediment samples (Appendix 15) suggests an oxidizing environment in surface sediments. The low pH of the pipe dredge sediment (<7) suggests strong aerobic decomposition of organic matter, and strongly oxidizing conditions. Without some estimation of the mass accumulation rate, it is not possible to estimate the period of time needed to cover the tailings with natural sediment during 2025-2100.

Very high concentrations of NH4, Fe, and Mn will likely occur in the pore water of the tailing plume and seabed deposits. The interactions between the rate of supply of marine organic matter and these elements will be extremely complex, and cannot be confidently predicted from geochemical literature (Thamdrup & Dalsgaard, 2000). That paper, and those papers cited therein, presents a scenario where the strongly oxidized and highly reactive oxides of Fe and Mn in the tailings sediment will completely dominate the reactions that oxidize organic matter, with little room left for sulfate reduction and iron sulfide formation. High concentrations of Mn are likely to inhibit the reduction of oxidized iron in the tailings (Lovley and Phillips. 1988). Microbial reduction of iron oxides in the seafloor tailings pile may release much of the FeOOH-sorbed trace elements (especially Co and Ni)(Zachara et al., 2001; Bousserrhine et al., 1999). Any authigenic iron sulfide minerals formed would be quickly oxidized by the great excess of (and rate of supply of) Mn oxides (Aller and Rude, 1988). The lack of sulfide minerals in the diagenetic products of the tailings seabed deposit may result in enhanced trace element mobility. It appears that these oxidized Fe and Mn species will not oxidize ammonia in anoxic sediments (Thamdrup & Dalsgaard, 2000, Luther et al., 1997). Benthic organisms in the vicinity of the seafloor tailings will accumulate excess metals from tailings pore water solution and by ingestion of sediment particles (Lee, B et al., 2000; Lee, J. et al., 2000; Wang et al., 1997; Wang et al., 2000). The experimental methods of these cited papers would be useful for laboratory and in situ field experiments in Astrolabe Bay and Vitiaz Basin sediments, and the proposed tailings material.

The STD proposal would like to indicate that the tailings and the natural sediments are anoxic in the Vitiaz Basin (800-1600 m water depth), and that iron sulfide minerals will be formed in the sediment. An abundance of FeS in the sediment requires the metabolism of organic matter by sulfate reducing bacteria under anoxic conditions. An abundance of FeS in the sediment would fix many of the tailing metals as insoluble sulfide phases (sorbed, co-precipitated), and would limit metal export to the water column. The work required to demonstrate this capacity is as follows:

1. Estimate the rate of supply of organic matter from sediment traps installed at 4-6 sites in the Vitiaz Basin, perhaps 50-100 above the bottom. This will provide an estimate of the food and energy supply to the macrobenthic and microbial community in the surface sediments.
2. Determine the gross exchange of oxygen and carbon dioxide between the overlying deep water and the surface meter of sediments. This can be done with benthic landers, or on sealed sediment cores with probe ports in the ship laboratory. Box cores can provide detailed information on solid phase and pore water properties (pH, Eh, O2, H2S, NH4, Mn, metals) in the surface 30 cm of the sediment column. Careful sampling of the top 10 cm would reveal some aspects of the distribution of short-lived isotopes, such as 234Th, which will help estimate the mixed layer thickness and oxygen supply rate to the natural and tailings sediments. Measurements of the rate of Fe, Mn, NH4, and sulfate reduction can be done shipboard.
3. Kasten and/or piston cores at 8-10 sites in the depth range 800-1600 m Vitiaz Basin would be useful to estimate sedimentation rates (14C, 210Pb), the depth of sediment mixing by physical and biological means, and the composition and source of deep sediments. Massive slump episodes from the shoreward canyons of Astrolabe Bay should be signaled by core horizons of riverine mud of composition similar to modern river suspended sediments. When operated by competent personnel, these coring methods can be used to estimate the variations of the redox boundaries, the thickness of the sediment mixing layer, and the zones of accumulation of iron sulfide deeper in the core. Accumulation rate in this region will be needed to estimate the rate of burial of the tailings after closure of the mine. Since tailings burial beneath the mixing zone of the sediment column will take many decades or centuries, this accumulation rate information should be based upon 14C methods on undisturbed sediment cores >2 m in length. Variations in pore water metal concentration and accumulation rate of metals for century-millennial scale periods can be estimated, and compared to model estimates of tailings sediment diagenesis and accumulation rate.

4. These kinds of sedimentation studies will be needed to demonstrate that the Ramu Nickel tailings sediment has actually reached the Vitiaz Basin. These sampling and analytical methods will be needed to demonstrate the environmental validity of the deep sea tailings disposal method. If the Ramu tailings are not in the Vitiaz Basin sediments, they are probably moving along the slope toward Madang and Wewak with the New Guinea Coastal Undercurrent at 1 m/sec.

These are all feasible activities for which research ships, scientific equipment, and expertise exist in the region.

Climate Change Scenarios

The Bismarck Sea and the Pacific Ocean north of Papua New Guinea are the La Nina location of the Western Pacific Warm Pool, amongst the warmest open ocean water in the world. During El Nino years, this warm water mass moves eastward to the central Pacific and coastal America, the western Pacific equatorial waters (Indonesia and PNG) are much cooler, and there is less rainfall. During these cool years, the thermocline is usually deeper, and increased entrainment of deep water occurs. The historical changes in the frequency of El Nino in the Madang and Nauru region has been studied by Tudhope et al. (1995) and Guilderson & Shrag (1999) from centuries of variations in oxygen isotopes in the annual growth layers of massive Porites sp. coral cores. They found that there has been an increase in the frequency of El Nino events since 1950, and this has been related to anthropogenic climate warming by greenhouse gases (various IPCC reports, and Timmermann et al., 1999). An increased frequency of El Nino events in the future suggests cooler surface waters in the Bismarck Sea, and deeper mixing of the surface waters off the north coast of Papua New Guinea.

Conclusions

Inadequate information is provided to assess the feasibility of environmentally reasonable deep sea refinery tailings disposal in the Basamuk Bay and Vitiaz Basin. Several contradictions are presented in the Ramu Nickel Mine proposal:

1. the proposal indicates the refinery tailings will flow along the bottom to deep water in the Vitiaz Basin with little mixing or upward movement to the euphotic zone, will be trapped in the sediment by sulfide minerals, and will be diluted and covered by natural river sediment,

2. the proposal indicates that seawater mixing will dilute the refinery waste to acceptable water quality standards within several kilometers of the pipeline orifice,

3. the proposal indicates that deep water Vitiaz Basin sediments are non-sulfidic, oxidizing, and hemipelagic,

4. the proposal indicates that deep water currents in the Vitiaz Basin are flowing at a speed that will erode fine sediments faster than expected deposition rates, and

5. the proposal information indicates that the natural Astrolabe Bay river sediment is not deposited in the Vitiaz Basin. Statements 2-5 are contradictory to the first statement.

Based upon this information, it seems unlikely that the Ramu Nickel Mine refinery tailings disposal plan will function as described in this proposal. It seems more likely that the tailings will accumulate in the nearshore canyons and inter-canyon platforms, and be transported to the west (toward Madang) in the New Guinea Under Current at about 1 m/sec.

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Chapter 5

An analysis of the ecology of Astrolabe Bay in relation to the Ramu Nickel Cobalt Mine

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Introduction

The Ramu mine is one of a number of large mining ventures under development or in operation in Papua New Guinea. The scale of these projects means that many aspects of their construction and/or operation have the potential to substantially impact the environment. Consequently, issues such as the disposal of waste materials and the siting and construction of processing facilities need detailed consideration. In January 1999 NSR Environmental Consultants Pty Ltd produced a detailed Environmental Plan for the Ramu Nickel Joint Venture (NSR 1999a). The purpose of the current work is to review the biological risks presented by the Ramu Nickel Project and in particular the submarine mine tailings disposal proposed for Astrolabe Bay, Papua New Guinea. The three specific aims are to:

1. Assess the potential risks posed to the ecology of Astrolabe Bay region by the mine proposal with a particular emphasis on local fish species.
2. Assess the international literature on the response of fish to tailings plumes.
3. Assess the outputs of the Highlands Pacific/NSR Environmental Impact Assessment. Specifically to comment on the confidence of the EIA predictions in relation to information available to the EIA process during its preparation.

A detailed review of the Environmental Plan and its appendices highlighted a number of issues that relate to these three specific aims.

1. Quality of the Biological Data Underpinning the Assessment of Risks to the Marine Environment

The accuracy and quality of the biological interpretations and predictions made by NSR rely on two types of information; 1) The accuracy of the estimates of types and amounts of inputs from the Ramu Nickel Project to the marine environment, and 2) the quality of the biological understanding of the systems likely to suffer impacts. The extent to which the full spectrum of risks seem to have been addressed is difficult to judge and is covered in point 2 (below). Assessing the quality of the biological data underpinning the assessment is more straightforward and is covered here.

1.1 DATA ON SHALLOW WATER BIOLOGICAL SYSTEMS

Compared to a long history of study of temperate marine systems, tropical marine ecosystems have only been studied intensively in the last 30 years, and so are relatively poorly understood. However, clear waters and warm temperatures make tropical shallow water coastal environments, such as reefs and soft bottom habitats, relatively easy to work in. The study of these systems has advanced rapidly, so they are among the best understood of tropical marine ecosystems, with a rich international literature to draw on. In addition, the extent of study of these systems by organisations such as the Australian Institute of Marine Science, means that there are a range of suitable protocols in place for surveying these systems. The extent of the background literature, and the use of standard protocols by NSR means that their conclusions about shallow water communities appear sound, aside from two caveats. Firstly, there are some questions about the depth, extent and detail of assessments of the likely extent of inputs (covered in 2 below). Secondly, it is not clear when or how often the shallow water communities were sampled (there is no mention of timing in the methods of Appendix 3). In the case of coral and sessile invertebrate faunas this probably not an issue. However, in the case of fish, it means that estimates of abundance or even occurrence might be suboptimal for at least three categories of fishes. Firstly, fish that are only abundant at particular seasons would have been underestimated if sampling did not match with their season of occurrence. This relates both to fish that occur on reefs for only short periods of time and those that are absent from most of the reef for periods, for instance due to migration to specific spawning sites. Fish that could fall into this category include important food species such as coral trout (Samoilys and Squire 1994). Secondly, many reef fish are nocturnal, so if sampling was confined to daylight hours these species would be underestimated. Thirdly, many important, active predators, such as trevallies, move in large schools and may range over a considerable area. Point sampling would be likely to miss or underestimate the abundance of such species, even though they can be vital both to the ecology of the area and as food fish. Because of these problems relating to the scope of sampling, it is not clear that the conclusions on the relative abundance of fish fauna at potential shallow water impact sites are soundly based, particularly conclusions relating to temporally variable predatory fishes.

These two problems mean that NSR's shallow water impact predictions need to be treated with some caution. In particular, shallow water impacts are likely to be underestimated if inputs to shallow waters are greater than predicted.

1.2 DATA ON DEEP WATER BIOLOGICAL SYSTEMS

The quality of the background information on deep water biological systems is of much greater concern. These systems are poorly understood both in a global and a local sense (Gwyther 1998, Lindsay et al. 2000). For instance, a recent survey of deep water fish off New Caledonia (Grandperrin et al. 1999) found 263 species of fish, and 37 species of sharks and rays, of which 40% were new to science. The presence of such rich fauna, with so many undescribed species, means that obtaining clear, strongly supported, accurate case-by-case base-line information on these systems is critical, particularly when these deep water environments are intended as the major sites for the repository and impact of some 100mt of tailings.

1.2.1 Deep water benthic biota: There are two problems with the sampling of benthic deepwater biota. Firstly, the sampling gear used (pipe dredge) is, in the words of the experts used by NSR to identify the benthic fauna (Wilson & Taylor, Attachments F & G of Appendix 3), "....an inefficient collecting method for benthic invertebrates". Importantly, pipe dredge sampling is unrepresentative in that it samples the sediment surface poorly, and this is the area where most organisms are found. Additionally, the sampling protocol (the minimum sieve size of 0.3mm) meant that meiofaunal animals would have been almost totally lost from the samples (these organisms are defined as those passing through about a 500 micron sieve but retained in about a 4 micron sieve). This is despite meiofauna being abundant in many deep sea sediments (Gwyther 1998, Soltwedel 2000), being one of the few deep water fauna that "...can be sampled with anything approaching statistical rigor..." (Gwyther 1998), and being particularly important as sensitive indicators of change in deep sea disposal sites (Boyd et al. 1998). Secondly, so little sampling was undertaken that there is virtually no likelihood that the sampling could adequately represent the deep water benthic fauna of Astrolabe Bay or of deep waters off Basamuk. To take the Basamuk sampling as an example. Figure 8.13 of the main report suggests that the tailings deposit footprint will cover an area of some 1002 km and extend some 27 km offshore. To represent this some 8 subsamples were taken below the depth of the tailings outfall (Appendix 3, Table 3.1). It is also unclear from the methods (Appendix 3, 3.2) what these subsamples represent. I am assuming that the subsamples listed in Table 3.1 are replicate samples and not the subsamples detailed in 3.2, otherwise only 5 samples were taken. Of these sites only one was at a depth of greater than 800m, even though most sediment settling is expected to occur between 1,000 m and 1,600 m water depth (Main report, Volume B, p130). Additionally, this deepest site was only about 11km offshore, although the footprint is expected to extend some 27 km offshore. The one thing we do know about benthic communities world wide is that they are not simply random distributions of animals but occur as patches of different densities on a range of different scales (Pentreath et al. 1988). Thus representation requires that sampling is both efficient and of substantial spatial and temporal extent. This is particularly true of deep water benthic systems where there is little previous understanding to draw upon, and what background information there is highlights the delicate nature of these faunas (Koslow and Gowlett-Homes 1998).

Taken together, these two factors (inefficient sampling gear and insufficient sampling intensity) lead to the conclusion that the inferences drawn about the benthic fauna of these regions (e.g. that they are biologically poor) and their trophic roles (e.g. that they are dominated by deposit-feeding polychaete worms) are without any substantive basis. In fact it is not even clear that the approach used could ever have addressed either of the aims posed in Appendix 3, 3.1.1. The sampling gear and sampling intensity were never likely to be sufficient to lead to accurate estimates of abundance, and identifying the trophic groups of benthic organisms could shed little light on their role in the food chain because no attempt was made to sample their potential predators.

Deep water fishes: An equal lack of representation and rigor characterises NSRs studies of deepwater fishes. Firstly, the sampling undertaken seems completely inadequate to represent the deep water fish community. The major sampling problems can be summed up in the following eight points:

1. Sampling was conducted over only 10 days with an average of only 2.417 hours sampled per day over the duration of that sampling period. This sampling effort produced only 43 (text of Appendix 24, 4.2.1) or 44 (Appendix 24, Table 1) fish. Neither the temporal extent of the sampling or the number of fish captured suggests any possibility of the sampling being extensive enough to represent the deep water fish fauna.
2. There is no clear indication of the exact spatial extent of the sampling - how many samples at which depths. However, Appendix 24, Figure 3 suggests that sampling in 1998 was confined to two small sections of the coast off Astrolabe Bay and to depths less than 600m (Appendix 24, Fig. 3). This depth range doesn't even cover the whole deep-slope environment (that extends to about 900m in Appendix 24, Fig. 2) that was the supposed target of the sampling. This means that sampling only extended some 3km offshore, and thus only covered a small part of the tailings footprint (Appendix 1, Fig. 2.5). Thus there is no information on the fishes that occur over most of the tailings footprint. There is even less information on the 1997 sampling except that it covered some offshore sites well away from the predicted footprint.
3. There is no information as to the skill level of the fishers involved. The skill level of fishers is well known to be a crucial factor in the success of hook and line fishing.
4. There was no attempt to sample at different seasons, even though deep water fishes are often characterised by substantial seasonal migrations and aggregations. For example, one of the most important commercial deepwater species around Australia and New Zealand, the orange roughy, Hoplostethus atlanticus, is harvested from large aggregations that form over structures such as seamounts for short periods each year (Smith et al. 1998).
5. Sampling was not conducted at night, even though deep water fish may carry out substantial diel vertical migrations, or may exhibit diel patterns of feeding activity.
6. There was no attempt to use acoustic methods to determine if there were aggregations of deep water fish in the area, even though this would probably be the most rapid and cost effective method of study (Grandperrin et al. 1999, Koslow and Kloser 1999).
7. There was no attempt to sample any but demersal fishes, even though many deep water fishes occur well away from the bottom. For example, the two fish most common in the samples, Etelis carbunculus and Pristopomoides multidens, often include considerable quantities of pelagic squid, and planktonic gastropods and urocordates in their diets (Allen 1985) so may feed well away from the bottom. In this case, estimates from bottom fishing could greatly underestimate true abundances.

8. Only large hooks and baits were used so there was no chance of catching small individuals. This means that there was no chance of identifying important nursery grounds. This is an important point because the nursery grounds of many species (even shallow water species) are still unknown, so nursery ground (and indeed spawning ground) identification is an important part of any evaluation. In fact using only a single sampling technique means that there was little chance of obtaining a representative picture of species or sizes present in the areas sampled.

The fish fauna of the deep water areas of the Astrolabe Bay/Basamuk remain unknown. In particular, there is no indication of the importance of the area to fishes. For instance, many important questions remain unanswered. Are there major unidentified deep water fisheries resources in the area? Is the area an important spawning ground for any species? These questions are particularly important in the context of deep water fishes. Deep water fishes usually have very slow growth rates and recovery times (from impacts like overfishing) compared to shallow water species (Clark 1998), making their populations particularly vulnerable to environmental impacts. Additionally, important commercial species, like orange roughy, spawn at a few localised aggregations to which they appear to migrate from distances of hundreds of kilometres (Francis and Clark 1998). This means that failure to identify a vital spawning ground, that may only be used for a short period each year, could have catastrophic consequences on stocks of the species over a wide area. The potential value of these fauna as a fisheries resource is highlighted by recent deep water surveys of New Caledonia (230 to1,860 m depth) that found 263 species including commercial stocks (Grandperrin et al. 1999), and by the rush by international companies to take up licenses to harvest deep water fishes of Namibia (Anon 1996). The importance of these questions illustrates clearly that an extensive spatial and temporal evaluation of the fish fauna should have been conducted as a basis for determining the suitability of the area as a tailings dump.

There are a number of additional points that should be made about the information presented in Appendix 24. What amounted to haphazard fishing was justified because the aim was to "...attempt to quantify the composition, range and extent of the fish resource..." (Appendix 24 pages 7-8). The low sampling intensity and failure to use methods likely to capture a range of species of different sizes renders this aim unattainable.

Only 43 (44 in table 1) fish were captured, with the greatest catch of one species only totaling 18 individuals. On page 20 (Appendix 24) it is stated that "Preliminary age data has been included here as it provides baseline information against which potential future changes in the age-class structure of the stock can be compared." This would be true if the sample was large enough to produce reliable data and the sampling had targeted a particular stock with a defined spatial extent, in a representative way. The small sample size and ad hoc sampling means the age, weight and length data set is too small and too unrepresentative to be of any practical use.

The sampling limitations also mean that any comparison to catches in other places is trivial.

1.2.3 Point by point evaluation of Appendix 24, 5. Conclusions (page 26-27): The points raised above about the lack of sampling intensity means that most of the conclusions of this section have little validity. Below is point by point evaluation of the conclusions:

- It is unclear that sufficient villages or villagers were sampled to provide useful information on utilisation of fisheries resources. In any event current utilisation is only part of the picture. It has been emphasised that whether exploited or not deep sea fisheries resources must be considered in light of their future importance (Gwyther 1998).
- The sampling was not intensive enough to determine if these two snappers were really dominant.
- Too few samples were collected for useful size/age analysis.
- Too little sampling was conducted, and was too restricted in spatial and temporal extent to provide useful information on catch rates.
- Too little sampling was conducted to determine if any species of deep slope fish was actually absent, or if they were really present but not captured.
- Too little sampling to make any comparisons of catch rates.
- Too little sampling was conducted to make any useful general statement on depth distributions.
- I agree; deep-water fish grow slowly and begin to reproduce when quite old, and are indeed, always in danger of overexploitation,
- The collection of *Branchiostegus japonicus* outside its range is the only piece of hard data presented; it emphasises how poorly understood deep water fish faunas are.

1.2.4 Conclusions: In my opinion the sampling of deep water benthos and fish conducted for the Environmental Review is inadequate to the extent that the data could not be relied upon to provide any basis for the evaluation of impacts. In short, the data provide no basis for the report's biological conclusions and no information that would allow anyone else to make an authoritative estimation of the likely outcome of the deep water tailings disposal.

1.3 CHEMICAL AND TOXICOLOGICAL CHARACTERISATION OF TAILINGS

Studies of the toxicological characterisation of the tailings followed standard protocols and appear to have been rigorously applied. The report found some toxic effects of both the tailings liquor and interstitial liquids. This issue has been addressed by Wagner (1999) and rebutted by NSR (NSR 1999b). I am not an expert in this field and see no reason to contest the claim by tailing interstitial waters would "pose a minimal risk to aquatic species" (Stauber et al. 1998). There is however still uncertainty about the extent to which sediment dwelling organisms are at risk from the ingestion of tailings particles (Stauber et al. 1998) because as NSR itself admits "...benthic organisms on the periphery of the depositional zone and recolonising organisms after tailing deposition ceases will be exposed to tailing solids containing elevated concentrations of metals....chromium, nickel and mercury..." (NSR 1999b, p7). This problem is argued to be unimportant but the strength of the qualifying arguments is unclear. For instance, it is suggested that "While mercury is known to biomagnify, the mix of tailing solids and terrigenous sediments is similar in value to the deep-sea clay reference value."(Appendix B Part 5, page 51). However, the exact level of dilution of mercury levels by terrigenous sediments seems to rely on a series of assumptions of unknown validity. This uncertainty is compounded by the lack of knowledge of exactly what organisms are present (as discussed in 1 above), and is of concern because of the vast volume of tailings (some 100mt) to be deposited.

2. Evaluation of the Major Risks to Marine Organisms Identified by NSR

The two major risks identified by NSR are risks to shallow water fauna due to the development of coastal facilities, and risks of impacts on deep sea fauna due to Deep Sea Tailing Placement (DSTP).

2.1 RISKS TO SHALLOW WATER FAUNA DUE TO DEVELOPMENT OF COASTAL FACILITIES

NSR expect the main source of impacts on shallow marine ecosystems to come from sediment runoff (via creeks) of material disturbed during construction, construction of port facilities, and shoreline dumping of incompetent wastes (NSR 1999a, 8.6.1), and these effects to be mainly limited to the construction phase. NSR predict zones of varying impact (NSR 1999a, Fig. 8.10) which seem consistent with the shallow water surveys and the levels of impacts expected by NSR from the three major sources identified above. There are however three additional issues relating to potential impacts on shallow water systems. Firstly, there are a number of potential sources of additional sediments and pollutants that may enter shallow waters. Some of these not identified by NSR and others mentioned but not treated in detail (Table 1). Secondly, there are a number of cases where the evaluation of risks and impacts has only extended to the situation prevailing in a best-case scenario: where the assumptions underlying the assessments are all justified and no accidents occur. For instance, there is no assessment of the risk of incompetent sediments not flowing to the deep ocean floor as NSR expect, or the effects on the biota of the repeated resuspension of such sediment if it was retained in shallow waters. Thirdly, some issues don't seem to be followed through to their logical conclusion. For example, NSR rate the risk of rupture to the slurry pipeline as unlikely. This seems somewhat over optimistic in such a seismically active area as graphically illustrated in Figure 6.4 of the Environmental Plan (p55). By NSRs own assessment a pipeline rupture is most likely at a low point and would release up to 2,000t of ore slurry. If this occurred where the slurry could be washed into the sea, 2,000t of ore slurry could be deposited into shallow water habitats. Any events like these would lead to greater than estimated inputs of sediments to shallow marine systems.

Taken together, there is a clear possibility that the inputs to shallow waters may be greater than expected, with the consequence that damage to the biota could be more extensive than expected.

Table 1: Additional Risks to Shallow Water Marine Environments

Potential Risks	Details
Rupture of slurry pipeline between Erima and Basamuk due to mechanical failure, seismic activity, volcanic activity etc.	NSR rate risk as unlikely. But safety measures mean there is the potential for a maximum loss from one event 2,000 tonnes of ore slurry.
Incompetent waste dumped in shallow water does not flow to deep ocean but remains in shallow water where it is repeatedly resuspended.	NSR suggest waste is likely to flow to deep ocean floor. No discussion of consequence should this assumption not be justified.
Treated sewage discharge from accommodation area.	NSR indicate no significant biological effects expected. But NSR do not detail level of sewage treatment.
Accidental flushing of toxic chemicals in water draining from general refinery site.	No assessment provided by NSR.
Accidental flushing of toxic chemicals in water draining from bunded areas of refinery site.	No assessment provided by NSR.
Failure or overtopping of bunding, refinery buildings etc. (e.g. due to tsunami)	Tsunamis with wave heights to 8m have occurred in the area, return period unknown.
Fuel spillage from ships Training and regulations to control this.	But NSR give no information on likelihood.

2.2 RISKS OF IMPACTS ON DEEP SEA FAUNA DUE TO DEEP SEA TAILING PLACEMENT (DSTP)

Potential impacts on deep sea fauna are related to the dumping of some 100mt of tailings into the deep sea over the life of the project. NSR state that the only likely effect is smothering of the benthos. This may be the case "...as long as ideal DSTP operation is assumed..." (Kline 1994, p 45). As with shallow water impacts projected effects of DSTP seem to be based almost entirely on best-case-scenarios. Consequently, the same uncertainty exists as discussed for shallow water impacts (see 2.1 above). I have previously discussed possible toxicity of the tailings and the fact that it is uncertain if pollutants such as mercury, that are known to bioaccumulate and biomagnify (Chen & Chen 1999), will really be diluted to background levels (1.3 above). The two difficult issues here are the actual extent of the tailings footprint (covered in 2.2.1 below) and the lack of knowledge of the type and abundance of organisms likely to be affected by burial. The lack of knowledge of the biota is covered in 1.2 (above). The possible responses of fish to DSTP are covered in 2.2.2 (below).

It is important to note that, even in ideal conditions, the reestablishment of a mature benthic community may take decades after the completion of tailings disposal (Thiel 1992). This recovery time is likely to be much longer if the tailings placement procedure does not go as planned (for instance see 2.2.1 below).

2.2.1 Additional possible effect of DSTP: As well as the effects of burial and possible toxic effects of the tailings there are a number of other issues to do with the DSTP (Table 2). Most important of these seems to be whether or not the slope below Basamuk Bay is great enough to allow tailings to flow away into the deep ocean as expected by NSR. In assessing the suitability of the Basamuk site for DSTP, NSR conclude that the submarine slopes below Basamuk have "very good" suitability in having slopes >120 that would allow tailings to flow away (NSR 1999a, Table 4.15). This has been disputed by the Minerals Policy Institute (MPI 1999, p6 & Fig. 1) who suggest that "...substantial quantities of tailings material will be deposited in the vicinity of 300m depth, and will not be transported as a coherent flow to abyssal zones"(MPI 1999, p6). The idea that sediment may be retained in shallow waters is supported by the consultant's data (NSR 1999a, Appendix 1, Fig. 2.5), which show that slopes of around 30 occur at about 600m and around 10 at 1000m. In fact no slopes below about 450m are steeper than 70. Although this is not my field, it seems clear that, based on the 120 principle, there is little chance of the tailings behaving as predicted and flowing into the deep ocean.

Table 2: Potential of Deep Sea Tailing Placement

Potential Risks	Details
DSTP smothering of benthos	Expected by NSR
DSTP chemical effects	Chemicals of potential environmental significance: Ni, Co, Cr, Mn, NH3
DSTP food chain effects	Metals known to biomagnify should be reduced below natural levels, but this is uncertain.
Slope may be too shallow to for DSTP waste to flow to deep waters	MPI (1999) suggest that substantial quantities of sediment may be deposited at shallow depths.
DSTP rupture	NSR suggest localised smothering of benthos.
Resuspension of DSTP waste by upwelling	Maximum depth of upwelling 100m from review in Appendix 2.
Resuspension of DSTP waste by bottom currents	Deep water current metering suggests lack of strong deep water currents.
DSTP outfall depth not below actual maximum depth of surface mixed layer	No assessment provided by NSR.
Resuspension of DSTP waste by abyssal storms	No assessment provided by NSR.
Resuspension of DSTP waste due to seismic activity	No assessment provided by NSR.
DSTP outfall material returned to surface layers of the sediment by biological activity	No assessment provided by NSR.
DSTP outfall material returned to surface layers of the ocean by biological activity	No assessment provided by NSR.
Sediment from DSTP may be different size to the natural sediments, so changing substrate type, and leading to change in biological communities	No assessment provided by NSR.
DSTP may produce more waste than predicted (already suggested that the project may be extended)	No assessment provided by NSR.

If the sediment fails to flow to deep waters a range of unpredicted biological effects are likely:

1. A different (shallow water) fauna from that predicted would be influenced by the tailings,
2. Large build-ups of sediment at shallow depths may provide the opportunity for catastrophic slumping leading to scouring of existing sediments, producing unexpected habitat changes,
3. Large tailings build-ups mean much deeper and more rapid burial of fauna leading to increased mortality that may even influence mobile fauna able to deal with slow burial by burrowing upwards,
4. Build ups close to shore would mean that much less natural terrigenous sediment would be available to mix with the tailings because few streams enter Basamuk Canyon itself (NSR 1999a, Fig. 8.13), leading to increased danger of toxic effects due to failure of assumptions about dilution due to burial,
5. Large repositories of sediment in relatively shallow water increase the danger of resuspension of sediments due to upwelling, abyssal storms and turbulent, turbidity plumes generated by catastrophic slumping.
6. Retention of sediments in shallow waters transfers the impact of tailings disposal into the 100-400m depth range preferred by Pristopomoides multidens and Etelis carbunculus (Allen 1985, NSR 1999a), thereby impacting the potential fishery identified in the Environmental Plan.

There are at least eight other issues to do with DSTP. The first four of these are out of my area of expertise so I am not qualified to determine whether or not the expectations of NSR on these issues are justified. However, I note them here because they relate to assumptions that, if not justified, suggest that the damage to fauna may be more extensive than expected.

1. The possibility of resuspension of DSTP waste or its redistribution due to upwelling or stronger than expected bottom currents.
2. That DSTP outfall depth may not be below the actual maximum depth of surface mixed layer.
3. That wastes deposited in the deep sea may be resuspended by abyssal storms. Violent abyssal storms are known to occur in the deep ocean and appear to be related to such things as severe surface weather or seismic activity (Gross and Dade 1991). At present these storms are difficult to predict but are known to be capable of resuspending large volumes of sediments. The danger is that such events may increase the footprint of the tailings impacts or, particularly if the tailings do not flow to deep waters as expected, cause the tailings sediments to impact shallow water environments. Similarly, resuspension of sediments by seismic activity seem a possibility in such a seismically active area.
4. The project may produce more waste than predicted (it is already suggested in the Environmental Plan that the project may be extended). If this happens the estimates of volumes of tailings and consequently the extent of impacts would need to be revised upwards.
5. There is the possibility that buried DSTP material could be returned to surface layers of the sediment by biological activity. Due to the lack of knowledge of the deep sea benthic organisms of the area there is no way to evaluate this possibility.
6. It is possible that DSTP material could be moved to surface layers of the ocean by biological activity such as vertical migration. Vertical migration may occur over hundreds of metres for some plankton and deep sea fishes, with migrations of 400-500 m recorded for a number of deep sea fishes (Pearcy et al. 1977, Willis and Pearcy1980, Williamson & Koslow 1997). Gwyther (1998) suggests that it is generally considered unlikely that significant volumes of pollution could be transported to shallow depths by this process. This may well be correct but, once again, out lack of detailed understanding of deep sea fauna and faunal processes means that this possibility is difficult to evaluate. At face value, a vertical migration of 500 m by small fish or invertebrates does seem unlikely to transport a great deal of material to surface layers. However, a number of complicating points need to be considered. Firstly, vertical migrations usually occur every day (Watanabe et al. 1999), so even small quantities of pollutants moved per day could represent large volumes over time. Secondly, deep sea species occupy a variety of preferred depth ranges (Hopkins et al. 1994) with vertical migration occurring at all depths. Thus there is the possibility that over time pollutants could be passed towards the surface through the action of predators feeding on species migrating up from greater depths. Thirdly, the percentage of the total biomass migrating vertically can be substantial. Williamson & Koslow (1997) found that during the day most deep-water fish biomass of southern Tasmania was found below 400 m, while at night 53% was found in the upper 300 m of the water column. Fourthly, vertical migration is not confined to a daily pattern. For example, it is common for deep water fish to change their depth distribution with growth (Willis and Pearcy1980). Additionally, the broad depth ranges reported for some deep sea fishes (e.g. 400-1,600m for Sebastolobus altivelis, (Wakefield & Smith 1990)) suggests that individual fish may be able to move from very deep to quite shallow waters over time. This seems particularly likely for demersal fish moving along the bottom profile. These complicating issues suggest considerable uncertainty in our understanding of the biological processes likely to lead to vertical transport of pollutants. When this is coupled with the poor understanding of the nature of the fauna of the deep ocean off Basamuk, it is clear that no simple evaluation of the likelihood of biologically mediated transport to shallow waters could be made with great surety.
7. Sediment from DSTP appear likely to be of a different size distribution to that of the natural sediments. The sediment size data presented by NSR suffers from the same paucity of sampling as the biological data because it is derived from the same pipe dredge samples as the benthos samples. If it was accurate it would present a worrying picture. The distribution of tailing solids (81% silt; 13% clay; 6% fine sand (Appendix 16, p24)) is very different in composition to the natural sediments (e.g. 1200 m (deepest sample): 59.4% silt; 1.1% clay; 39.4% sand (Appendix 15, Table 3.3). In fact the deep ocean sediments of Basamuk decreased in silt content with depth (from 200m) (Appendix 15, Table 3.3). This means that the post-tailings placement sediment composition will probably be quite different to that of the existing sediment. The composition of benthic faunas is greatly dependent on sediment characteristics, so the post-tailings placement fauna is likely to be taxonomically different to the existing fauna. This may mean a change in the trophic structure leading to changes in food chains with unknown outcomes for organisms higher up deep sea food webs.

8. When plumes develop along density interfaces (NSR 1999a, Fig. 8.11) substantial quantities of tailings can separate from the primary flow and spread out horizontally (MPI 1999). These plumes are likely to influence, perhaps adversely, mid-water fish and invertebrates. There is no evaluation of this likelihood and no biological information on such organisms.

2.2.2 Possible responses of fish to DSTP: NSR suggests (Appendix 5, Part B, p57) that fishes will move to or from affected areas. Movement of fish away from tailings plumes might be to escape toxic chemicals or to prevent clogging of their gills by sediment. Movement into sediment plumes may represent prey species taking advantage of the cover afforded by increased turbidity (Abrahams and Kattenfeld 1997). Whether or not fish can and do detect and respond to tailings plumes is important because of the assumption that fish will move away from the tailings plume, so limiting the adverse effects on fishes to displacement rather than direct mortality (Appendix 5, Part B, p 54 & p 62).

There is little published literature that relates directly to the response of deep sea fishes to tailings plumes or tailings sediments. There have, however, been a number of studies in shallow marine waters and fresh waters that shed some light on the subject. Field and experimental investigations have repeatedly found that fish can detect and avoid such things as changes in pH, turbidity and chemical pollutants (Barry 1978, Tatsukawa and Hidaka 1978, Cherry et al. 1979, McMahon and Kynard 1979, Schumacher and Ney 1980, Giattina et al. 1981, Gunkel et al. 1983, Peterson et al. 1989, Gagen et al. 1994, Newman and Dolloff 1995). Video observations suggest that benthic fish detect and respond to chemical gradients and current information in an olfactory plume (Montgomery et al. 1999). Fish do not only respond to tailings plumes by avoiding them. Particularly where toxic substances are absent, fish may enter spills repeatedly, as was seen for a kaolin spill on a coral reef in Hawaii (Dollar and Grigg 1981). Such behaviour may be exhibited by prey fish using turbidity as a refuge from predation (Cyrus & Blaber 1992) or predators seeking prey in areas where they are likely to hide. It is clear that in general fish have the ability to detect and respond to tailings plumes and their various chemical constituents.

The particular situation of deep water marine species is less clear, mainly due to the difficulty of obtaining quality data on the behaviour of mobile deep water animals. There is probably no reason to think that deep water fish would be less able to detect and respond to environmental cues than their shallow water counterparts. However, deep sea fish are often relatively poor swimmers so their ability to respond by moving away from a fast moving tailings plume requires further study. One study using acoustic imaging of turbidity currents resulting from mine tailings discharge in British Columbia, detected discrete acoustic scatterers, interpreted as fish, that appeared to avoid surges of turbidity (Hay 1987). Despite this, there are no clear data available on the ability of particular species to avoid tailings plumes.

Although fish do seem to avoid settled sediments (see below), there appears little or no hard evidence that fish actively avoid tailings plumes. Consequently, it seems that rather than assuming that fish will actively avoid plumes, it would be better to take a precautionary approach and assume that fish will come into contact with tailing plume sediment. Again this seems a situation where some attention could have been paid to a "worst-case" assessment. A "worst-case" assessment would also need to consider the possibility that if a plume developed at the outfall numerous shallow water fish would be impacted, including some current and/or potential fisheries species.

Even the avoidance of tailings plumes may cause problems. Turbidity plumes are likely to form as sediment breaks away from the tailings stream at discontinuities in the water column (NSR 1999a), and/or onshore currents may transport turbid water to shallow depths (Luick 2001). Oceanic fish, such as tuna and billfish, are sensitive to turbid waters, actively avoiding them (Barry 1978). Tuna are very important commercial species in Papua New Guinea, supporting a large harvest by distant water fishing nations (Tanaka 1989, Opnai and Aisti 1995) and a developing local fishing industry. Tuna are highly migratory (Suhendrata et al. 1986, Aqorau 2000), regularly covering large distances, often along predictable migratory routes. Consequently, given their tendency to avoid turbid waters, the potential exists for turbidity plumes to disrupt migrations, or impact on spawning aggregations or nursery grounds. The potential for human activities to adversely effect bluewater fishes, particularly during their early life stages is already of concern in the western Atlantic Ocean (de Sylva et al., 2000).

A second issue is the response of fish to the settled tailings sediments themselves. It seems likely that fish may avoid tailings sediments for extended periods. In an experiment with gold mine tailings in Alaska, yellowfin sole avoided fresh tailings in favour of natural sediments or weathered tailings unless the fresh tailings were covered by at least 2 cm of natural sediments (Johnson et al. 1998a). Similarly, tanner crabs, particularly ovigerous females, avoided areas affected by tailings (Johnson et al. 1998b). In fresh water habitats cutthroat trout are known to avoid habitats contaminated by mining wastes (Woodward et al.1997). Additionally sub-lethal effect may occur. Growth of young-of-the-year walleye showed reduced growth in areas impacted by tailings spills (Leis and Fox 1996).

2.2.3 Pollutants and Fishes

Given the lack of worst-case evaluation and the poor quality of the biological data, it is not possible to make predictions of the likely effects of toxins that are specific to the Ramu mine project. However, NSR indicate that ammonia and a number of metals (e.g. Hg, Cd, Cu, Co, Cr, Fe, Mn, Ni) are likely to be at elevated levels in either the tailings solids, tailings plume or interstitial water (Appendix 16), so it seems appropriate to assess the potential effects of metals and ammonia on fishes if they did reach toxic levels. As is the case with most aspects of the biology of deep water fishes, there is little information on responses to pollutants, so I will rely on the extensive literature that relates to shallow marine and freshwater fishes.

A range of metals can be taken up directly from the ingestion of sediments by some species of fish (Chen & Chen 1999). For other species metals may be taken up from the water column over gill membranes (Meyer et al. 1999), while in still other cases the most common route for metal uptake is via the food chain. Where concentrations are high enough, metals such as Hg, Pb, Cu and Ni are known to produce acute toxicity, leading to death (Qureshi et al. 1980, Hutchinson & Sprague 1982, Denton & Burdon-Jones 1986, Alam & Maughan 1995), and reproductive failure (Hutchinson & Sprague 1982), but more subtle effects such as cell damage (Delvalls et al. 1998) have been detected at lower levels of pollution.

Each pollutant has its own range of effects depending largely on its concentration. For example, a number of metals, especially Cu and Ni, have been shown to inhibit hatching of freshwater zebrafish (Dave & Xiu 1991). Additionally, Ni has been shown to induce hyperglycemia (elevated blood sugar levels) in freshwater fish leading to acute toxicity (Chaundhry & Nath 1985). Mercury is known to cause a range of problems, including immune system damage (Sweet 1999), growth and reproductive inhibition (Friedmann et al. 1996), adverse effects on blood composition (Hilmy et al. 1980), and alteration in feeding behaviour (Weis & Khan 1990). Metals do not usually occur alone, and the effect of combinations of metals is unpredictable. In some cases combinations of metals can lead to reduced toxicity, probably because the less toxic metals blocks the more toxic metals from entering receptor sites (Verma et al. 1982). However, other combinations (e.g. Cr/Ni) can work in synergy, to produce toxic effects that are greater than the additive contribution of the individual metals (Khangarot 1981, Khangarot et al. 1981, Verma et al. 1982, Khangarot & Ray1990). Additionally, a number of studies have shown that pH can effect the toxicity of individual metals such Cu (Hickie et al. 1993) or groups of metals (Hutchinson & Sprague 1982). For instance, at low pH reproductive failure and juvenile mortality can be induced by levels of metals only 0.5 of natural levels (Hutchinson & Sprague 1982).

Ammonia, together with a variety of nitrogenous chemicals, can also be acutely toxic to fish (Buhl and Hamilton 2000). However, estimating the exact concentration of ammonia that will produce toxic effects is difficult because different species of fish show different tolerance levels (Parra and Yufera 1999). Even at concentrations below those producing acute toxic effects ammonia can produce sublethal effects such as reduced growth and gill damage (Frances et al. 2000). Sublethal effects, such as reduced growth, have the potential to reduce the health of fish together with there reproductive success and fecundity.

Different pollutants are taken up by, and effect, different species in different ways (Qureshi et al. 1980, Hanson 1997). As a consequence, it is vital to have a detailed knowledge of the fauna likely to be impacted when assessing likely effects of metal pollutants. Moreover, the exact level at which toxicity is detected can vary by as much as 1-2 orders of magnitude between different studies (Dave & Xiu 1991), suggesting that a conservative approach to such evaluations is sensible.

3. Conclusions relative to the three specific aims

1. Assess the potential risks posed to the ecology of Astrolabe Bay region by the mine proposal with a particular emphasis on local fish species.

The lack of any substantial knowledge of the marine fauna of the deep waters of Astrolabe Bay renders assessment of potential risks a futile task. This is exacerbated by the fact that the Environmental Plan limits the assessment of most risks and impacts to the best-case scenario: where the assumptions underlying the assessments are all justified and no accidents occur. It is unrealistic to expect all assumptions to be justified and no accidents to occur. As a consequence, developing an understanding of risk requires an understanding of worst-case, as well as best-case scenarios. Of particular concern is that the poor quality of data on deep sea fishes means that important or vital spawning, feeding or nursery grounds could have been overlooked, and that major deep sea fisheries resources may not have been identified.

Baseline information on shallow water fauna is much more detailed and relevant, but again worst-case scenarios are rarely evaluated, meaning that the risks and impacts stated may be over optimistic.

If sediment levels in coastal waters were to increase substantially (for instance due to one or more of the uncertainties mentioned above) there could well be serious consequences to the fisheries stocks in the area. The fish fauna of the shallow waters off Basamuk (Appendix 3, 2.4.2 & table 2.3) are largely those characteristic of clear water areas (Randall et al. 1990). Even without considering the potential presence of toxic materials, a substantial increase in turbidity, especially if it was maintained for an extended period, would be likely to exclude many of the species that rely on clear water conditions, from the area. This is likely to be a large proportion of the species recorded in Appendix 3, 2.4.2, because, although most of those species also occur on the Great Barrier Reef (Randall et al. 1990), only a few of them have been recorded in turbid coastal areas adjacent to the Great Barrier Reef (Blaber 1980, Robertson & Duke 1987, Sheaves 1992, 1998).

2. Assess the international literature on the response of fish to tailings plumes.

The international literature on the response of fish to tailings plumes relates mainly to shallow water situations. However, it is clear that, in general, fish can detect and respond to tailing plumes and chemical pollutants. Unfortunately, there is little detailed information on the response of deep sea fish or of their ability to escape from tailings plumes if they do detect them.

3. Assess the outputs of the Highlands Pacific/NSR Environmental Impact Assessment. Specifically to comment on the confidence of the EIA predictions in relation to information available to the EIA process during its preparation.

As stated under 1 (above) the Highlands Pacific/NSR Environmental Impact Assessment suffers from two major problems; a lack of detailed biological assessment of deep water fauna, and tendency to base evaluations on best-case situations. This means that the EIA predictions are probably over optimistic, and, in the case of the deep sea fauna, without substantive foundation.

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Chapter 6

A **Global review** of STD operations

One of the major challenges for a metal mining operation is the disposal of the spent tailings in a cost effective and environmentally responsible manner. Aside from the technically difficult alternatives of dry disposal or mine back-filling, this leaves two options in a coastal mining operation: a tailings dam or STD.

On-land tailings disposal often involves costly construction of an impoundment to flood the tailings, raising concerns over the potential impacts on aesthetics, recreation, wildlife and surface and ground water quality. Any dissolved metals or residual milling reagents in the spillover water will, if not treated, be released into the sea regardless. On-land impoundments also create the long-term responsibility and expense of maintenance to avoid catastrophic flooding and contaminant release. In a best case scenario, STD should result in temporary impacts. Given the proper circumstances it is often preferred over on-land disposal from an environmental and economic view. The economic advantages to the mine operator, particularly during construction and reclamation are self evident with regard to dam construction and maintenance.

The basic thrust of STD design is that the virtually unlimited supply of oxygen in air, plus rainfall, makes onland deposition of potentially acid-generating tailings more environmentally risky over the very long term, than underwater disposal. The concept of STD is based on discharge at the edge of an extended drop-off, say to 1000m, and at a depth below the euphotic zone. Discharge must be at a location where the tailings slurry from the pipeline will form a turbidity current flowing coherently with minimum dispersal until it reaches the base of a drop-off. Submarine canyons or naturally excised channels beyond fringing coral reefs are in principle suitable sites. There must be very little or no risk at the site of impacting amounts of the tailings upwelling back into shallow water.

The biological impact of STD:

The available literature concerning STD lacks detailed laboratory and field studies addressing specific biological aspects of STD. It is also largely published in in-house 'gray' literature, rather than in peer-reviewed scientific journals. Consequently potential impacts must largely be inferred from related research concerning dredging, deep-sea mining, and disposal of other industrial effluent.

Much of the available literature concerning STD is unpublished and limited to a restricted number of sites. From this information and related research it appears that benthic smothering is the most common major consequence of a properly designed STD system. However there have been cases of metal bioaccumulation due to inadequate preliminary evaluation and shallow water habitat alteration has resulted from STD. In all STD operations, a reduction in biological production is likely due to benthic smothering. STD can result in massive sea floor sediment deposition. STD may also increase suspended sediment, trace metals and residual milling reagents in receiving waters. These perturbations which are highly site dependant, invariably smother benthic organisms and could potentially affect or alter fish plankton and benthos through acute and chronic toxicity, bioaccumulation, behavioral changes, smothering, derived secondary effects and habitat alteration. The rate of ecological recovery after termination of an STD operation varies and is difficult to assess.

The consequences of STD are site specific and it is generally problematic to extrapolate success or failure at one site, to sites elsewhere. Additional research is needed concerning possible consequences of milling reagents and the broad implications of benthic smothering. Also, methodologies are needed to allow better prediction of benthic recolonisation and ecological implications of metal bioaccumulation.

Case Studies:

Large-scale tailings disposal presents many engineering challenges and there is considerable potential for environmental problems. These chosen cases are valuable as they show how STD design options need to be established for specific mining and environmental parameters.

Island Copper Mine, British Columbia

No review of STD operations is complete without discussion of the Island Copper mine, which is one of the most intensively studied STD operations. It is located on Vancouver Island, British Columbia and has been discharging tailings at a depth of 40m into Rupert Inlet since 1971 at rates varying between 33,000 and 55,000 metric tonnes per day. Rupert inlet is a well mixed fjord, 10km long, approximately 1.8km wide and is connected to Holberg Inlet. Both fjords are separated from the Pacific Ocean by an 18m deep sill. At Island Copper reported environmental impacts have been minimal (Poling et al, 1993) though there have been instances involving the resuspension of deposited tailings (Goyette and Nelson, 1977). However, the example of Island Copper has been over-extrapolated to non-analogous situations in other regions of the planet.

In a laboratory study, upon submersion of tailings in sea water, iron, copper, and lead water concentration peaked after 3 hours and declined to background levels within a month. (Hoff et al, 1982). The advancing tailings deposit could be delineated by higher total concentrations of copper and zinc relative to the natural sediment (Thomson and Paton, 1975). One of the main reasons cited by Pedersen and Losher (1988) for a lack of appreciable metal leaching into Rupert Inlet was the rapid burial of the tailings, limiting their exposure to oxygenated bottom waters. The authors questioned if mobilisation of metals may increase when the operation ceases but before a natural sediment layer covers the deposit

Aerial photograph of Island Copper during operation.

Occasionally tidal currents flowing into Rupert Inlet through a narrow passage have caused a considerable resuspension of deposited tailings. The possibility of this occurrence was apparently disregarded during planning studies. The suspended tailings have extended throughout Rupert Inlet and into the adjoining water bodies, periodically rising into the water surface and depositing in intertidal areas. In the process a formerly rocky intertidal area has been converted to a fine grained habitat (Poling , 1992). No information was found addressing the biological relevance of this habitat alteration. Waldichuck and Buchanan (1980) mention the possibility for effect on the local fauna including prawn, crabs, salmon, herring, mussels and various fish species.

In other studies:

- Ellis and Heim (1985) noted an absence of phytoplankton in the layers with visible sediment
- A study employing acoustic sounders in Rupert Inlet detected what appeared to be fish in close association with the turbidity current at approx 130m (Hay et al, 1982)
- Benthic sampling suggested a complete absence of fauna only in areas directly affected by the erosion from the turbidity current (Ellis and Hoover, 1990b), and in other areas there was a gradual succession of invertebrates.
- Young and Ellis (1982) concluded that there was no evidence of bioaccumulation of metals in biota although Waldichuck and Buchanan (1980) stated that long term changes in the deposit could not be predicted.

Misima Gold Mine, Papua New Guinea

The Misima Gold and silver mine is located on Misima Island, one of the most southerly islands in Papua New Guinea. The mine is important in the context of STD for a number of reasons (US Dept of Interior OFR 37-94);

1) It was the first case outside Canada (after Island Copper and Kitsault) in which the exploration of STD as a tailings option was documented.

2) The STD involved is the first example of "Very Deep STD", utilising an engineered seawater mixing outfall discharging to a slope leading to abyssal depths of more than a thousand metres.

3) The milling process involved the use of cyanide, for which special precautions need to be taken.

4) The waste soft rock is dumped at a shoreline site with significant environmental impact. This environmental impact needs assessment to distinguish it from that of the STD.

5) The environmental assessments, predictions and monitoring at Misima are being used widely as role models for other mines there and elsewhere in the South Pacific Region.

The Misima Mine was permitted in 1987 and began operation in 1989. The STD outfall terminus is at 118m depth and is about 200m from shore on a steeply sloped >45° degree seabed. Tailings are rich in cadmium, copper, lead and cyanide. The State of PNG has granted the mine a 'mixing zone' of 1.2km around the outfall and to a depth of 70m. Within this area the environmental regulations concerning water quality do not apply. At the edge of the mixing zone dissolved concentrations of metals are expected to be below the total metal concentrations stipulated in the schedules of the Water Resources Act (1982), (NSR, 1996). Water quality below this mixing zone is not monitored for compliance purposes.

The marine monitoring program at Misima has been largely limited to assessing impact in shallow water. At one stage there was an attempt to observe the movement of soft waste down the submarine slope but this was not successful due to excessive turbidity in the water column. However a compliance validation survey carried out by RESCAN used a submersible to check for the development of suspended turbidity fields and found several such fields at varying depths. Thus there was either some secondary plume development from the tailing density current or the turbidity fields could have been generated from other mine-derived sediment sources such as the soft waste dumping or turbid run-off from disturbed land onshore (NSR, 1996).

The conventional wisdom in the mining industry considers the abyssal plains as a calm place unaffected by near-surface oceanographic dynamics. In any one place abyssal plains support a low biodiversity fauna with low productivity although there is considerable heterogeneity in these communities. Extension of this theory implies that the abyssally deposited tailings will smother almost all organisms even at the edges of the tailings and that recovery to a productive ecosystem will be very slow. The conventional wisdom may not be accurate in the real situation at Misima. It is now known that the deep sea ecosystem is not always a calm place and has potential to recover after natural catastrophes arising from 1) turbidity current flow, erosion and deposition, 2) massive slumps of perched turbidities and 3) abyssal storms generated by surface events.

This satellite picture shows the effect of mine discharges including STD and barge dumping from Lihir Mine in PNG.

During examination of the tailings discharge to a depth of 160m, some 48m deeper than the outfall, the following was found (NSR, 1997):

- plumes of suspended tailing solids shear off horizontally into the water column as the tailing density current descends the submarine slope.
- plumes occur where ever relatively strong density discontinuities occur.
- plumes of turbidity appear to be vertically trapped by density stratification and spread out horizontally along the density discontinuities where they are dispersed by prevailing ocean currents
- the shallowest plume was at 150m and others at 250, 370 and 450m
- subsurface plumes were still detectable some 5km to the east and 3km to the south west of the outfall

Effects on Marine Biota: In shallow water, monitoring has been comprehensive. This work has accurately determined that extent of impact zones: severe (1km on either side of the mine), transitional (3km on either side of the mine) and minor (5km on either side of the mine). Natural Systems Research (NSR, 1999) found that at Port Maika levels of lead, copper and zinc in shellfish (Turbo argyrostoma) were high and "may be attributable" to Misima Mine's activities. High levels of copper and lead were also found in Common Rock Crab hepatopancreas tissue, also suggesting Misima Mine's activities are responsible.

In regard to the danger marine contamination to local people, NSR suggests:

> "metal values in some edible seafood species exceed food standards and there is evidence that MMLs activities may have caused increased metal levels in seafood at some potentially impacted sites compared to control sites. While there is a potential human health impact to villagers who consume any of the seafood types with elevated metal values, the potential exposures ranged from exceedingly low to very low in all cases....This may change however with mine closure and a return to a more traditional way of life based on a natural harvest."(NSR, 1999).

In 1994 the Ocean Sciences Institute of Sydney undertook ocean floor coring project and found that tailings deposits greater than 1.5m in thickness occupy an area of approximately 20km_ (NSR, 1997). A larger area is covered in thinner deposits throughout the Bwagaoia Basin. There is no understanding of the impact of these deposits on the deep sea ecology as there was no baseline study to determine what was there prior to the development of the mine. Similarly, NSR's predictions of post-mine recolonisation of tailings are entirely based on what happened at Island Copper and Alice Arm in Canada – both temperate locations.

In regard to the impact of STD on deep-water fish (by their definition, 80-300m), NSR and Misima Mine have relied on the theory of 'avoidance behaviour' in their claim to have had no impact. Due to poor baseline surveys and little monitoring of the deep-water fish fauna, there is no evidence that the discharges have or have not, had an effect on the fish populations.

At Misima, the social implications of STD are summarised by Hughes (in US Dept of Interior OFR 37-94), and often repeated by Placer Pacific and NSR; "The Misima people do not fish at such great depths and there is little potential for commercial deep water fishing." At this time we can conclude that the STD at Misima has had some but unmeasured effect on the local abyssal fauna.

Black Angel Mine, Greenland

The Black Angel lead-zinc mine located at Marmorilik within a complex of fjords in mid-western Greenland around a sulphide ore body comprised of pyrite, sphalerite and galena. It is considered to be the first modern mine in the western hemisphere to be brought into operation in arctic conditions. The Black Angel is an important case history as the STD system adopted did not prevent contamination of the receiving area. This arose through a complex of causes which are well documented. The case demonstrates some mining and environmental parameters which must be accommodated within the design of the STD system, and in operation of the milling system and is a good example of the need for adequate mining and environmental information prior to detailed design of an STD system.

With the absence of suitable land disposal sites close to the mine, the Danish Government gave approval by mid-1972 for the disposal of the tailings underwater. Tailings discharge was equivalent to a discharge of 6,075kg of lead per day and 12,150kg of zinc per day and occurred some 33m below the surface of the sea. In a description closely akin to many of the present era, Eric Mikkelborg, associate editor of the Canadian Mining Journal said "there is no trace of tailing to be seen anywhere. Of course the obvious place for them is in the fjord and that's where they go...Even at the shoreline the Fjord is well over 200ft deep and the tailings are just swallowed up" (US Dept of Interior OFR 37-94).

As it turned out these statements depicted a far too simplistic evaluation. By 1974 Danish scientists found significant increases in dissolved lead and zinc in the sea water near the bottom of the fjord. In order to understand the tailing characteristics it is important to understand the essential features of the flotation process:

- The flotation process used sea water instead of fresh water
- In order to make lead-zinc separation, in addition to Xanthate collector and Dowfroth (propylene–oxide) frother, sodium cyanide and zinc sulphate were added in the lead flotation circuit.
- After the galena was floated off, copper sulphate was added to activate the sphalerite and then the zinc concentrate was floated from the pyrite and silicate tailing.
- Antifreeze drilling brine in the mining operation contributed to the available lead and the zinc sulphate was a major source of available lead in the tailing.

Samples taken in 1974, 1 year after operation, showed statistically significant increases in lead and zinc in blue mussels and seaweed in nearly all sampling locations. At a distance of 6km from the discharge site, levels of zinc and lead in mussels were 3.4 times and 69 times normal background respectively (Asmund et al , 1975). High lead concentrations in the fjord mussels was most likely due to their preferential uptake of available particulate lead. Later studies on spotted wolf fish showed increases in lead contents of both livers and kidneys but no increase in the lead of mussel (Bollingberg and Johansen (1979). Since wolf fish is non-migratory and feeds heavily on blue mussels they were very sensitive to metal contamination.

These problems arose because:

- it as assumed the residual heavy metals would be present as insoluble sulphides
- detailed oceanographic studies through a full year were not commissioned. These would have shown that while the fjord stratified in summer it became well mixed in winter, which resulted in the transport of contaminants out of the fjord
- the mill tailing contained significant oxidised lead and zinc species that were rapidly soluble in water, and that while they were insoluble in the tailings flow they were liberated due to dilution and reduction of pH on entry to the fjord.

Atlas Copper Mine (Philippines)

The Atlas Mine is located on the central part of Cebu Island, about 7km from Tanon Strait. The major gangue minerals of the orebody are silica and silicates, with residual copper, pyrite, gold, silver, molybdenite and magnetite. It was retrofitted to discharge its tailings into the sea in 1971. By 1981, 100,000 tonnes per day were being discharged. It vies with Island Copper for being the first to adopt true STD and is important as one of the first STD operations in the tropics.

Tailings discharge occurs at a site selected from bathymetric surveys because of the presence of a deep trench with 15° slope near shore leading to the Tanon Channel with depths of 350m only 1.5km from shore. A strong shoreline current was expected to disperse suspended slimes. The tailings were discharged at 10m below sea level.

By 1981 Alino (1984) found evidence for some elevated sedimentation, metal contamination and coral cover around the outfall. Elevated copper levels in traps with highest values closest to Ibo Point indicated that some tailings were surfacing. The major environmental impact reported in an otherwise sparse literature is the absence of benthic fauna over an area 3.5km by 12km.

Cayeli Bakir Copper-Zinc Mine, Turkey

The Cayeli Bakir Copper-Zinc Mine discharges to the Black Sea through an outfall 350m deep and 3.5km long. It is permitted to discharge 427,000m_ of solids and 4,000,000m_ of treated liquid and all other kinds of wastes into what are believed to be anoxic waters.

The Turkish regulatory agency did not accept an initially proposed 150m discharge depth, but increased it to 350m. This added substantially to the cost and technical difficulties in installing and maintaining the system. As the eastern Black Sea contributes approximately 57% of the total Turkish sea fish harvest, the authorities felt that it was important to discharge at such a depth (US Dept of Interior OFR 37-94).

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