An Overview of Mining-Related Environmental and Human Health Issues, Marinduque Island, Philippines: Observations from a Joint U.S. Geological Survey – Armed Forces Institute of Pathology Reconnaissance Field Evaluation, May 12-19, 2000

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Boac River, tailings from 1996 spill

Tapian pit lake

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Executive Summary

This report summarizes results of a visit by the report authors to Marinduque Island, Philippines, in May 2000. The purpose of the visit was to conduct a preliminary examination of environmental problems created by a 1996 tailings spill from the Marcopper open-pit copper mine. The mine was operated from 1969-1996 by Marcopper Mining Corporation, under 39.9% ownership, and design and management control, of Placer Dome, Inc.

Our trip expenses to and from the Philippines were funded by the USGS. In-country expenses were paid by the offices of Congressman Reyes and the Governor of Marinduque, Carmencita O. Reyes.

This report includes observations we made based on our relatively short visit to the island, and observations based upon a preliminary review of the literature available on the island's mining-environmental issues. In addition, we have included preliminary interpretations and analytical results of some water, sediment, and mine waste samples collected during our trip. We also highlight the environmental and human health issues we feel are in need of further study and consideration for mitigation or remediation. *This report is preliminary and is not intended to be a comprehensive or final review of the island's mining-environmental issues; many areas of further study are clearly needed.*

Mining-related environmental problems have greatly affected several areas on Marinduque. Most of the observed problems stem from large-scale open pit copper mining at Marcopper, and primarily affect:

- The Mogpog and Boac River systems, which received or are still receiving acid rock drainage, high sediment loads, and tailings transported from the mine site;
- The beaches and ocean at and near the mouth of the Mogpog and Boac River systems;
- Calancan Bay, into which very large volumes of tailings were disposed for 16 years; and
- The area within and adjacent to the mine site, which is affected by multiple sources of acid-rock drainage into ground and surface waters, and by sediments eroded from mine waste piles.

Less well-known but potentially significant environmental problems may also exist as a result of open pit mining at the CMI mine near Mogpog. Potential problems at CMI include:

- Effects of acid-rock drainage from mine dumps, tailings impoundments, and the mine's open pit on local surface and ground waters; and
- Effects of mine wastes and tailings on the marine ecosystem.

Our team has identified a number of concerns associated with each of these areas, and has summarized for many of the areas actions that can be taken to better understand and (or) help mitigate the problems.

Boac River tailings

The main priority of our visit was to get an overview of the 1996 Boac River tailings spill, and the proposed options to remediate the spill. From information gathered on our trip, a limited review we have made of reports on the tailings, and the results of simple leach experiments we performed to examine metal mobility from the

tailings, several conclusions are clear. The tailings deposits in the Boac River, as concluded in earlier studies by the mining company, will be a long-term source of acid and metals into the environment, and are therefore in need of remediation. Due to oxidation of sulfides in the tailings, the generation of acid waters during rainstorms, and the evaporation of these acid waters during dry periods, substantial deposits of soluble salts have built up within the tailings. These salts store acid and metals in a readily soluble solid form until the next rainstorm, when they are likely to dissolve and produce an ecologically damaging flush of acid and metals into the Boac River. The cycle of salt formation and dissolution can be repeated each dry and wet period.

Remedial options: A number of remedial options are available for the Boac River tailings, including many options identified by the mining company and other options proposed by residents, companies, or groups. Many reports have been generated by the mining company that evaluate their proposed options. Using a risk analysis process, the company has determined submarine tailings disposal to be its preferred remedial option. *However, based on the reports we have reviewed, it is not clear whether key scientific data and interpretations have been made that in our minds are crucial to adequately understand the strengths and weaknesses of each of the remedial options.*

Assessing the remedial options: We have outlined a process by which remedial options available for the Boac River tailings can be assessed. The purpose of an independent assessment should be to review each option and present information on the scientific and engineering strengths and weaknesses of each option. This then would allow the people of Marinduque to make the best, most scientifically informed choice possible regarding remediation. *Ultimately, no single option may prove ideal, but rather a combination of options may be best.*

The first step is a thorough, independent, and unbiased scientific review of all information and reports gathered to date, to determine if enough information is available to adequately judge the scientific strengths and weaknesses of each of the options. If not, then new data or information must be gathered. Similarly, for options not covered in the published reports, scientific and engineering data must be gathered to assess the strengths and weaknesses of each option. *The monetary and time costs of gathering new data and information to assess a particular option should be carefully weighed. If new data acquisition for a particular option is too costly, then that option may not be viable.*

We have provided in the report examples of the types of scientific questions needing to be addressed for any proposed remedial option in order to assess its strengths and weaknesses. These include such issues as the long-term viability of the proposed option, potential ways that the option could fail, and potential environmental impacts should the option fail to work properly.

An example of one type of scientific information that can be used to help assess the remedial options is a simple leach experiment we performed to understand reactions of Boac River tailings with sea water. *This leach test raises significant concerns that submarine disposal of the salt-rich tailings from the Boac River banks and tailings flats into the ocean may have substantial adverse environmental impacts. Due to the substantial amounts of soluble salts in the tailings and the strong ability of chloride in sea water to complex metals from the tailings, there is considerable potential that a highly acidic, metal-enriched, and environmentally detrimental plume would develop in the ocean around the tailings discharge point during tailings disposal; it is unclear whether acid and metals would continue to leach from the tailings once disposal is finished. Unless proven otherwise by further studies, the potential development and environmental effects of such a plume should be considered as a major shortcoming of this remedial option.*

Assessing, monitoring, and remediating other mining-environmental problems on Marinduque

We are not aware of plans for mitigating or remediating mining-environmental problems on Marinduque other than the 1996 tailings spill. However, the potential magnitude and impacts of these other problems are so great that we strongly recommend the implementation of a general mining-environmental and health assessment and monitoring program on the island. The primary goals of such a monitoring and assessment program should be to (1) understand and define the magnitude of the different environmental problems, (2) prioritize the problems for remediation, and (3) look for creative, cost-effective ways to help mitigate or remediate the problems.

In fact, the review of the Boac River tailings remedial options should be carried out as only one part of such an overall assessment. Because so many different sources from Marcopper contribute acid and metals into the Boac River system, only cleaning up the tailings in the river ultimately may not completely clean up the river to the desired state. Hence, the Boac cleanup should be carried out with a full understanding of the potential sources for metal, acid, and sediment input into the system, as well as the extent to which these Marcopper inputs are naturally mitigated by tributary streams and ground water input along the river.

A risk-based system approach to assessment: We recommend that a general mining-environmental assessment of the island should follow a risk-based approach. Risk analysis involves environmental description, identification and characterization of contaminant sources, assessment of human and ecosystem exposure to the contaminants, assessment of contaminant effects, characterization of future risk, and risk management or remediation.

The risk assessment should also examine entire mining-environmental systems as a whole, and not just focus on selected parts. For example, the environmental impacts of Marcopper on the Mogpog and Boac Rivers and their inhabitants should be assessed by evaluating the entire system that includes the mine site, Mogpog and Boac river watersheds, and marine environment affected by the two rivers, such as:

- Contributions of acid, metals, and sediments from Marcopper;
- Contributions of acid, metals, and sediments from other mine sites and disturbed areas;
- Contributions of acid, metals, and sediments from natural sources;
- The ground- and surface-water hydrology of the mine site, and Boac and Mogpog river watersheds;
- Contributions of ground and surface waters from other tributaries in the Mogpog and Boac Rivers;
- Processes that affect contaminant transport in ground, surface, and ocean waters;
- Processes that affect fate of the contaminants in the river system, offshore marine environment, adjacent farm lands, ground waters, and villages;
- Extent and health effects of contaminant uptake by humans, wild animals and farm animals, fresh water and marine aquatic organisms, and terrestrial and aquatic plants.

A key aspect of a risk-based system assessment will be to monitor changes in the environmental impacts of mining over time. For example, changes in water flow, water quality, sediment transport, and ecological impacts along the Mogpog and Boac Rivers must be measured regularly to assess longer-term seasonal variations and shorter-term variations related to storms.

Another key aspect will be to assess the natural, pre-mining environmental conditions. Many mineralized areas are the sources of natural acid-rock drainage, and so the extent of impacts of acid-rock generated by mining are appropriately measured in comparison to the pre-mining impacts of natural inputs of acid and metals. There are a variety of ways that the pre-mining conditions can be assessed in a mineralized area.

Calancan Bay and the adjacent coastal environments affected by the tailings disposed in the bay constitute another system upon which an environmental risk analysis should be focused. Similarly, the CMI mine, the areas potentially affected by mine wastes and acid rock drainage from the mine (possibly including the town of Mogpog), and the portions of the ocean affected by marine disposal of mine wastes and tailings constitute another system to be assessed.

Assembling the expertise: A risk-based systems approach to analyzing mining-environmental impacts on Marinduque will require expertise in and information from a broad spectrum of disciplines, such as economic, structural, and coastal geology; hydrology; risk analysis; environmental geochemistry; ecology; toxicology; human health; mining engineering; environmental engineering; and social sciences.

Whenever possible, appropriate local experts from the Philippines and (or) Marinduque should be involved with the assessment due to their crucial knowledge of local geology, hydrology, ecology, cultural practices, etc.

In addition, local residents should be trained in appropriate water sampling and other monitoring procedures so that they can help provide long-term and rapid-response on-ground monitoring capabilities, especially during storm events.

A potential opportunity

The mining-environmental impacts on some parts of Marinduque have been substantial and pose significant long-term challenges for remediation, both from a technological and monetary standpoint. These problems and remedial challenges may also pose, however, a potential opportunity for Marinduque. The island residents, government officials, government, and educational institutions could develop on Marinduque a center of educational excellence in the southwest Pacific for understanding, assessing, predicting, and cleaning up the environmental impacts of mining in tropical areas. Such a center, if established on the island, could oversee and coordinate assessment and remediation activities. At the same time, it could provide hands-on learning and training opportunities in both technical and research fields about mining-environmental issues. Expertise learned on Marinduque could then be transferred to other places in southwest Pacific and southeast Asia where similar large-scale mining-environmental problems are occurring. The center could not only provide education and employment opportunities for local residents, but also attract a large number of students, teachers, and others to the island.

Marinduque provides a unique and logical physical setting for such a center of excellence because a spectrum of tropical mining-affected and unaffected river systems and marine environments are in close proximity for easy study. The island's proximity to Manila facilitates collaboration with Philippine government agencies and universities. Collaborative arrangements could also be developed with universities elsewhere in the world that have established mining-environmental programs, but that may lack ready access to tropical study areas in a near-ocean setting.

Funding for such a center of excellence could be pursued through the mining industry, world monetary institutions, environmental groups, and a variety of other sources.

Marinduque as a case study

Marinduque's mining-environmental issues are not unique within southeast Pacific and southeast Asia. A number of large-scale metal mining operations across the region are gaining increasing publicity for potentially environmentally damaging practices followed over the last 20-30 years.

The mining-environmental problems on Marinduque, whether a result of systems failures (Mogpog and Boac Rivers), or designed practices (Calancan Bay, acid-rock drainage at the Marcopper and CMI mines) present a very useful case study in how similar mining-environmental challenges across the region can be better assessed, mitigated, remediated, and, hopefully, prevented in the future.

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Introduction

This report summarizes results of a visit by the authors to Marinduque Island, Philippines, in May 2000. The purpose of the visit was to conduct an overview of environmental and human health problems created by a 1996 tailings spill from the Marcopper open-pit copper mine. Our visit was at the invitation of Philippine Congressman Edmund O. Reyes, and grew out of discussions between Congressman Reyes and U.S. Geological Survey (USGS) representatives during the Congressman's spring, 1999, visit to the United States.

The trip expenses to and from the Philippines were funded by the USGS. In-country expenses were paid by the offices of Congressman Reyes and the Governor of Marinduque, Carmencita O. Reyes.

This report includes observations we made on our relatively short visit to the island, and based upon a preliminary review of the literature available on the island's mining-environmental issues. We have included preliminary interpretations and analytical results of some water, sediment, and mine waste samples collected during our trip. We also highlight environmental and human health issues we feel are in need of further study and consideration for mitigation or remediation.

This report is preliminary and is not intended to be a comprehensive, final review of the island's mining-environmental issues; many areas of further study are needed.

A glossary of geological, technical, and environmental terms is included at the back of this report.

The island of Marinduque is located approximately 150 km south of Manila (Fig. 1). Access to the island is by commercial airplane from Manila or ferry from Lucena on the main island of Luzon. Marinduque is approximately 960 km^2 in area, and has a tropical climate with seasonal monsoonal rains from May through November.

Mining-related environmental problems have had visible and detrimental environmental impacts on several parts of the island.

History of Marcopper

Details of the Marcopper mine history are available in Loudon (1976), Ante (1985), Zandee

Figure 1. Map of the Philippines showing the location of Marinduque Island. Figure from Coumans (1999).

Q Figure 2. Map of Marinduque highlighting the major mining-related features (dark brown), roads (red), cities (white circles), rivers (blue), reefs (green zig-zag), and approximate topography of the island (shaded green, tan, light brown). Modified from maps on Coumans (1999) and Marinduque (1999) web sites.

(1985), UNEP (1996), and PDTS (1999). Background information summarized here is based primarily upon these published reports, and unpublished written and electronic documents which are in some cases contradictory in their content and conclusions. It is also based on discussions we had while in Marinduque with Congressman Reyes, local residents, several representatives of Marcopper Mining Corporation, and Catherine Coumans (MiningWatch Canada).[1]

The Marcopper mine, located in the north central highlands of Marinduque (Fig. 2), began copper production from the Tapian open pit in 1969. The mine was operated by Marcopper Mining Corporation (MMC), with 39.9% ownership by Placer Development, Limited, and the remainder by the Philippine government. According to Zandee (1985), MMC was "under design and management control" of Placer Development, Ltd. (now known as Placer Dome, Inc.).

Production from the Tapian pit spanned the years 1969-1991. Ore was crushed and concentrated on-site, with tailings initially sent to a tailings impoundment north of the pit until 1975. In 1975, Marcopper shifted to near-shore marine disposal of its tailings in Calancan Bay on the north side of Marinduque (Zandee, 1985). As of 1985, at least 120 million tonnes of tailings had been disposed of in the bay (Zandee, 1985); estimates (Coumans, 1999) of the total amount of tailings discharged into the bay from 1975 to 1990 are 200-300 million tonnes.

Marcopper also produced copper from the early 1970's through at least the mid-1980's via acid-leaching of oxide and sulfide mine dumps, using scrap iron to precipitate cement copper (Ante, 1985).

In 1991, production shifted from the Tapian open pit to the San Antonio open pit several kilometers to the north. At the same time, at the direction of the Philippine government, tailings disposal was shifted from Calancan Bay to the old Tapian Pit. This tailings backfill practice required the plugging of a dewatering tunnel that

[1]At the request of Congressman Reyes, Catherine Coumans served as an intermediary between the local people of Marinduque and our group during our visit.

had drained the Tapian open pit from the 195-m level into the Makulapnit River.

Mining at Marcopper ceased on March 24, 1996, when the plug in the 195-m level drainage adit failed catastrophically. The plug failure resulted in the release of an estimated 1.5-3 million cubic meters (UNEP, 1996) of sulfidic tailings slurry from the Tapian Pit storage area into the Makulapnit River, Boac River, and eventually the ocean west of the island. Substantial tailings deposits were formed along the Makulapnit and Boac Rivers, and in the ocean at and near the Boac River mouth. After the tailings spill, Placer Dome divested its financial interest in Marcopper, but promised to clean up the tailings spill along the Makulapnit and Boac Rivers. Placer Dome also created a subsidiary, Placer Dome Technical Services (PDTS), to carry out post-spill environmental studies and remedial activities.

After the spill, PDTS used bulldozers to make berms from the tailings deposited along the lower Boac river system, thereby trying to prevent further overbank flooding of tailings materials into adjacent farmlands during storms. PDTS also dredged a 20-m deep channel along approximately 1 km of the Boac River channel near its mouth to catch tailings washed downstream by storm waters and to reduce flooding in the Boac River delta. In addition, PDTS re-plugged the 195-m level drainage adit in 1996 to prevent further discharge of tailings from the Tapian pit into the Makulapnit and Boac rivers.

The initial remedial plan proposed by PDTS was to remove tailings deposits from the Boac river system and the dredge channel, and dispose of them using submarine tailings disposal (STD) — the tailings would be piped into the ocean from an outfall point west of the Boac River mouth, where it was presumed that the tailings solids would drop to the ocean bottom and be carried by density-driven flow to greater ocean depths in Tablas Strait. Pending a detailed environmental impact statement (EIS) for STD, the Philippine Department of Environment and Natural Resources (DENR) halted progress on the final disposal of the tailings. Over the next several years, PDTS, their consultants, and a number of different groups have carried out environmental studies as part of the EIS preparation. The final EIS was submitted by the mining companies in 1999 (PDTS, 1999). The EIS described and evaluated a number of possible remedial options, but still concluded that submarine tailings disposal (STD) was the remedial alternative having the least overall risk and cost. However, very limited supporting data and analyses of the data were included in the 1999 PDTS report.

The Philippine DENR did not approve the 1999 PDTS remedial plan. Instead, the politically contentious nature of the plan led to the DENR determination that an independent panel should be convened to provide an independent review of the plan and its proposed remedial actions. A memorandum of agreement between the People of Marinduque and the Philippine DENR has recently been established that provides for an independent technical review of the available options for environmental remediation and restoration after the tailings spill. Our visit to Marinduque was arranged by Congressman Reyes to give the People of Marinduque an opportunity to determine if a U.S. intergovernmental team led by the USGS would be acceptable to them to carry out an impartial review of the Boac River remedial plan.

A Brief Background on the Environmental Impacts of Metal Mining

For many mineral deposits like Marcopper, which contain sulfide minerals such as pyrite, (an iron sulfide), or chalcopyrite (a copper-iron sulfide), a primary concern is the formation of acid-rock drainage (ARD). When sulfide-bearing mineral deposits are exposed to the atmosphere by mining (or naturally by erosion), the sulfides react with oxygen and water to form ground and surface waters having elevated concentrations of sulfuric acid (and correspondingly lower pH values). The greater the concentrations of the sulfide minerals (especially iron sulfides) in the mineral deposit, the greater the tendency of the deposit to form low-pH ARD (Fig. 3).

Some rocks, especially those that contain carbonate minerals (such as limestones), can react with and consume some or all of the acid generated by sulfide oxidation. In addition, these types of rocks can generate ground and surface waters that also react with and neutralize the acid generated by sulfide oxidation. Hence, the greater amounts of minerals in or around a deposit that react readily with acid, the more likely the deposit will be to generate less acidic drainage waters (termed near-neutral rock drainage, NRD).

Metals contained in the sulfide minerals (such as iron, copper, lead, zinc, arsenic, cadmium, and others) in a mineral deposit are also released into ARD by sulfide weathering. Less acidic waters draining carbonate-rich mineral deposits can still contain elevated levels of some metals such as arsenic, zinc, copper, and selenium.

ARD and NRD can form as a result of natural weathering and erosion processes. Thus, most mineralized areas (including, most likely, Marcopper) had some level of natural acidic and (or) metal-rich drainage prior to mining. However, mining can greatly accelerate the for-

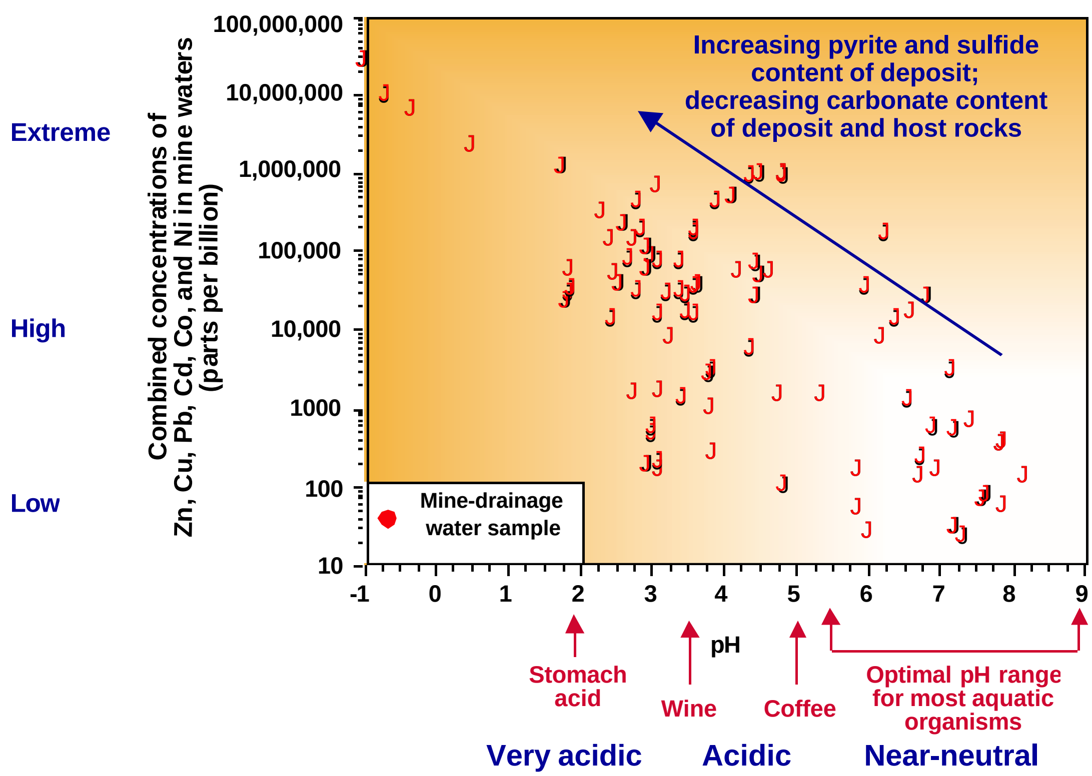

Figure 3. This graph shows the pH and summed concentrations of some metals (zinc, Zn; copper, Cu; lead, Pb; cadmium, Cd; cobalt, Co; and nickel, Ni) in mine waters draining a number of different mines in the United States (Plumlee et al., 1999). The graph shows that mine waters (including those in open pit lakes and those that drain underground mine workings, mine waste dumps and mill tailings) can have a wide range of pH values and concentrations of metals. The geological characteristics of the deposits play an important role in controlling the mine water compositions. Deposits that have large amounts of pyrite and other sulfides (which generate acid when exposed to atmospheric oxygen and water), and that have small amounts of carbonate minerals (which react with and neutralize acid generated by sulfide oxidation) tend to generate the most acidic, metal-rich drainage waters. Waters that drain unmined mineral deposits can also be quite acidic and (or) metal-rich as a result of natural sulfide oxidation and weathering processes. Although human stomach fluids and beverages we drink can be quite acidic, the detrimental health effects of acid rock drainage and metal-rich near-neutral drainage waters result from the type of acid (sulfuric) and metals contained in the drainage waters. The metals and acid are also detrimental to aquatic life in streams affected by the drainage waters. See further details in Plumlee and Logsdon (1999).

mation of ARD and NRD in waters that fill open pits after mining, and that drain sulfide-bearing underground mine workings, mine waste dumps or mill tailings deposits.

As ARD and NRD flow from mine sites or mineralized areas, they are typically diluted by less acidic waters draining unmineralized rocks. The increased pH (decreased amount of acid) caused by this dilution commonly leads to precipitation of orange to white iron-rich and aluminum-rich mineral particulates in the stream. Arsenic, lead, and copper tend to adsorb onto and precipitate with these iron and aluminum particulates. As the particulates settle to the stream bed, they remove these sorbed metals from the stream waters, thereby improving water quality. However, metals such as zinc and cadmium tend to stay dissolved in waters affected by ARD and NRD because they tend not to sorb onto the iron and aluminum particulates. Other metals such as copper, arsenic, uranium, and selenium can desorb from the particulates back into solution in the stream waters if the pH of the stream increases sufficiently to near-neutral conditions.

Acid-rock drainage and metal-rich near-neutral drainage can adversely affect the environment, especially in streams and ground water into which the drainage waters flow:

- Most fish and the aquatic organisms upon which the fish feed are detrimentally affected by elevated levels of acid and (or) metals in many streams affected by ARD or metal-rich NRD.
- Iron- and aluminum-rich particulates can clog fish gills. The iron- and aluminum-rich particulates (which also have high levels of metals such as As, Pb, Cu, and other metals) can lead to health problems in fish and other organisms that ingest them.
- Terrestrial organisms (animals, humans) may also suffer health consequences if they ingest sufficient quantities of acidic, metal rich waters, metal-rich sediments, or aquatic organisms having elevated metal concentrations in their tissues.
- Plants that come into contact with acidic or metal bearing waters could potentially suffer adverse health effects due to the elevated levels of acid and some metals. The plants could also scavenge and concentrate metals from the waters.
- Metal-rich plants have been known to cause short- and long-term health problems in animals and humans that feed on the plants, depending on the metals and the amounts of the plants consumed.

When ARD in a mine dump or tailings deposit is evaporated to dryness, the acid and metals contained in the ARD precipitate as soluble metal-sulfate salts. These salts store acid and metals in a readily soluble form until the next rainfall. Dissolution of the soluble salts during a rain storm can flush acid and metals into nearby streams, where they can adversely affect aquatic life in the streams.

Other potential environmental impacts of mining include:

- Effects of sediments (including mine wastes and tailings) eroded from mine sites into surrounding streams, rivers, and oceans. The sediments can smother aquatic organisms and plants, and, if sulfide-bearing, can themselves generate ARD or NRD.
- Effects of mineral processing chemicals, if accidentally released into the environment. For example, the tailings slurry released into the Makulapnit and Boac Rivers in the 1996 spill likely had some levels of a variety of organic processing chemicals. However, these chemicals typically degrade with time if released into the surficial environment.

The environmentally important geologic characteristics of Marcopper

Marcopper is a porphyry-copper deposit (Fig. 4) that contains copper and iron sulfide ore minerals (pyrite, chalcopyrite, and bornite) disseminated through large volumes of igneous intrusive rocks (Loudon, 1976). Because of the high sulfide content and low carbonate content of the

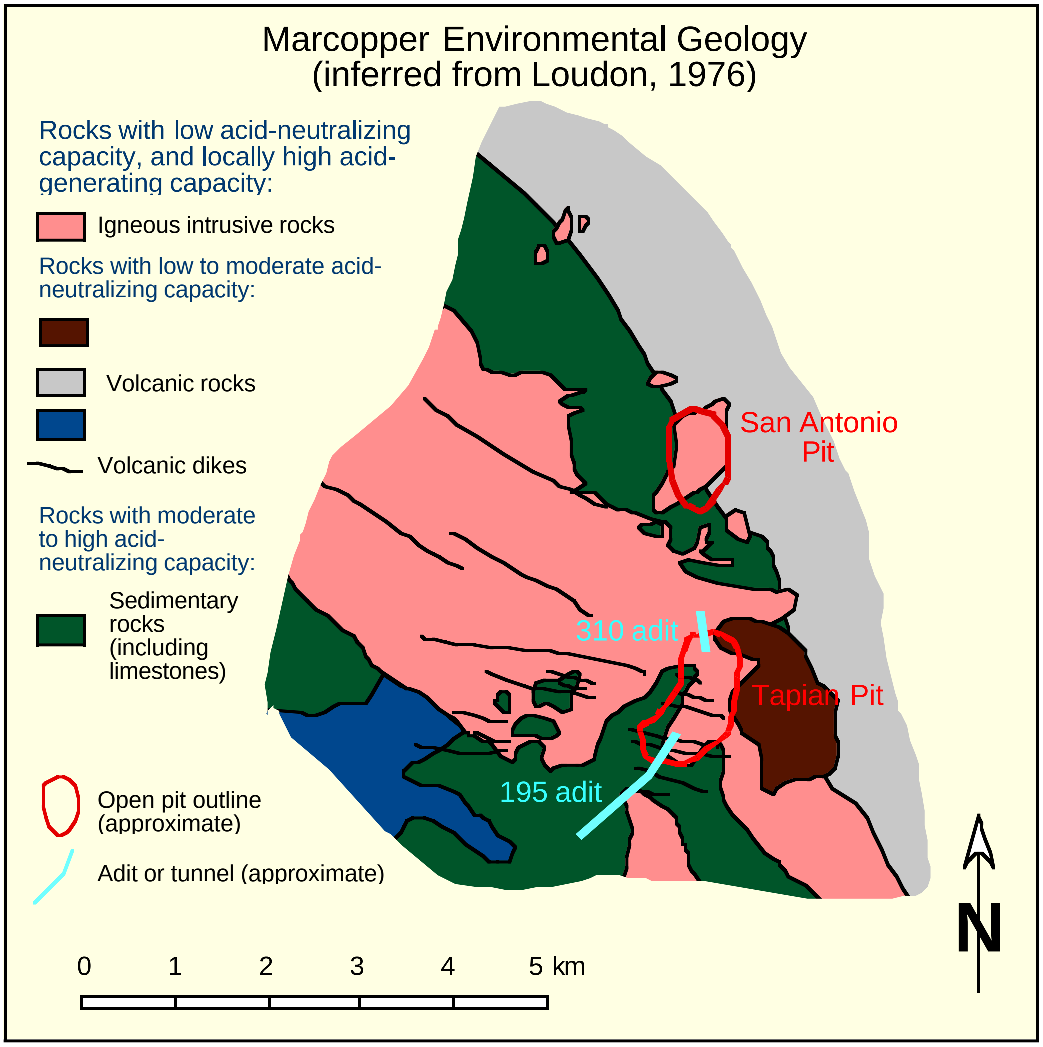

Figure 4. The rock units around Marcopper have varying abilities to react with and neutralize acid generated by oxidation of sulfide minerals in the Marcopper porphyry-Cu deposit. This figure is a geologic map from Loudon (1976) that has been modified to show the inferred environmental characteristics of the rock units around Marcopper, and the approximate locations of some adits around the Tapian pit.

Marcopper deposit, the mineralized areas in and around the Tapian and San Antonio open pits have high potential to generate acid-rock drainage via sulfide oxidation. Similarly, mill tailings from Marcopper would be expected to be acid-generating due to their relatively high sulfide content. Based on comparisons with similar deposits in the United States, we would expect the Marcopper drainage waters to contain elevated levels of copper, due to the Cu-rich nature of the ores.

Small copper skarn deposits are also present locally at Marcopper in sedimentary rocks adjacent to the igneous intrusions (Loudon, 1976). Carbonate minerals in the skarn deposits and in the unmineralized sedimentary rocks may locally help neutralize some of the acid formed by sulfide oxidation in the area immediately adjacent to the open pits. In addition, the carbonate-bearing sedimentary rocks and reactive volcanic rocks in some watersheds around the mine site may also help neutralize some of the acid waters in streams away from Marcopper.

USGS-AFIP May 2000 Trip Itinerary

The primary purposes of our trip, were to become familiar with the environmental and human health issues surrounding the 1996 tailings impoundment failure, and to meet with local citizens and government officials concerned with the effects of the impoundment failure. However, the trip also afforded us the opportunity to visit and learn about the spectrum of mining-related environmental issues on the island. The itinerary of the trip is summarized here:

13 May (Sunday)

- Met with Congressman Edmund Reyes and Governor Carmencita Reyes.
- Met with group of local Marinduque citizens (Boac Mayor Roberto Madla, Beth Manggol, Sharon Taylor, Myke Magalang), Catherine Coumans, and Congressman Reyes.
- Visited middle Boac River to examine 1996 tailings deposits.
- Visited lower Boac River to examine dredged channel in Boac River delta.

14 May (Monday)

- Visited Marcopper mine site (Tapian, San Antonio open pits; Maguila-guila siltation dam; Bol River Reservoir; Makulapnit reservoir overflow; Tapian drainage adits' outflows). Marcopper representatives accompanied us on the tour of the mine site and answered our questions regarding the site.

15 May (Tuesday)

- Visited Boac River delta to study coastal processes and tailings in the river delta.
- Met with the Marinduque Council for Environmental Concerns, Monsignor Senen Malapad, Director.
- Visited lower and middle Mogpog River to examine downstream effects of the 1993 Maguila-guila siltation dam collapse, and effects of current acid rock drainage from the Marcopper mine site on the Mogpog River system.
- José Centeno examined a number of local people for possible health effects of metals, and did a preliminary review of other human health studies previously conducted on Marinduque.

16 May (Wednesday)

- Airplane overflight of northwestern Marinduque coast between Gasan and Calancan Bay.
- Drove around southeastern and eastern side of Marinduque to examine stream draining unmineralized portions of the island.
- Visited tailings causeway in Calancan Bay.

18 May (Thursday)

- Made presentation to Marinduque town mayors, Baranguay captains, Philippine DENR representatives (including Director Horacio Ramos), and other concerned citizens at public meeting in the Marinduque Provincial government offices in Boac.
- Briefly stopped at mine waste dumps of the CMI mine along the road between Mogpog and the ferry terminal at Balanacan.

In subsequent sections of this report, we will present our observations by geographic area of the island, including: the Marcopper mine site, Boac River, Mogpog River, Calancan Bay, and CMI mine. We then will summarize potential human health issues, discuss in more detail a process by which remedial options for the Boac River tailings spill can be evaluated, and present a process by which the island's mining-environmental issues and their impacts can be assessed in more detail.

Marcopper mine site — Tapian and San Antonio open pits

With the cessation of mining at Marcopper and the re-plugging of the Tapian drainage adit in 1996, water started accumulating in both the Tapian and San Antonio open pits (Fig. 5; report cover). According to Marcopper personnel, the water levels of both pit lakes are still rising. The Tapian waters are nearing the elevation of the 310 adit, the access point through which tailings were piped into the pit from the mill from 1990-1996.

The water in both pit lakes at the time of our visit was a deep transparent green color; due to time constraints, we did not collect water samples from either pit lake. According to Marcopper per-

Figure 5. A. View looking northeast of the north end of the Tapian pit lake. Remnants of the tailings stored in the lake are visible in the central portion of the figure. A panoramic view of the Tapian pit looking southeast is shown on the cover of this report. **B.** The San Antonio pit lake, looking northwest.

sonnel, the pH of the Tapian pit lake waters at present is around 4; although the pH of the San Antonio pit lake water is unknown, we presume that it is generally similar to that of the Tapian pit water.

In the spring of 1996 soon after the Marcopper tailings spill, the pH of the Tapian pit water was 6.9, with elevated levels of Cu (1.2 ppm) and lesser amounts of other metals (UNEP, 1996). According to Marcopper personnel, the pit waters in 1996 were predominantly mill process waters with pH maintained to near-neutral values to optimize the mill recovery of sulfides. The drop in pH from 1996 to the present day presumably reflects an influx of acid waters generated by oxidation of sulfides in the rocks around the open pit, and the gradual neutralization by these acid waters of alkaline chemicals in the mill process waters. The present acid pH of the Tapian pit water is very similar to the pH of mine waters in porphyry-copper deposits in the United States. As we have observed with similarly colored mine waters draining the Summitville, Colorado, gold-copper deposit (Plumlee et al., 1995), it is possible that the clear, deep green color of the Tapian and San Antonio pit waters is indicative of high levels (possibly in excess of 100 ppm each) of dissolved ferrous iron and copper.

Environmental concerns

Possible pit water overflow: An immediate concern expressed to us by Congressman Reyes and others is whether the pit waters will continue to rise to the point where they will eventually overtop the pit walls and flow into nearby streams. There were also concerns expressed that the plug in the 310 adit could fail due to the buildup of pressure from the pit waters, leading to a catastrophic release of water through the adit. Mention was made to us of possible contingency plans to pump the pit waters into adjacent surface waters (such as the Bol River) to prevent a catastrophic overtopping of the pit lakes or failure of the 310 adit in the Tapian pit.

Impacts of ground water flow from the pit lakes on ground- and surface-water quality: Although water is still accumulating in the pit lakes, it is likely that acid ground waters are also migrating down gradient from the pits along fractures and other zones of permeability. These waters are a potential concern if they are migrating far enough away from the mine site to affect ground water quality in domestic wells, or if they discharge via springs into local surface waters.

Recommendations

- An analysis of the locations and elevations of pre-mining springs, as well as the elevation of the pre-mining water table in the pit area, will help in understanding the potential levels to which the pit lakes will rise. Hopefully the necessary data to do this analysis are available on pre-mining aerial photographs, maps, and well logs from the site.
- The amount of surface water inflow into the pit should be evaluated. If substantial, the surface water inflows should be decreased through diversion or other mitigation measures.
- If it has not already been done, an engineering geology analysis of the 310 adit plug and the rocks surrounding it is warranted to assess the potential for plug failure.
- Our first impression is that pumping of waters from the pit lakes into surrounding surface drainages should be considered only: (a) as a last resort, if catastrophic overtopping of the pit walls or failure of the 310 adit plug is thought to be imminent, or (b) if it can be shown that potential adverse impacts on the environment of such pumping would be minimal.
- Information needed to understand the potential environmental impacts of pumping pit water into local streams includes: (1) more detailed information on the pH and metal concentrations of the Tapian and San Antonio pit waters; (2) more detailed information on the compositions, pH, metal contents, and acid-neutralizing potential of the adjacent stream waters; and (3) more information on the aquatic ecosystems in adjacent streams.
- Methods to minimize adverse impacts of the pit dewatering should be devised in case dewatering is needed. For example, potential ways to treat the pit waters before they are released into the surface waters should be evaluated.
- Recovery of copper from the pit waters (perhaps using the cement copper extraction facilities already on-site?) could also be evaluated as a potential way to offset water treatment costs.
- Ultimately, a better understanding of the environmental geology (amounts, types, and distribution of acid-generating sulfide minerals, and acid-neutralizing carbonate minerals), structural geology (orientation and hydrologic conductivity of faults, fractures, and joints), hydrology, and ground- and surface-water quality of the Marcopper mine site and the surrounding watersheds is needed. Such an environmental assessment of the site would help Marcopper and local residents to understand and address issues such as: (1) the potential environmental impacts of ground-water flow away from the open pits, (2) the potential impacts of pumping of waters from the pit, and (3) the extent to which water levels will continue to rise in the open pits.

Marcopper mine site — Mine waste dumps, mill tailings, and Maguila-guila siltation dam

There are a number of large mine waste dumps at the Marcopper mine (Figs. 6A, B). We did not have time to inspect the mine waste piles up close. However, many piles observed from a distance appear to contain abundant gray, sulfide-rich, mineralized rocks. In addition, orange to yellow secondary salts formed by sulfide oxidation and evaporation of acid waters are readily apparent on many of the dumps.

At least one of the Marcopper dumps (Fig. 6A) was turned into an acid-leach heap during the course of mining, where sulfuric acid was added to the dump and the resulting acidic solutions were processed in a cement copper facility to extract the copper (Ante, 1985). Based upon compositions provided by Ante (1985), these acid-leach solutions were even more acidic and metalliferous than most mine-drainage waters. The soils upon which the dump was placed were deemed to be sufficiently impermeable as to not require a clay pad to prevent infiltration of the acid leach solutions into the rocks beneath the dump (Ante, 1985). Acid drainage emanating from other mine dumps was also processed at the cement copper plant (Ante, 1985).

Mill tailings from early in the mine's life (from 1969 to 1975) were stored in an impoundment located largely on top of the San Antonio orebody. Although it is our understanding that most of these tailings were moved to make way for the San Antonio open pit, there still are remnants of old tailings deposits south and west of the San Antonio pit. The tailings appeared to be sulfidic, and well cemented by secondary salts.

The Maguila-guila siltation dam (Fig. 6C) was installed on a tributary of the Mogpog River approximately 1 km north of the Marcopper mine site to catch sediment eroded from the northern end of the mine. As recounted to us, this siltation dam failed catastrophically during a typhoon in December 1993. The dam failure sent a deadly debris flow down the Mogpog River that reportedly killed two people and numerous livestock downstream. The dam was rebuilt in 1994. At the time of our visit, the catchment area behind the dam had, in the span of 5 to 6 years, already filled to capacity with sediment, and sediment-laden waters were coursing directly over the dam overflow spillway. A quick inspection of the sediment in the catchment area revealed sulfide-bearing, fine-grained, tailings-like material, very fine-grained orange clayey material, and pebble- to cobble-sized mineralized and unmineralized rocks.

Environmental concerns

Acid-rock drainage: The numerous and substantial mine waste piles located around the mine site clearly are significant potential sources of acid-rock drainage into ground and surface waters. We observed both long-term drainage from the mine dumps, and rainfall-induced acidic runoff generated by dissolution of soluble secondary salts in the mine waste piles.

Transient rainfall-derived puddles and ponds on top of the mine dumps commonly display a green tint, indicating that they are acidic and copper bearing (Fig. 7A). The Bol River Reservoir (Fig. 7B), which receives surface waters (and probably ground waters) draining the Tapian and San Antonio pit areas and waste dumps, is a similar deep green color. An acid-drainage stream that flows into the Makulapnit River from substantial mine dumps on the southwestern portion of the mine site (Fig. 7C) has waters with pH around 4.0 and conductivity of 3000 µS/cm. We did not sample these drainage waters. However, high copper concentrations are indicated by the precipitation of a complex assemblage of copper sulfate minerals and a copper silicate mineral on stream-bed rocks where the mine waters are diluted by a near-neutral pH, low conductivity tributary stream (Fig. 7C).

Sedimentation: The rapid rate at which the sediment catchment behind the Maguila-guila siltation dam filled up after the rebuilding of the dam indicates that there is very rapid erosion of

Figure 6. A. Mine dump that was used as an acid leach dump for copper extraction. **B.** Mine dump north of the San Antonio pit above the Maguila-guila siltation dam. The yellow-to-orange colors on the dump indicate the presence of secondary salts, which show that sulfide-rich rocks (gray) are generating acid drainage. **C.** The Maguila-guila siltation dam, downstream from the dump shown in B, no longer fulfills its purpose to trap sediment eroded from the mine site. Sediment has completely filled the ~25 (?) m high impoundment and water is now flowing out the overflow spillway. Note the high-water mark on the dam, indicating that the overflow spillway is not big enough to prevent debris buildup and backup of waters during high stream flows. **D.** Looking north at sediment trapped behind the Maguila-guila dam.

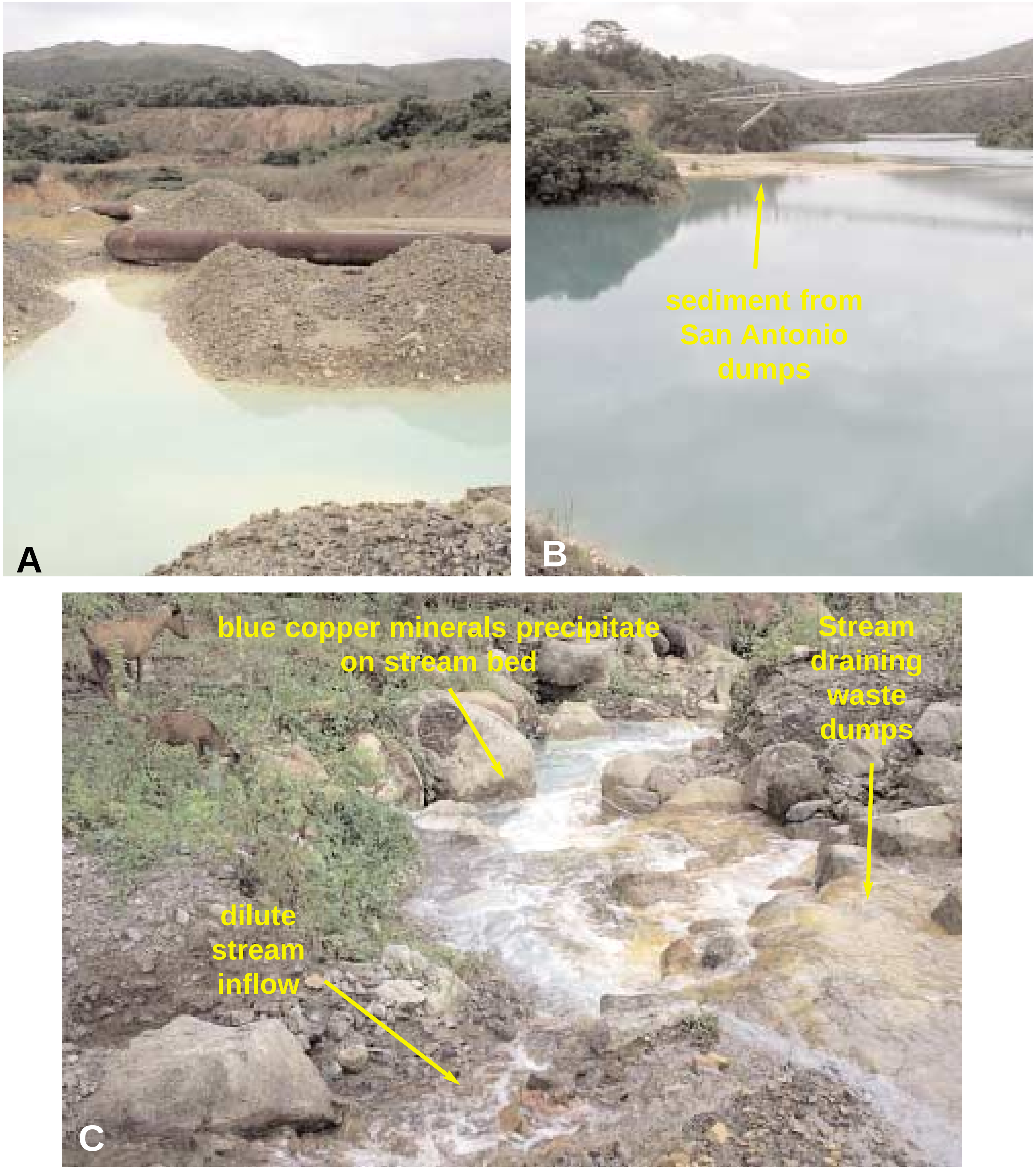

Figure 7. A. Acidic, copper rich puddles form on waste dumps after rains. **B.** The deep green color of the Bol River Reservoir waters indicate high copper contents. **C.** Mine waters draining from the Makulapnit siltation dam overflow, below waste dumps on the southwestern side of the mine, have pH 4 and a conductivity of 2000 µS/cm. Orange iron hydroxides are precipitating from the acidic mine waters in the stream bed (right). As these mine-drainage waters are diluted by higher-pH, more dilute waters flowing in from the left of the photo, a complex mixture of blue copper sulfate and copper silicate minerals precipitates on rocks in the stream bed in the upper central portion of the photo.

material from the mine site. Because the dam is no longer trapping sediment, the sediment load on the Mogpog River and its tributary will continue to be substantial. Due to time constraints, we were not able to observe if any other drainages from the mine site have similar sedimentation problems.

Potential failure of siltation dams: A concern was expressed by local residents to us that the Maguila-guila siltation dam could collapse again, leading to another deadly debris flow downstream. Marcopper personnel indicated to us that the dam is regularly inspected for indications of structural integrity. However, the apparent backup of water behind the overflow spillway during high-runoff rain events (Fig. 6), is a potential indication that the dam needs further design scrutiny. It was unclear whether other siltation dams on site are also inspected on a regular basis.

Recommendations

- If it is not already being done, all siltation and water-control dams on the site should be regularly inspected for structural integrity.
- The high sediment loads into the Maguila-guila sediment catchment area indicate to us that more extensive sediment control efforts are warranted at the mine site. *These efforts should focus on minimizing erosion of the source waste rock dumps, rather than trapping the eroded sediment in downstream siltation dams..*
- Temporal variations in composition, flow rate, and downstream impact of waters draining all the mine waste dumps at Marcopper should be characterized as part of an overall environmental assessment of the site.
- If such an assessment indicates that the waters draining mine wastes are having a detrimental impact on downstream surface waters, potential remedial options should be evaluated, such as capping of the waste dumps with impermeable barriers, and (or) treatment of the waters. Recovery of copper from the waters draining the mine dumps (perhaps using the cement copper facility already on site) may offer a potential way to offset remedial costs.

Marcopper mine site — 195 drainage adit and access adit

We did not observe the entrance of the 195-m level drainage adit due to vegetation overgrowth. A low-volume seep in the vicinity of the adit had pH of 6 and 3000 µS/cm conductivity (Fig. 8A). It was unclear to us whether this seep is emanating from the drainage adit or from fractures in the rock near the adit.

The 195-m level access adit was driven parallel to the 195-m level drainage adit in 1996 to provide access to the drainage adit during the re-plugging efforts; the exact position of the access adit relative to that of the drainage adit was not clear to us on our visit. At present, a sizeable flow of water (estimated to be at least 30-50 liters per minute) is discharging from the access adit (Fig. 8B). The water has a pH of 6.6, and a conductivity of 2300 µS/cm; copious orange-brown hydrous iron oxides are precipitating in its stream bed.

Environmental concerns

Possible re-failure of the 195-m adit plug: Congressman Reyes and several residents expressed concerns to us that the plug in the 195-m drainage adit could fail again, leading to another catastrophic loss of tailings and acid waters from the pit into the Makulapnit and Boac Rivers. An independent review of the plugging process and stability of the plug has been requested by the Congressman and the Philippines Department of Environment and Natural Resources.

Drainage from the adits into the Makulapnit River: At present, drainage from the 195 access adit and from the 195 drainage adit (or nearby fractures) appears to be a relatively minor contribution to the overall metal and acid loadings already entering the river from mine dumps up gradient (Fig. 7). The near-neutral pH but high conductivity of the adit waters indicate that they

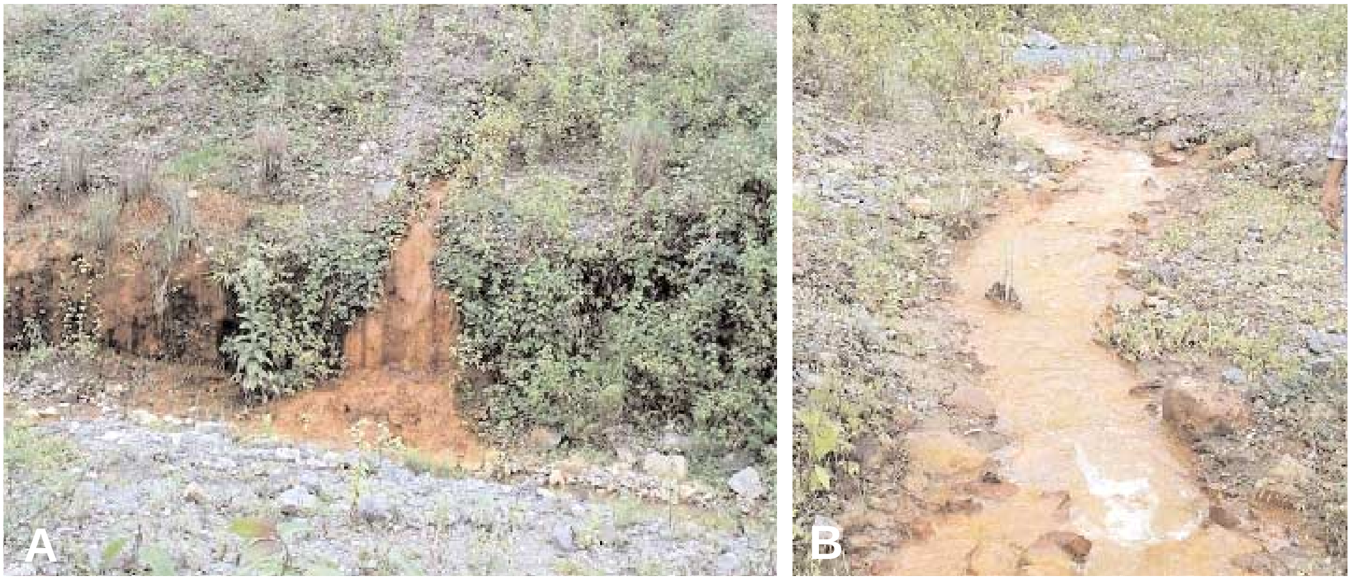

Figure 8. A. Seep near the portal of the 195 drainage adit. The seep water has a pH of 6.2 and a conductivity of 2000 µS/cm. The seep discharges into the stream draining from the Makulapnit siltation dam. **B.** Discharge from the 195 access adit, pH 6.6, conductivity 2300 µS/cm. The stream from the Makulapnit siltation dam is visible in the central background.

likely are acid-rock drainage waters partially neutralized by dilution or by interactions with carbonate minerals in the rocks hosting the adits.

Recommendations

- An independent review of the adit plug, in addition to a review of the plug engineering, should also include a review of the engineering geology characteristics (physical strength, amount of mineralization and alteration, etc.) of the rocks hosting the plugs. This review should also include an assessment of earthquake risk and potential earthquake-induced failure of the plug.
- If it is not already being done, the flow volumes and compositions of the waters draining the 195 drainage and access adits, as well as all identifiable springs and seeps in the vicinity of the adits, should be monitored regularly. Sudden increases in flow volume or water chemistry could indicate potential decreases in plug integrity.
- If it has not already been done, and if there is still access to the adits, detailed geologic mapping of the rocks and fractures around the adits should be completed. Similarly, if it has not already been done, a structural analysis of fracture orientations and past motions (using slickensides), coupled with the extent to which they are transmitting water, could provide important insights into the hydrogeology near the plugs. Such an analysis could also provide important information useful for assessing the long-term integrity of the plug. This type of analysis should be done in conjunction with a general hydrogeologic study of the entire area around the Tapian pit.

Mogpog River

According to local residents, the Mogpog River was severely affected by the 1993 Maguila-guila siltation dam collapse. These effects included loss of riverine habitat and fisheries in the river, and mention was made of a substantial increase in the frequency and magnitude of flood events along the river after the siltation dam collapse.

In spite of the impacts of the dam collapse and continuing sedimentation and drainage input from the mine site, the local residents still use the river as a place to bathe, swim, wash clothes, and water their farm animals.

Our visit to the river occurred two days after a major thunderstorm, which according to the local residents resulted in a vigorous flood event along the river.

At the time of our visit, abundant orange clayey material was readily visible along the river bed over the length of its course from its mouth at the ocean to some 5 km from the mine site, the highest point in the river system that we visited (Fig. 9). In low-flow portions of the stream, the river waters were a translucent green color, whereas in higher-flow portions of the river, the river waters were carrying substantial quantities of yellow to orange material in suspension (Fig. 9A).

Abundant debris from the recent and previous flood events was readily apparent along the river, even near its mouth (Figs. 9C, D).

Based on a quick inspection of the active river channel we observed no fish or aquatic invertebrates in the main stem of the Mogpog River. Local residents told us that such aquatic life was present in the river prior to the 1993 siltation dam failure. We did observe a diverse community of aquatic organisms in uncontaminated tributary streams draining into the Mogpog from unmined, unmineralized areas.

Environmental concerns

Effects of acid-rock drainage from Marcopper: We collected filtered and unfiltered water samples at a point on the Mogpog River approximately 5 km downstream from the mine site (Fig. 9A). The analytical results for these samples are summarized in Table 1. In spite of dilution from tributary streams , the Mogpog River waters at this locality are quite acidic (pH 4.5), have quite high conductivity (1000 µS/cm) and contain high dissolved concentrations of a variety of metals including copper (22 ppm), iron (4.4 ppm), aluminum (7.8 ppm), manganese (7.7 ppm), and zinc (1 ppm). The concentrations of metals in the unfiltered fraction of the waters are even greater; hence significant quantities of metals are being transported by the water both in solution and in the suspended particulates. These levels of metals and acid are potentially quite detrimental to aquatic organisms, and also raise concerns about health effects on any people who regularly use the river water for consumption, bathing, swimming, and washing clothes.

Leaching of metals and acid from the sediments: If the sediments in the Mogpog River contain significant quantities of sulfide minerals eroded from the Marcopper mine dumps, then they may serve as a potential long-term source of acid and metals that can be leached into the river during storm events.

Effects of sediments from Marcopper: The high rate of sediment transport from Marcopper will continue to have adverse effects on the aquatic ecosystem, and on the ability of the river system to handle large flood events. We also observed high erosion rates and rapid sediment transport in several other rivers on Marinduque that were not affected by mining. However, the fine-grained, metal-rich, and potentially acid-generating nature of sediments from Marcopper is likely to have been a substantial change from the natural condition of the Mogpog prior to mining. For example, fine-grained sediment from the mine site may fill in the pore spaces of the originally coarser river-bed sediments, thereby adversely affecting the habitat of fish and aquatic invertebrates living on the river bottom.

Recommendations

- Sediment-laden, acid-rock drainage from the mine site is adversely affecting water quality along the Mogpog River. This underscores the need for more effective sediment control and treatment of acid-rock drainage at Marcopper. This is especially true given the extensive use of the water by residents along the Mogpog River.
- The potential health effects of Mogpog River water use by local residents and their farm animals should be evaluated. The potential health effects on the aquatic habitat and biota should also be evaluated.

Figure 9. Photos of the Mogpog River. **A.** The site where we collected a water sample (Table 1), approximately 5 km downstream from Marcopper. The water is a yellowish-tan color due to its high suspended sediment content. **B.** The Mogpog River approximately 10 km downstream from Marcopper. Although difficult to see in the photo, a group of children was swimming in the river at the time the photo was taken. **C.** Mogpog River approximately 2 km from its mouth. The sand bar on which Jack Medlin is walking was under water two nights previously due to a flash flood. Debris piles from the recent flood (and previous floods?) are visible near the right bank of the river. **D.** The Mogpog River mouth. According to locals, the tire (originally from one of the mine's dump trucks) was carried in by the river during a flash flood; however, the tires are used by the mining company to create artificial reefs, and so may have been carried in by the ocean during a storm. Note the milky-orange color of the water due to suspended sediments from the Mogpog.

Table 1. Chemical analyses of water samples we collected in mining-affected areas of Marinduque, and of water samples from leach experiments we conducted using mixtures of Boac River tailings, tap water, and sea water. Anion concentrations were measured using ion chromatography. Concentrations of major cations and trace metals were measured on acidified samples using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS). For comparison, we have also included an average sea water composition from Quinby-Hunt and Turekian (1985) and Bearman (1989). Analyses are listed in either parts-per-million (ppm) or parts-per-billion (ppb) concentrations.

Sample	Mogpog river	Boac river		Boac domestic well		Boac tailings-tap water leach	Boac tailings-sea water leach	Calancan tailings pore water	"Average" sea water
	(filtered)	(filtered)	(unfiltered)	(filtered)	(unfiltered)	(filtered)	(filtered)	(filtered)	
pH	4.5	8.3		8		3.72	3.08	7.6	7.6 - 8.2
Conductivity uS/cm	1000	800		200		1610	45000	>20000	35000-48000
Cl ppm	4.4	4.4		7.6		29	19000	19000	19353
F ppm	1.1	0.5		02		2.9	2.8	2.1	1.3
NO3 ppm	0.3	<.08		0.8		4.1	<7.0	<7.0	
SO4 ppm	510	320		130		2200	5000	2600	2715
Ag ppb	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1	4	0.002
Al ppb	7800	33	140	11	690	110000	210000	29	1
As ppb	<0.2	0.3	0.5	1	2	1	30	44	3.7
Ba ppb	39	22	24	8.8	7.9	0.2	4	40	20
Ca ppm	120	100	100	100	100	590	1100	380	415
Cd ppb	11	1	1.1	<0.02	<0.02	14	30	3	0.1
Ce ppb	68	0.3	0.64	<0.01	0.5	42	76	<0.1	0.001
Co ppb	180	17	18	<0.02	0.3	730	730	<0.2	0.003
Cr ppb	<1	<1	<1	<1	1	6	<100	<10	0.3
Cu ppb	22000	100	300	3	7	53000	62000	60	0.1
Fe ppb	4400	76	170	130	1100	620	4800	1000	0.055
K ppb	3500	2700	2600	4600	4600	4800	410000	440000	399000
Li ppb	11	3.2	3.1	3.4	3.7	92	270	140	180
Mg ppm	59	50	50	19	19	170	1600	1300	1280
Mn ppb	7700	1500	1500	150	160	13000	12000	49	0.01 - 0.1
Mo ppb	0.57	18	18	2.1	1.9	0.3	5	81	11
Na ppm	14	12	12	22	23	120	11000	11000	10781
Ni ppb	69	6.4	6.7	<0.1	<0.1	440	460	<1	0.48
P ppb	5	8	10	53	64	19	500	90	60
Pb ppb	2.5	0.3	0.2	0.2	0.51	0.08	<5	0.6	0.001
Rb ppb	3.2	1.8	1.8	1.4	1.7	4.2	20	120	124
Sb ppb	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<2	0.5	0.2
Se ppb	<0.2	1	2	<0.2	<0.2	2	100	150	0.17
SiO2 ppm	63	35	35	37	41	83	<50	6	
Sr ppb	570	380	390	440	450	580	7100	7300	7800
U ppb	0.63	0.05	0.05	0.09	0.1	2	4	2.2	3.2
V ppb	0.1	1	1	0.1	3	1	<10	<1	2.5
Zn ppb	1000	27	42	30	35	2300	2300	50	0.39

- An analysis of the extensive sediment deposits in the Mogpog river bed is needed to understand the sulfide mineral content (and hence the acid-generating capacity) of the sediments. Even if ARD and sediment transport from Marcopper were significantly reduced, the sediments already deposited along the river could themselves have adverse impacts on water quality if they contain sulfides.
- The pre-mining character of the river can be reconstructed to understand the extent of impacts of mining and the 1993 siltation dam collapse. Comparison of pre-mining and post-mining photographs is a useful way to reconstruct pre-mining conditions. There are also a variety of geological and ecological methods that can be employed to understand the pre-mining geological, geochemical, and ecological conditions of the river. Such information is crucial to understand the extent of remediation necessary along the river, and to help guide the remediation.
- The water quality and aquatic toxicology of the entire Mogpog watershed should be assessed. This is needed to understand the contributions of sediments and degraded waters from Marcopper relative to inputs from other tributaries. Water quality should be assessed regularly (at least every month) and during storm events to understand seasonal and storm-related variations in water quality. Local residents can be trained in water sampling and other field monitoring techniques as appropriate to help carry out this regular water quality assessment.
- An ecological survey of the Mogpog's current fish and aquatic invertebrate populations should be carried out, and the results compared with inferred or known pre-mining ecological conditions along the river.

Boac River

We visited the lower and middle portions of the Boac River to evaluate the impacts of the 1996 adit plug failure and resulting catastrophic release of tailings into the Makulapnit and Boac Rivers.

As a result of the release, substantial tailings deposits were formed along the Makulapnit and Boac Rivers (UNEP, 1996). Some portions of these tailings deposits have been removed by erosion during storms, and some portions were bulldozed by mining company personnel into berms along the river. However, as of our visit, there are still extensive tailings deposits visible in many places along the Boac River streambed (Fig. 10). According to local residents, there are also still ½- to 1-meter thick tailings deposits under water in the active river channel.

The tailings deposits we observed in the Boac river bed contained visible sulfides, and as a result have a typical grayish color on unweathered surfaces (Fig. 10A). In addition, many of the tailings deposits are coated by abundant white, brown, and yellowish secondary minerals (Figs. 10B, C), including abundant soluble salts. These secondary minerals formed directly from oxidation of sulfides in the tailings deposits, and from evaporation of acid waters generated in the tailings deposits by sulfide oxidation. The tailings deposits are typically hard, like concrete, most due to the buildup of soluble secondary salt cements in the tailings deposits. Little vegetation is growing on the tailings.

We observed a large amount of coarse-grained sediment within the Boac River channel along most of its length, indicating that rapid erosion is occurring in the headwaters of the Boac and its tributaries, and that vigorous transport of coarse sediments occurs during storms (Fig. 10A). Gravels in the middle and upper portions of the Boac have abundant cobbles of altered, mineralized rocks that presumably were eroded from the Marcopper deposit. However, gravels and sands dredged from deep in the Boac River channel near its mouth (Figs. 10E, F), which most likely were deposited well before mining started, have very few mineralized cobbles. This indicates that, prior to mining, there was likely substantial dilution of sediment eroded from the Marcopper

Figure 10. Photos of the Boac River. **A.** An extensive tailings deposit in the middle Boac River. Since 1996, the river has cut a channel down through the tailings deposit, which originally filled most of the river bed. Coarser sediments deposited on top of the tailings indicate rapid rates of erosion in the headwaters of the Boac and high sediment transport during storms. **B.** Soon after the spill, tailings were collected in sandbags and stacked on top of the tailings deposit shown in the photo to the left. Now, the sandbags have corroded due to exposure to sunlight and to acid generated from the tailings. **C.** Closeup of tailings deposited on the edges of the river bed. The yellow oxidation rind on exposed surfaces of the deposit are soluble iron sulfate salts. The gray color of the unweathered tailings is due to the high sulfide content. **D.** Boac River above Boac. Tailings berms visible on the far side of the river were bulldozed by PDTS after the spill to prevent overbank flooding of adjacent farmlands. **E.** View of Boac River mouth from the air, showing the dredge channel (top of photo). **F.** Sedimentary material dredged from the Boac River delta. Mineralized rocks (blue-green mineralized cobble, central portion of the photo) from the Marcopper deposit are only rarely present in the sediments.

deposit by sediment eroded from unmineralized areas in the Boac headwaters. Such observations are important to understand likely pre-mining conditions along the Boac River.

Environmental concerns

Effects of acid-rock drainage from Marcopper on Boac water quality: As indicated previously, a substantial volume of acid-rock drainage enters the Makulapnit River from the mine site. However, a water sample collected from the middle Boac River has near-neutral pH and quite low concentrations of dissolved metals (Boac River sample, Table 1). This indicates that ARD from Marcopper is relatively well diluted by tributary streams draining unmined, unmineralized areas, by the time the waters reach the middle stretches of the Boac River. This is in contrast to the Mogpog River, which remains quite acidic and metal-rich well below the mine site.

Leaching of acid and metals from the tailings into the Boac River: As noted in the Boac River remedial plan (PDTS, 1999), the sulfide content of the Boac tailings deposits makes them a substantial source of acid and metal in the river system. In order to test this, we carried out a simple leach test where we mixed in a bottle one part tailings collected from the river bank with five parts Marinduque tap water (used as a proxy for local fresh water). We then measured the pH and conductivity of the leach water, and collected filtered samples of the leach water for chemical analysis. The results of this leach test are shown in Table 1 (Boac tailings—tap water leach sample). The leach waters are quite acidic (pH 3.72) and have very high levels of a variety of heavy metals such as copper (53,000 ppb), aluminum (110,000 ppb), and manganese (13,000 ppb). These results show that extensive soluble salts observed in the tailings deposits (Fig. 10) can dissolve quite easily, and could therefore potentially cause an environmentally damaging flush of acid and metals from the tailings into the river during rain storms.

Little or no fish and invertebrate aquatic life was visible in the Boac River in its middle stretches. This lack of aquatic life indicates that the repeated flush of acid, metals, and sediment from the tailings during rainy periods is having a detrimental impact on the river system. In addition, local residents told us that there are periodic fish kills in the lower (presumably estuarine) portions of the Boac River, which could also result from storm-induced flushing of acid and metals from the tailings deposits.

Leaching of acid and metals from the tailings into local ground water: The tailings deposits are a potential source of acid and metals into ground water near the river. The 1996 UNEP study found relatively little impact on ground water quality at that time; however, the study was conducted too soon after the tailings spill to adequately assess impacts of long-term sulfide oxidation in the tailings deposits.

We were able to collect a water sample from one domestic well several kilometers north of the lower Boac River near Boac (Boac domestic well sample, Table 1). The well water analysis indicates little or no interpretable impact of acid or metals from the tailings in the river bed. However, the well may be sufficiently far enough away from the river that either acid and metals leached from the tailings into the ground water are mitigated before reaching the well, or that metals-contaminated ground water has not reached the well.

Potential impacts on food crops: There is a justifiable concern about potential impacts of the tailings deposits on food crops growing in the river floodplain. These could include, for example, uptake of metals from the tailings by the food crops, and effects of the tailings on plant health and crop viability. We did not have time on this trip to assess these potential impacts.

Potential impacts on the marine environment: There have been and are some ongoing studies of the effects of the 1996 tailings spill on the marine environment near the Boac River mouth. Potential impacts include physical smothering of the marine floor ecology by tailings sediments, and metal uptake by aquatic marine organisms that come in contact with the tailings or with seawater chemically affected by the tailings.

Recommendations

In its 1999 Boac River rehabilitation plan PDTS proposed a variety of remedial options for the tailings deposits in the Boac River. A process for evaluating different remedial options will be discussed in a later section of our report.

- Based on our observations, discussions with local residents, and our preliminary sampling results and interpretations, it is easy to concur with the conclusion that leaving the tailings in the river bed is not a viable option. The tailings deposits will continue to be a long-term source of acid, metals, and sediment into the river system, especially during storms. These contaminants will continue to make it difficult for aquatic life to reestablish in the river, and will have negative effects on the human population living near the river.
- Any remedial action to remove the tailings will require an accurate accounting of the total volume of tailings remaining in the river bed, river banks, river floodplain, and dredge channel. As the total amounts of tailings present may influence the choice of the optimal remedial solution, it is important that this accounting be made as soon as possible. There are a number of options by which this accounting can be made.
- As recommended previously for the Mogpog River, a more detailed assessment of temporal and spatial variations in water quality within the entire Boac River watershed should be made. Such an assessment should pay specific attention to the relative contributions to acid and metal loadings along the Boac of ARD from Marcopper versus the tailings deposits, and the mitigating effects of tributary streams. Seasonal and storm-related variations in water quality should be assessed. Local residents can be trained in water sampling and field analysis measurements to help in this assessment.
- An assessment of water quality of domestic wells near the river should be made to see if acid and metals leached from the tailings are working their way into local ground water supplies.
- Also, if it has not already been done, a more detailed ecological, toxicological, and public health assessment of the Boac River watershed and ocean near the river mouth is necessary to understand the full impacts of the 1996 tailings spill on the aquatic fresh-water and marine ecosystems. This assessment should include an evaluation of the pre-mining and pre-spill ecological and human health conditions along the river. Photographs, as well as any other pre-mining or pre-spill studies or anecdotal information would prove useful in this regard. The assessment should also be coupled with a ecological, toxicological, and public health characterization of a nearby river/marine river mouth unaffected by mining.
- Where the river floodplain affected by tailings deposits is still being farmed, an assessment of metal uptake by plants and biota used as food is recommended. Metals uptake by plants depends on many factors, of which the bioavailability of the metals in the soils is one.
- A health assessment of residents along the river who use the river water on a regular basis for drinking, swimming, bathing, or other uses should be made. The assessment should include, for example, a screening for metals in urine, blood, and hair.

Calancan Bay

Approximately 16 years of tailings disposal in Calancan Bay resulted in the formation of a tailings causeway extending approximately 6-8 km offshore (Figs. 11, 12), and built up approximately 1-2 m above sea level. The tailings causeway itself is composed primarily of sand-sized particles, with some clay layers. Submarine tailings deposition occurred in a very large area around the causeway (Fig. 11). We did not have access on our trip to detailed bathymetric maps that

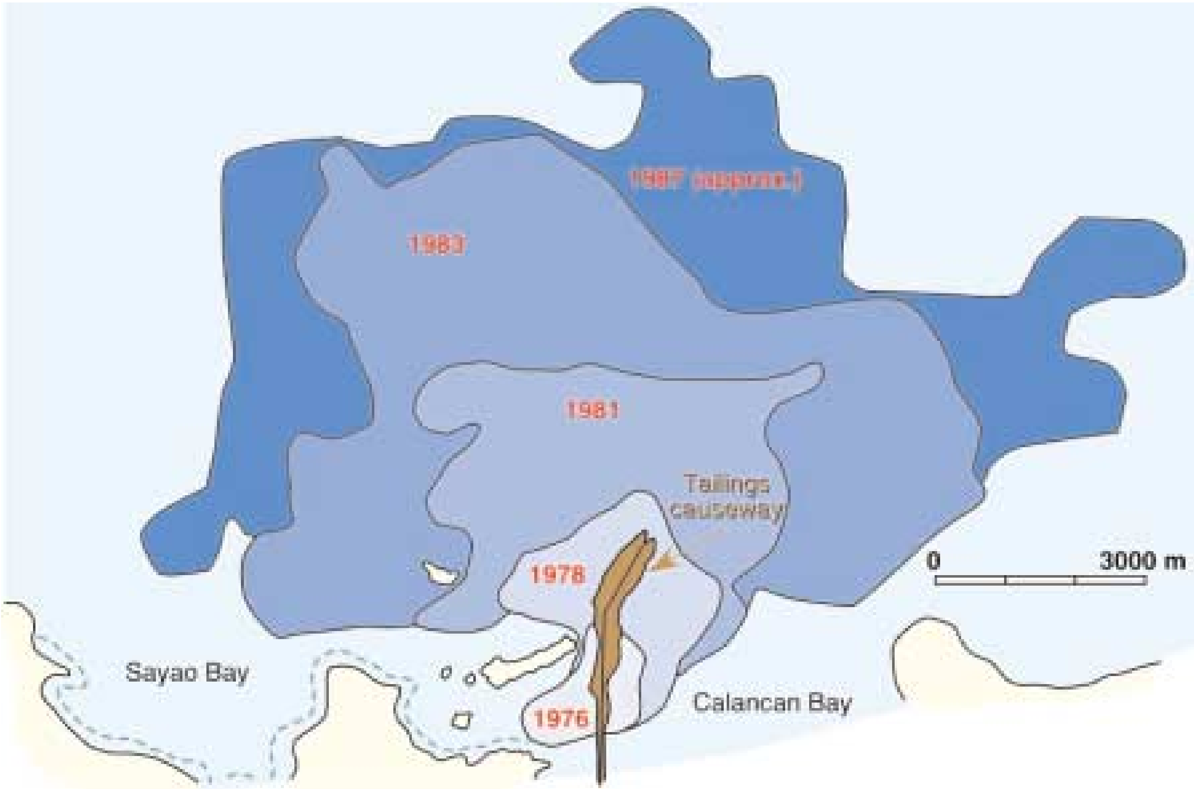

Figure 11. Map showing approximate extent of underwater tailings deposition over time in Calancan Bay. The 1987 boundary is an approximation of a gridded distribution shown in the original map. Modified from figure in Ellis et al. (1994).

would allow us to estimate the thickness of the submarine tailings deposits.

Ten years after the cessation of tailings disposal in the ocean within and north of Calancan Bay, the tailings causeway is now undergoing substantial modification by natural erosion and weathering processes (Figs. 12A-C). The end of the causeway is actively eroding on its western, up-current side, and a low erosional scarp has formed on the western side of the causeway (Fig. 12C). Redeposition of sediment eroded from the end of the causeway is forming spits on the eastern down-current side of the causeway. Also, sediments reworked from the north end of the causeway are being transported landward into shallower water of the bay, where they will be more susceptible to continued reworking landward. According to local residents, the end of the causeway has already receded substantially due to the erosion. Pipes used to transport the tailings slurry to the ocean are now falling into the ocean due to erosion of the tailings from beneath them (Fig. 12C). From the air, extensive suspended sediment plumes are readily apparent on both sides of the causeway, indicating easy suspension of sediments by wave action and ocean currents (Figs. 12A, B).

Trees, grasses, and other vegetation planted on the causeway appear to be quite healthy in places where the tailings deposits were covered with topsoil prior to planting. However, vegetation growth is minimal in areas without topsoil and in shoreline areas affected by wave action.

With the exception of isolated pods, there is little apparent visible evidence that the Calancan Bay tailings deposits are undergoing sulfide oxidation. The yellowish, acid-generating soluble salts so readily apparent in the Boac River tailings deposits (Fig. 10) are largely absent in the Calancan tailings. Fresh, unoxidized sulfides are visible with a magnifying glass in the Calancan tailings materials. Mineralogical analyses of

Figure 12. Photos of Calancan Bay. **A.** Aerial view looking south of the northern end of the Calancan Bay tailings causeway. The end of the causeway is undergoing active erosion and sediment redistribution, as seen by the suspended sediments (lighter blue shades) in the ocean on both sides of the causeway, and the hook-shaped spits forming on the eastern side of the causeway (left hand side of photo). **B.** Aerial view looking north of the middle and northern portions of the causeway. The erosion of the causeway on both sides is apparent. **C.** From the ground, erosion at the end of the causeway is apparent. Erosion has led to the collapse of the tailings transport pipes into the water. **D.** A Marinduque reef substantially west of Calancan Bay that has not been affected by the tailings.

Calancan tailings samples collected from the east side of the causeway near its terminus identify calcite, an acid-neutralizing calcium carbonate mineral. Calcite was not found in the Boac River tailings samples. It is possible that the Calancan Bay tailings calcite either originated from a calcite-rich zone in the old Tapian orebody, or, more likely, formed as a secondary mineral in the tailings deposit by reactions of calcium-bearing silicates with dissolved carbonate in the sea water. Along with the carbonate alkalinity in the sea water, the calcite in the tailings undoubtedly helps consume acid generated by oxidation of sulfides in the tailings.

On our visit to the tailings causeway, we observed a number of people using the tailings beach for recreation; it also appeared to us that a family is residing on the tailings causeway next to the beach used for recreation.

Environmental concerns

Effects of the tailings on water quality and *ecology in Calancan Bay:* We are aware of, but have not been able to review in detail, a number of studies examining the impacts of the tailings deposits on water quality and the marine ecology of Calancan Bay. These studies have noted environmental impacts such as the burial of the reef ecosystem by the tailings and the decline of aquatic life in the bay. In published reports (i.e., Zandee, 1985), the mining companies indicate that there has been a revival of aquatic life in the bay. Philippine DENR officials were quoted in the 1996 UNEP report as saying that a recovery of the near shore marine fishery was occurring. Local residents dispute that there has been a significant recovery of the bay's aquatic ecology.

The UNEP study (1996) also measured metal contents in the muscle tissues of fish collected from Calancan Bay, and found no evidence of elevated concentrations of a number of elements in the fish tissues that would be problematic to humans who consume the fish. However, the UNEP report also noted that, because fish regulate metal concentrations in their muscle tissues, the analysis of metal concentrations in other tissues or organs is needed to understand fully the bioavailability of metals in the tailings and metal uptake by fish.

We did not have time to either assess in detail the current environmental condition of Calancan Bay nor to verify the extent of ecological recovery in the bay. However, we found no evidence that crabs, worms, or other marine organisms live in the tailings on- or near-shore.

We were able to collect a sample of pore waters from the tailings in the intertidal zone at the end of the causeway. This sample raises our concern about potential metal mobility from the tailings into the bay waters and potential metal uptake by aquatic organisms. The sample was collected after digging a shallow trench in the tailings and allowing water to seep from the adjacent pore spaces into the trench. Chemical analysis of the pore waters reveals elevated dissolved concentrations of a number of metals (such as selenium, arsenic, copper, aluminum, iron, and molybdenum) compared to regular sea water (Fig. 13, Table 1). These elevated metal concentrations indicate that, contrary to visual appearances discussed previously, sulfides in the tailings are being oxidized by sea water in the tailings pore spaces. Sulfide oxidation is also indicated by the lower pH of the pore waters compared to adjacent sea water (pH 7.6 versus 8). In general, the elements enriched in the tailings pore fluids are those that are more mobile at near-neutral to alkaline pH values. The high dissolved iron concentrations (which are very unusual in oxygenated water) presumably result from complexing with chloride ions in the sea water.

Several of the heavy metals present in the tailings pore waters (copper, selenium, arsenic, and silver) exceed the U.S. Environmental Protection Agency (EPA) Recommended Chronic or Acute Water Quality Criteria for salt water (Table 2; U.S. EPA, 1998a). These metals could therefore pose potential ecological risks if the metals are taken up by marine organisms that live on the ocean bottom in the near-shore marine environment. It is unclear whether similar metal enrichments are present in the tailings pore fluids farther offshore away from the intertidal zone. It is also unclear whether these metal enrichments are translated into the bay's sea water through contact with the tailings deposits or tailings brought into suspension by ocean currents.

Redistribution of the tailings in the ocean and along the coast away from the causeway: Continued erosion of the tailings from and adjacent to the causeway will result in a significant movement of metal bearing, tailings-derived sediments along the Marinduque coastline, and possibly toward the inhabited mainland. We were not able to assess the potential ecological impacts of this reworking and sediment transport on the adjacent coastal areas.

Recommendations

It is our understanding that the tailings in Calancan Bay are not presently being considered for remediation. Nonetheless, continued assess-

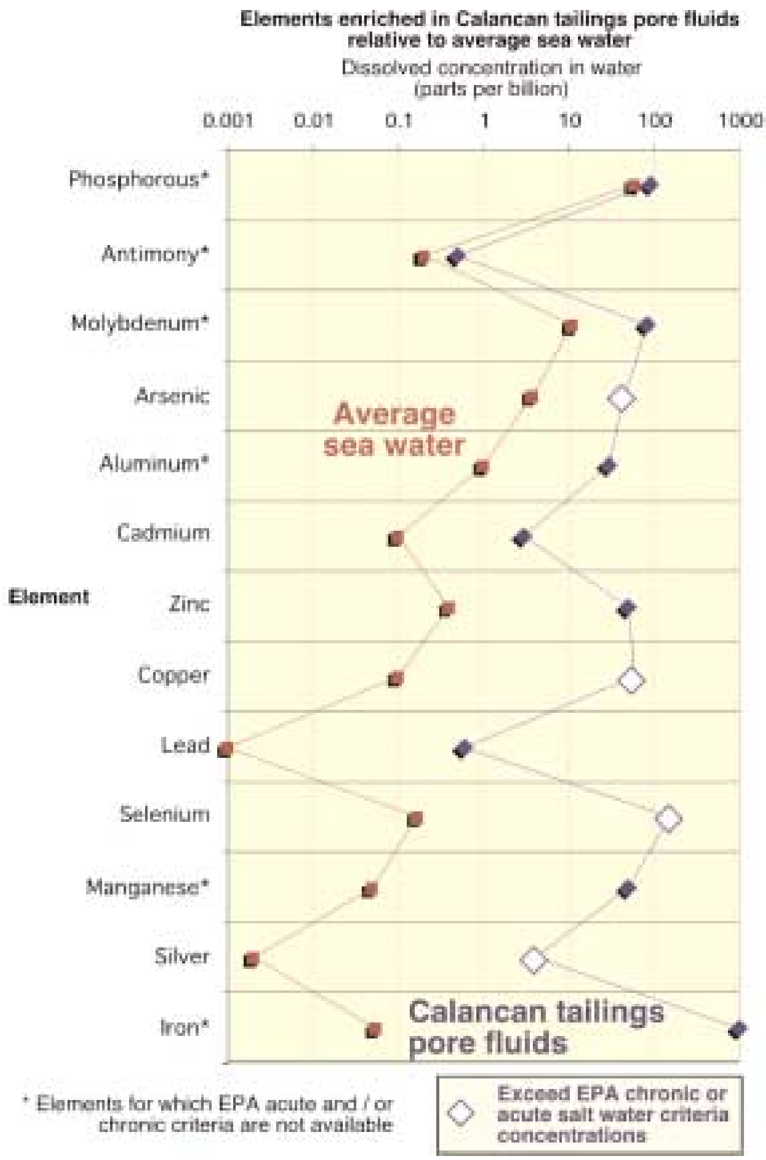

Figure 13. Pore waters collected from the Calancan tailings causeway in the intertidal zone have elevated dissolved concentrations of a number of metals compared to regular sea water (data from Table 1); the elements are plotted from top to bottom in order of increasing difference in concentration. These elevated metal concentrations indicate that sulfides in the tailings are being oxidized by sea water in the tailings pore spaces. Several elements in the tailings pore fluids have concentrations that exceed EPA's chronic (long-term exposure) or acute (short-term exposure) criteria for salt water (see Table 2). This indicates that the pore waters are potentially toxic to marine organisms that burrow in the tailings.

ment of the tailings' substantial environmental impacts on the bay and other affected coastal and marine areas is clearly warranted.

- This assessment should include regular water-quality sampling, as well as detailed ecological and ecotoxicological assessments of the marine environment. *Trace elements such as selenium, silver, molybdenum, cobalt, and nickel (which are not normally analyzed for in many water sampling or toxicological studies) should be routinely examined in these assessments.*
- A major focus of these assessments should be to assess the potential long-term environmental impacts in the bay and adjacent coastal areas. An assessment of the human health impacts (e.g., metal screening in blood, urine, hair) of local residents who rely upon the local fisheries for food should also be done.

Table 2. Concentrations of dissolved metals measured in Calancan Bay pore waters compared to U.S. EPA recommended acute (short-term exposure) and chronic (long-term exposure) water quality criteria for selected metals in salt water (U.S. EPA, 1998a). Criteria are not available for other metals we analyzed. All concentrations are in parts-per-billion (ppb).

	Calancan tailings pore water (filtered)	**EPA Acute**	**EPA Chronic**
Arsenic	44	69	36
Cadmium	3	42	9.3
Zinc	50	90	81
Copper	60	4.8	3.1
Lead	0.6	210	8.1
Selenium	150	290	71
Silver	4	1.9	
Nickel	<1	74	8.2

- Another major focus should be to identify creative and cost-effective mitigation and (or) remediation opportunities to help minimize or eliminate these impacts.
- A thorough review and summary of results of all environmental studies carried out in the bay to date is needed to guide future studies.

CMI Mine

Although we had been made aware of the presence of another metal mine on Marinduque, the CMI mine near Mogpog (Fig. 2), we were unaware of the size and potential environmental impacts of this mine until our airplane overflight. Apparently, the CMI mine operated in the 1970's. At this point, we do not know details of the mine's history, ownership, commodity mined, nor geologic characteristics. Nonetheless, the mine's proximity to a major town (Mogpog), the ocean, and the Mogpog and Boac River mouths make it an important site whose potential environmental impacts relative to those of Marcopper should be assessed.

From the air the CMI mine site can be seen to include (Fig. 14):

- a large open pit that is now filled with water;
- large mine dumps with abundant yellow secondary salts;
- at least one large mine dump that extends into the ocean, and which is showing signs of erosion and dispersion of potentially contaminated sediments into the ocean;
- the remains of a substantial mill, indicating a large amount of ore was processed on the site;
- large, flat, tailings impoundments with brown-colored water on top;
- an elongate causeway extending into the ocean that looks strikingly similar to the Calancan bay tailings causeway.

On a very brief stop at the CMI mine dumps, we observed highly acidic water (pH around 3.5) draining one of the mine dumps, as well as an area downhill from the dump where vegetation appears to have been killed by acid-rock drainage. A quick inspection of the rocks on the waste dump indicates that the deposit has characteristics both of porphyry deposits similar to Marcopper and deposits similar to Summitville (Colorado, USA) and Lepanto (Philippines); both deposit types have high geological potential to generate acid-rock drainage.

Signs that some of the CMI dump material had recently been removed by earthmoving equipment were readily apparent on our brief visit to the CMI dump. We subsequently observed the use of what appears to be mine

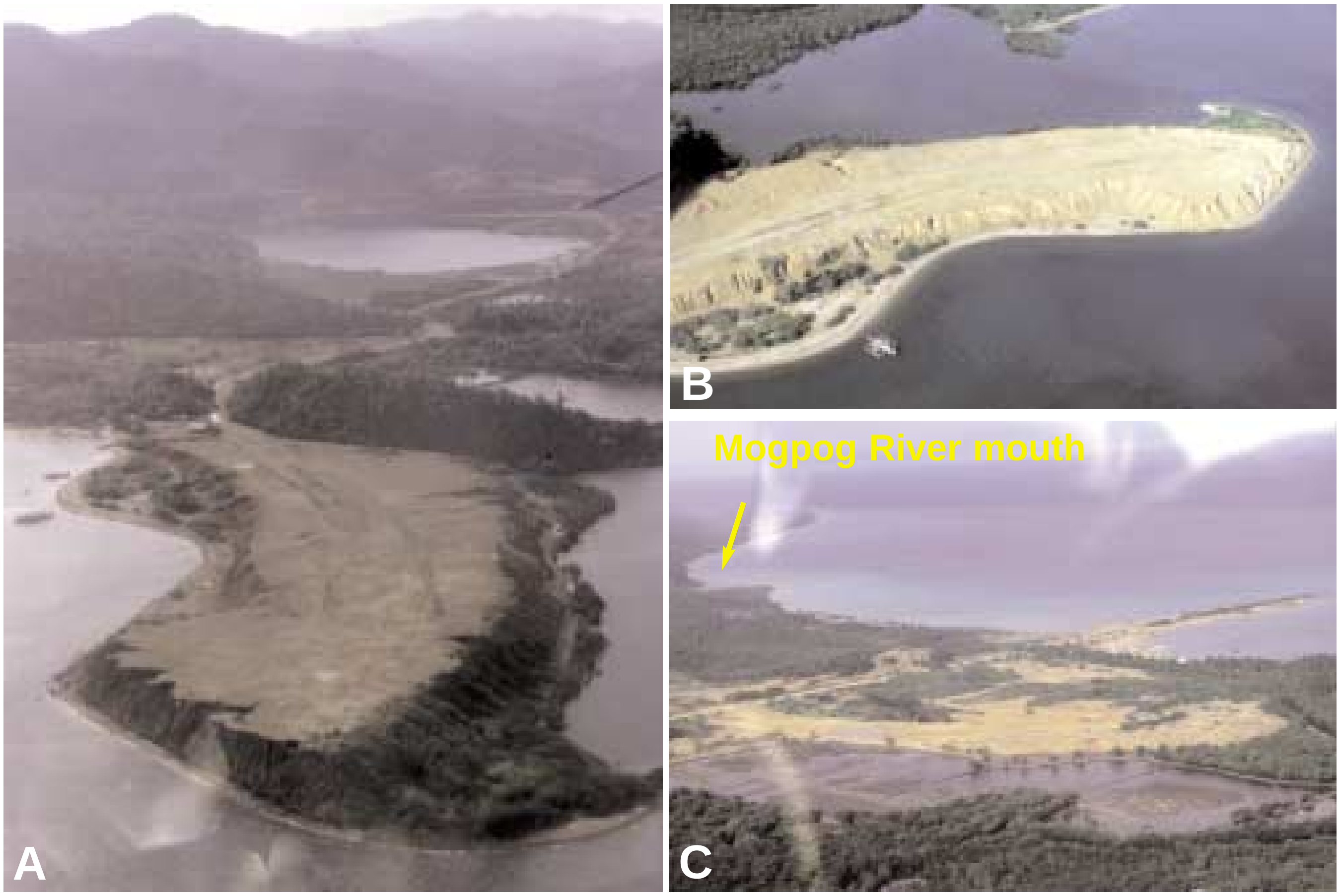

Figure 14. The CMI Mine near Mogpog. Photos by R. Morton. **A.** Aerial view looking east of the CMI open pit lake (visible in background) and a major mine dump built out into the ocean (foreground). **B.** Yellow oxidation minerals and soluble salts are readily apparent on the same CMI mine dump from the photo on the left. **C.** View looking west-southwest of an extensive flat area south of the major mine dump with weathering mine or milling wastes. Some of this area is covered in a brownish water that may be ARD. The long causeway extending into the ocean in the middle of the photo looks strikingly similar to the tailings causeway in Calancan Bay. If tailings from the CMI mine were disposed in the ocean, then the same potential environmental impacts are likely present here as well, although at a smaller scale. The mouth of the Mogpog River is at the left of the photo.

wastes as road fill material on the main road near the mine between Mogpog and the ferry terminal at Balanacan.

Environmental concerns

Effects on ground- and surface-water quality: The acid waters and vegetation kill zones downhill from the dump we visited, coupled with the geological characteristics of the material on the dump, indicate that the CMI mineral deposit, mine wastes, and mill tailings are potentially quite acid generating, and therefore should be considered a potentially significant source of acid and metals into the environment.

The close proximity of the CMI mine and pit lake to the town of Mogpog raises potential concerns about the impact of the mine waters on ground-water quality, especially if ground water near the mine is used as the municipal water supply for Mogpog.

Effects on the marine ecosystem: The observed disposal of acid-generating mine wastes, and possible disposal of mill tailings into the ocean next to the CMI mine raises substantial concerns about potentially adverse environmental effects on the near-shore marine ecosystem adjacent to the mine.

Recommendations

- Further characterization of the CMI mine's environmental geology and environmental impacts is clearly needed. This should include an assessment of water quality in the pit lake, in waters draining mine dumps and tailings impoundments, in nearby water wells, and in the ocean adjacent to in-ocean mine dumps and tailings deposits. The extent of environmental impacts on the coastal environment away from the mine site should also be assessed.
- An ecological assessment of the mining impacts on the nearby terrestrial and marine ecosystems should be carried out, including an analysis of metal uptake by aquatic and terrestrial flora and fauna.
- If the environmental assessment reveals substantial metal contamination from the mine site in drinking water supplies or food crops, a health assessment of local residents should also be carried out.
- Use of CMI mine waste material as road fill away from the mine site should be very carefully evaluated and possibly stopped. In other cases we are aware of, the use of sulfidic, acid-generating rock materials as road fill has led to acid-kill of vegetation downhill from the roads, as well as destabilization of the road fill.

Results of a preliminary human health assessment

José Centeno of the U.S. Armed Forces Institute of Pathology joined our team's visit to Marinduque to provide an important perspective on potential effects of the mining-environmental problems on human health, and to develop preliminary plans for a more detailed human health assessment in the future.

Dr. Centeno also reviewed preliminary environmental health studies that had been conducted by various local groups prior to the team visit to Marinduque. Some of these groups included the Department of Health and the University of the Philippines Toxicology Department.

The written protocols and the experimental rationale for these environmental health studies were not available to the team. However, based on Dr. Centeno's review of the available scientific data and observations, we have several substantial concerns with the studies, including lack of focus, poor design methodology (e.g., the studies were based on a very small number of subjects), lack of subject assurances and lack of proper controls which are usually included in environmental health studies. Moreover, it was not clear from these studies the rationale used by the investigators to justify metal "chelation" therapies (with or without mineral supplementation) that were performed on subjects with blood lead levels well below 25 mg/dL, and at potential risks of nutritional deficiencies. It is generally unwise and often harmful to chelate patients that may be at risk of nutritional deficiencies.

Recommendations on future environmental health interventions

- We recommend increasing the number of subjects to be recruited in these human health studies. This becomes extremely important for future considerations on health prevention and intervention strategies;
- An equal number of well described control (non-exposed) population (hopefully similar in size, age, sex, and nutritional status) be included in the design of future environmental health studies;
- A detailed study questionnaire should be developed and completed on every subject (including those who are exposed and those used as controls) recruited for the study;
- To support any clinical and (or) public health conclusions/recommendations on the impact of possible exposures to toxic metals, an epidemiological study should be developed that compares the exposed area versus a non-exposed population with similar geographical, nutritional, and demographic parameters.
- A biological monitoring program should be implemented to study metals exposure and effects. Elemental analysis and isotopic tracer

techniques, including inductively coupled plasma-mass spectrometry (ICP-MS) and lead isotopic analysis can be used to determine the isotopic compositions of and concentrations of other metals in blood ("spot" sample), urine (24-hour sample), hair, and nails. The results of these studies will help in identifying the metals of concern to human health, as well as their potential sources.

- Efforts to assess environmental pollution and bioavailability of metals to plants, fish, and selected animal tissues should be considered in any environmental health study.

Observations made on this trip

As we traveled around the island, Dr. Centeno screened a number of local residents for signs of chronic arsenic poisoning and fluorosis (Fig. 15). Only one person, an elderly gentleman from a baranguay along the Mogpog River, had symptoms (e.g., hyperpigmentation and hyperkeratotic lesions of the hands) suggesting long-term arsenic exposure. The potential source of the arsenic exposure was not readily apparent; the drinking water used by the gentleman came from a water well in the hills well above the Mogpog River, and so is seemingly unlikely to have been affected by mining-related metals from Marcopper. The gentleman's wife did not show symptoms of arsenic poisoning.

This preliminary assessment underscores the need for a more detailed human health assessment in the baranguays and countryside that have been most affected by mining on Marinduque. If metals-related health problems are found, understanding the source of these problems, whether due to natural exposures or from human activities such as mining, will be crucial.

Figure 15. Dr. José Centeno (wearing the blue shirt in the center of the photo) examined a number of local residents we met on our travels around the island for the presence of skin lesions indicative of arsenic poisoning. The gentleman being examined, who lives along the Mogpog River near where we collected the pH 4.5 water sample of the Mogpog River water (Table 1), showed no signs of arsenic poisoning. The AFIP publication being examined in the foreground (AFIP, 2000) shows pictures of the skin lesions symptomatic of arsenic poisoning. The potential human health effects of other metals was not assessed on our short trip, but needs to be done.

Guidelines for evaluating the effects of and remedial options for the Boac River tailings spill

The people of Marinduque have a memorandum of agreement (MOA) with the Philippine Department of Environment and Natural Resources that provides for an independent technical review of the available options for environmental remediation and restoration after the 1996 tailings spill. On our trip, we represented some of the expertise in the U.S. Federal government that might be available for the independent study called for in the MOA. Congressman Reyes is currently pursuing possible sources of funding to support the independent study.

The remedial options considered by PDTS in its 1999 Boac River EIS and rehabilitation plan included:

- Leaving the tailings in the river and allowing natural riverine transport to the sea.
- Removing the tailings from the Boac River and re-placing them in the Tapian Pit.
- Removing the tailings from the Boac River and placing them in an unsaturated landfill.
- Removing the tailings from the Boac River and placing them in a saturated landfill.
- Removing the tailings from the Boac River and placing them in the deep marine environment in the Tablas Strait offshore from the Boac River mouth (managed submarine tailings disposal, or STD).
- Various combinations of some of the above options.

Other remedial options that have since been mentioned by a variety of people include:

- Tailings solidification using cement, with possible use of the tailings-concrete solids for the construction of submerged breakwaters or other structures.
- Tailings solidification, with re-placement in the Tapian Pit.
- Disposal of the tailings in the CMI open pit, with or without tailings solidification.

There are likely other remedial alternatives that have not yet been considered, as well.

We did not have access to a number of reports cited by PDTS in its 1999 Boac River EIS and rehabilitation plan that provide key details and data. We therefore cannot at this point evaluate the scientific merits or drawbacks of each of the remedial options proposed by PDTS.

Similarly, there is not enough information available to us to render any judgement at this time about other remedial options not proposed by PDTS. However, we will present here some preliminary observations about the remedial options and guidelines by which the remedial options can be evaluated.

Above all, we feel that the purpose of an independent review of the remedial options should be to assess the scientific merits and drawbacks of each of the available options, which can then be used by the People of Marinduque to make a scientifically informed remediation choice. As we discussed in our public meeting on Marinduque, this is directly analogous to the role of medical doctors, who present their patients with the positives and negatives about different potential treatment options, thereby allowing the patient to make the best informed choice of treatments.

Submarine tailings disposal

The remedial option favored by PDTS (1999) is submarine tailings disposal in the deep waters of Tablas Strait. This plan involves removal of the tailings from the river bed and dredge channel, and pumping of a tailings slurry to a discharge point 1 km offshore and 35 m below the sea surface, where the ocean floor is approximately 80 m deep. According to this plan, the discharged tailings-water mixture would then travel in a density current on the sea floor to a depth of ~ 700 m.

There is considerable opposition to the STD option by many local residents of the western Marinduque coast. On our visit, we repeatedly heard from the local residents that they do not consider STD to be a viable option because of their concerns about the development of adverse impacts on the marine and coastal environment, and on the marine fisheries in the Tablas Strait.

Because of the controversy, we feel that it is appropriate to discuss here some observations about STD as a potential remediation option. This discussion also provides examples of the types of scientific questions that should be asked when evaluating the strengths and weaknesses of the different remedial options.

What information is needed about STD to judge its suitability for the Boac tailings?: In order to assess as completely as possible the potential environmental impacts of STD, there is an extensive set of information that must be gathered. For example, the following questions regarding physical processes must be considered:

- What are the sea-floor conditions and oceanographic conditions? How do these conditions vary spatially across the ocean bottom and within the sea water column? How do these conditions vary with time (seasonally, and during storms or typhoons)?
- What are the directions of sediment transport in the water column and on the sea floor? How do these directions vary with time, both seasonally and during storms or typhoons?
- What are the forces that drive the primary physical processes (local wind, swell, tides, fluvial discharge)?
- What are the high-energy events that affect the physical setting (riverine flooding, typhoons, earthquakes, tsunamis)?
- What are the sea-floor conditions in the directions of sediment transport and at the anticipated site of tailings deposition?
- What is the composition and size distribution of the waste material?
- What are the proposed method, rates, and duration of waste emplacement?
- Are offshore slopes sufficiently steep to maintain density flow to the basin floor?
- Can the tailings discharge system be designed to withstand the impacts of storms? Storm induced failure of the piping discharge system could lead to catastrophic release of tailings in the near-shore environment.

The following questions regarding the geochemical impacts of the disposal must be considered:

- What are the minerals in which heavy metals occur in the tailings materials? How soluble are these minerals in sea water and in the digestive tracts of marine organisms? Heavy metals residing in more soluble or reactive phases will be more readily taken up by marine organisms.
- How readily will sulfides in the tailings oxidize in sea water?
- What processing chemicals are present in the tailings fluids?
- What chemical reactions will occur between the tailings solids, tailings fluids, and sea water?
- If metals are dissolved from the tailings by sea water, what geochemical attenuation reactions with sea water will occur, and how far away from the tailings discharge outfall will these metals affect sea water quality?

The following questions regarding ecological impacts of the tailings disposal must also be answered.

- What are all of the marine organism communities that could be affected by the tailings disposal, given the predicted area of impact?
- What is the economic and ecological value of each of the marine biological communities identified in the disposal area?
- How will physical processes (such as sedimentation) and geochemical processes (such as dissolution of metals from the tailings) affect each of the different aquatic marine communities?
- What are the maximum chronic and acute toxicity concentrations of heavy metals in sediments and sea water for each type of marine organisms found in the areas affected by the tailings discharge, and will these levels be exceeded?

Only by satisfactorily answering each of these many questions can a scientifically sound decision be made regarding the potential suitability of each site proposed for submarine tailings disposal. Based on USGS studies of sites proposed for submarine sewage sludge disposal, addressing all of these questions in adequate detail is a very costly undertaking, requiring the use of a variety of time consuming bathymetric, geophysical, chemical, remote sensing, engineering, and other advanced technologies. In fact, recent developments in these technologies have enabled scientists to re-study long-term sewage disposal sites. In one recent study of Charleston Harbor, South Carolina, scientists have identified sufficient environmental problems that regulators as a result have mandated cessation of submarine sediment disposal at that site.

Based on the literature we have reviewed to date and the Boac River remedial plan (PDTS, 1999), we have been unable to determine whether sufficiently detailed information has been compiled to adequately address all of the many questions outlined above. Sufficiently detailed data for a variety of key parameters are not readily apparent in the Boac EIS/Remediation plan (PDTS, 1999), or in an assessment of deep-sea ecology and marine fisheries baselines in the Tablas Strait done for PDTS by Woodward-Clyde (1998). For example, submarine bathymetry data in the disposal area do not appear to be sufficiently detailed. Data on both long- and short-term temporal variations in ocean currents in and around the disposal site are not presented in the reports. Spatial and temporal data on the dissolved oxygen content of the ocean waters are not readily identifiable in these reports. Further, we have not been able to determine if geochemical tests were performed on the present-day tailings material to determine potential metal mobility from the tailings into sea water.

As another example, there is insufficient data in the Woodward-Clyde (1998) report to indicate whether deep-water (80-100 m) “pinnacle” reefs or other ecologically favorable shelf-edge habitats are present in the area to be affected by the proposed STD. Such deep-water reefs are increasingly viewed as crucial parts of reef ecosystems in the United States, as they have been shown to be key spawning grounds for a variety of fish communities.

Potential metal mobility from the Boac tailings in sea water: It is possible to place some constraints on potential metal mobility from the tailings into sea water. We performed another leach test on the same Boac River tailings discussed previously, only with sea water (collected from near the Boac River mouth) as the leach agent rather than tap water. As with the tap water leach, the sea water leach was done using a water:tailings ratio of 5:1, and using a split of the same tailings sample used in the tap water leach. The analytical results of the sea water-tailings leach were somewhat surprising in that the sea water leachate developed an even lower pH (3.08 versus 3.72) than the tap water leachate, and leached even greater quantities of many metals than the tap water leach (Table 1, Fig. 16). When compared to average sea water (Fig. 16), the sea water leach is exceptionally enriched in a wide variety of dissolved metals, including aluminum, iron, manganese, copper, zinc, cobalt, and nickel.

These experimental results clearly show that soluble salts in tailings that have been sitting exposed to air and rain along the Boac River (Fig. 12) readily dissolve in sea water, releasing their stored acid and metals. The lower pH and higher metal concentrations of the sea water leach compared to the tap water leach most likely are due primarily to complexation of the metals with chloride ions in the sea water.

When compared to the U.S. EPA Recommended Water Quality Criteria for sea water (U.S. EPA, 1998a), the sea water-tailings leach has several elements, for example copper, whose dissolved concentrations greatly exceed the EPA recommended maximum acute and chronic concentrations in sea water (Table 3).

The results of this simple experiment suggest that there is a substantial potential for an acid- and metal-rich plume of sea water to develop at and around the discharge point of the tailings disposal system. Key issues that must therefore be addressed are:

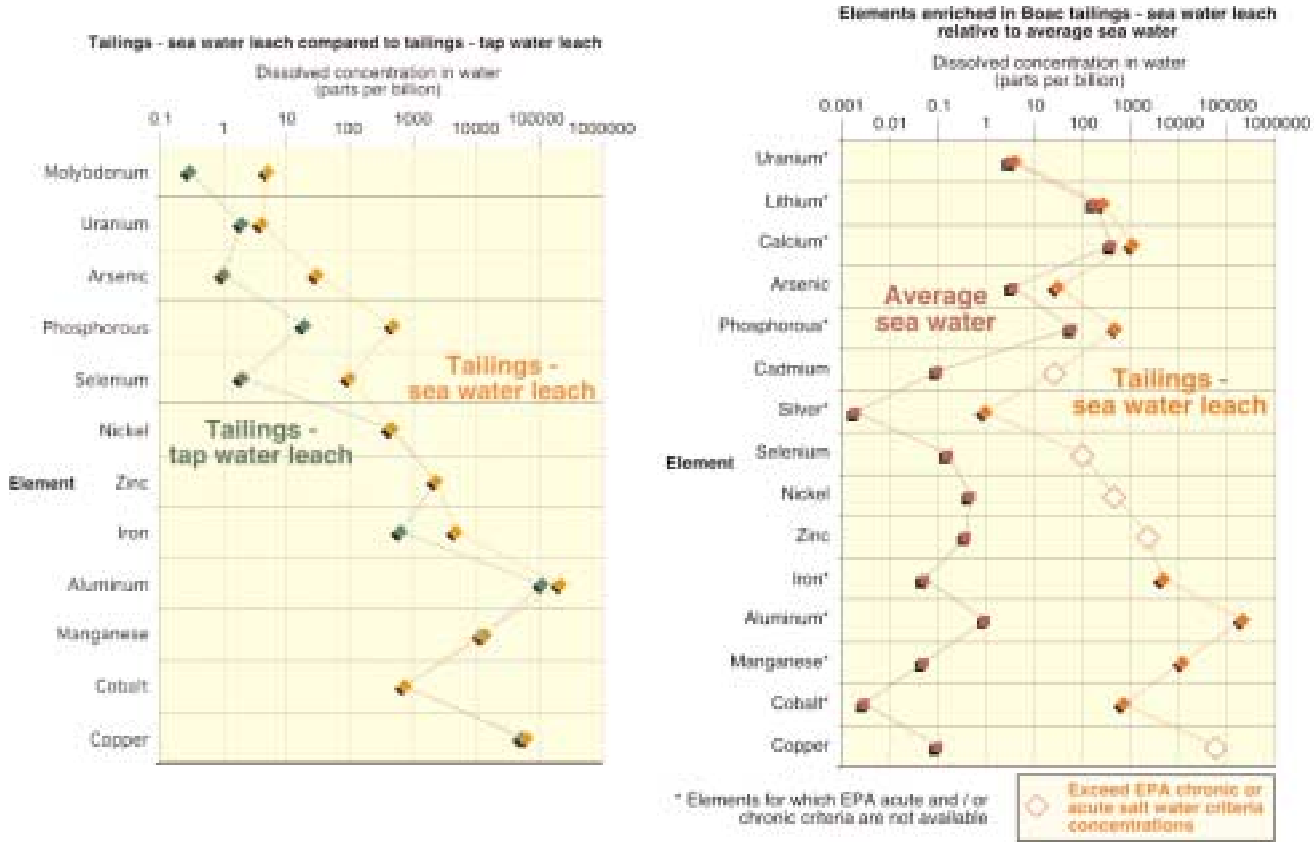

Figure 16. Graphs comparing dissolved heavy metal concentrations in the Boac tailings sea water leach to those of the tailings-tap water leach discussed earlier in the report (**left**), and average sea water (**right**).

Table 3. Concentrations of dissolved metals measured in the Boac tailings sea water compared to U.S. EPA Recommended acute (short-term exposure) and chronic (long-term exposure) water quality criteria for selected metals in salt water (U.S. EPA, 1998a). Criteria are not available for other metals we analyzed. All concentrations are in parts-per-billion (ppb).

	Boac tailings sea water leach (filtered)	**EPA Acute**	**EPA Chronic**
Arsenic	30	69	36
Cadmium	30	42	9.3
Zinc	2300	90	81
Copper	62000	4.8	3.1
Lead	<5	210	8.1
Selenium	100	290	71
Silver	1	1.9	
Nickel	460	74	8.2

- Will such a plume predicted by this experiment actually develop in the ocean?
- If such a plume developed, how spatially extensive and long-lived would it be before its contained metals and acid were diluted to safe levels by the surrounding sea water?
- How great would the environmental impacts be on marine life in the area affected by the plume?
- Will acid and metals continue to leach from the tailings solids into sea water once STD has ceased, due to long-term dissolution of less soluble secondary salts in the tailings? If so, will the concentrations of acid and metals that leach into the sea water be ecologically damaging?

Unless each of these questions can be satisfactorily addressed and shown not to be of concern, then STD of the tailings in deposits along the river banks is a seemingly problematic solution.

Evaluating other proposed remedial options for the Boac River tailings

As with the questions asked for submarine tailings disposal, a similar detailed set of questions can be developed for each of the proposed remedial actions for the Boac River tailings. *Ultimately, no single option may prove ideal, but rather a combination of options may be best.*

Examples of general scientific and engineering questions that should be addressed for each option or combination of options include:

- Can the remedial option(s) be engineered to avoid potential future re-releases into the environment, such as an adit plug failure or failure of a tailings impoundment? What are the natural and human processes that could lead to such a failure, and how can these processes be accounted for in the remedial planning process?
- What are the potential short- and long-term impacts on the environment and human health? How can these impacts be identified and their magnitude estimated accurately?
- What are the pathways by which the tailings or waters that have interacted with the tailings could be released into the environment, and how can these pathways be shut or minimized?
- What are the potential societal impacts of each option? How will the option affect the local economy and cultural practices?
- Because no option can be guaranteed as 100% fail safe, what water quality, ecological, and toxicological monitoring programs need to be established to detect as early as possible potential environmental impacts of the chosen remedial option(s)?

For example (we use this only as an example, and not to suggest that this is a favored option), tailings storage in an on-land impoundment would require an understanding of:

- The geologic, topographic, and climatic conditions of the site chosen for the impoundment, and the type of tailings impoundment most appropriate for these conditions
- The risk of earthquake- or storm-induced failure, or general deterioration of the structure built to contain the tailings
- The potential for leakage of water into and out of the tailings impoundment structure
- The ecological impacts of building the impoundment

The Boac River EIS and rehabilitation plan (PDTS, 1999) presented results of a quantitative risk analysis of a variety of proposed remedial options. However, based solely on the information contained in this report, it is unclear the extent to which fundamental scientific questions such as those listed above were addressed.

Steps in a review process

The following steps are appropriate to truly understand the range of remedial options available for the Boac River tailings, and to assess the strengths and weaknesses of each of the different options:

- Carry out a thorough scientific review of all reports prepared to date on the Boac River tailings issue.
    - Of the options examined in these reports, all

the scientific information collected to date must be evaluated. It must then be determined whether enough information is available to adequately assess the strengths and weaknesses of each option.

  - If there is insufficient information to assess a particular option, new information must be collected as appropriate.
  - *The extent of new studies and data collection needed to adequately judge remedial options should be carefully weighed; if the monetary or time costs of required new data collection are too high, this in itself may indicate the option is not viable.*
- Identify and compile other remedial options not included in existing reports. Gather the appropriate scientific information needed to assess each of these options.
- Provide the People of Marinduque with a summary of the strengths and weaknesses of each of the remedial options, so that a scientifically informed choice can be made.

Evaluating the range of scientific and engineering implications and concerns about each proposed remedial option will require the involvement of a number of different scientific disciplines. These include, for example: earthquake risk assessment, structural and economic geology, environmental geology and geochemistry, oceanography, sediment transport in the fresh water and marine environments, terrestrial ecology and toxicology, fresh water aquatic ecology and toxicology, marine aquatic ecology and toxicology, and human health and toxicology, mining and civil engineering, and engineering properties of concrete, and social sciences such as economics and social anthropology. *Wherever possible, appropriate local experts from the Philippines and Marinduque should be involved with the assessment due to their knowledge of local geology, ecology, cultural practices, etc.*

Environmental assessment and human health studies for evaluating potential impacts of the 1996 Boac River tailings spill

The following options may be developed to evaluate the environmental health aspects from the 1996 tailings spill in Marinduque.

- The development of a detailed environmental epidemiology study is suggested in order to understand the possible sources of exposure, their impact on human health and the future development and implementation of preventive and intervention measurements. These type of studies should involve the following design:
  - Develop a health-based questionnaire (in collaboration with local authorities);
  - Provide information on the identification of study subjects (e.g., exposed area), quality controls, quality assurance and demographical procedures;
  - Provide information on the development of protocols and procedures for the collection of biological specimens;
  - Provide information on the development of interlaboratory methods for the toxicological analyses of blood-lead, urine-cadmium, etc.;
  - Evaluate protocols requiring clinical testing;
  - Correlation of toxicological data with environmental geochemistry assessment data (e.g., soil, water, etc.);
  - Statistical and (or) biostatistical evaluation of the data.

Summary

This report has presented observations about a number of significant mining-related environmental problems on Marinduque. Most of the problems stem from large-scale open pit copper mining at Marcopper, and primarily affect:

- The Mogpog and Boac River systems, which received or are still receiving acid rock drainage, high sediment loads, and tailings from the mine site;
- The beaches and ocean at and near the mouth of the Mogpog and Boac River systems;
- Calancan Bay, into which very large volumes

of tailings were disposed for 16 years; and

- The area within and adjacent to the mine site, which is affected by multiple sources of acid rock drainage into ground and surface waters, and by sediments eroded from mine waste piles.

Less well-known but potentially significant environmental problems may also exist as a result of open pit mining at the CMI mine near Mogpog. Potential problems include:

- Effects of acid-rock drainage from mine dumps, tailings impoundments, and the mine's open pit on local surface and ground waters; and
- Effects of mine wastes and tailings on the marine ecosystem.

In this report, our team has described a number of concerns we have with each of these areas, and we have summarized for many of the areas actions that we feel can be taken to better understand and (or) help mitigate the problems.

Assessing, monitoring, and remediating other mining-environmental problems on Marinduque

We are not aware of plans for mitigating or remediating mining-related environmental problems on Marinduque other than the 1996 tailings spill. However, the potential magnitude and impacts of all these problems are so great that we strongly recommend the implementation of a general mining-environmental assessment and monitoring program on the island. The primary goals of such a monitoring and assessment program should be to (1) understand and define the magnitude of the different mining-environmental problems, (2) prioritize the problems for remediation, and (3) look for creative, cost-effective ways to help mitigate or remediate the problems.

In fact, the review of the Boac River tailings remedial options should only be carried out as one part of such an overall assessment. Because so many different sources from Marcopper contribute acid and metals into the Boac River system, only cleaning up the tailings in the river ultimately may not completely clean up the river to the desired state. Hence, the Boac cleanup should be carried out with a full understanding of the potential sources for metal, acid, and sediment input into the system, as well as the extent to which these Marcopper inputs are naturally mitigated by tributary streams and ground water input along the river.

A risk-based system approach to assessment: We recommend that a general mining-environmental assessment of the island should follow a risk-based approach. Risk analysis involves environmental description, identification, and characterization of contaminant sources, assessment of human and ecosystem exposure to the contaminants, assessment of contaminant effects, characterization of future risk, and risk management or remediation (Boyle, 2000; U.S. EPA, 1998b).

The risk assessment should also examine entire mining-environmental systems as a whole, and not just focus on selected parts. For example, the environmental impacts of Marcopper on the Mogpog and Boac rivers and their inhabitants should be assessed by evaluating the entire system that contains the mine site, Mogpog and Boac River watersheds, and marine environment affected by the two rivers, including:

- Contributions of acid, metals, and sediments from Marcopper;
- Contributions of acid, metals, and sediments from other mine sites and disturbed areas;
- Contributions of acid, metals, and sediments from natural sources;
- The ground- and surface-water hydrology of the mine site, and Boac and Mogpog River watersheds;
- Contributions of ground and surface waters from other tributaries in the Mogpog and Boac Rivers;
- Processes that affect contaminant transport in ground, surface, and ocean waters;
- Processes that affect fate of the contaminants in the river system, offshore marine environment, adjacent farm lands, ground waters, and villages;

- Extent and health effects of contaminant uptake by humans, wild animals and farm animals, fresh water and marine aquatic organisms, and terrestrial and aquatic plants.

A key aspect of a risk-based system assessment will be to monitor changes in the environmental impacts of mining over time. For example, changes in water flow, water quality, sediment transport, and ecological impacts along the Mogpog and Boac Rivers must be measured regularly to assess longer-term seasonal variations and shorter-term variations related to storms.

Another key aspect will be to assess the natural, pre-mining environmental conditions. Many mineralized areas are the sources of natural acid-rock drainage, and so the extent of impacts of acid-rock generated by mining are appropriately measured in comparison to the pre-mining impacts of natural inputs of acid and metals. There are a variety of ways that the pre-mining conditions can be assessed in a mineralized area (Plumlee and Logsdon, 1999).

Calancan Bay and the adjacent coastal environments affected by the tailings constitute another system upon which an environmental risk analysis should be focused. Similarly, the CMI mine, the areas potentially affected by mine wastes and acid rock drainage from the mine (possibly including the town of Mogpog), and the portions of the ocean affected by marine disposal of mine wastes and tailings constitute another system to be assessed.

Assembling the expertise: A risk-based systems approach to analyzing mining-environmental impacts on Marinduque will require expertise in and information from a broad spectrum of disciplines, such as geology, hydrology, risk analysis, environmental geochemistry, ecology, toxicology, human health, mining engineering, environmental engineering, and social sciences.

Whenever possible, appropriate local experts from the Philippines and (or) Marinduque should be involved with the assessment due to their crucial knowledge of local geology, ecology, hydrology, cultural practices, etc.

In addition, local residents should be trained in appropriate water sampling and other monitoring procedures so that they can help provide long-term and rapid-response on-ground monitoring capabilities, especially during storm events and other emergencies.

A potential opportunity

The mining-environmental impacts on some parts of Marinduque have been substantial and pose significant long-term challenges for remediation, both from a technological and monetary standpoint. These problems and remedial challenges may also pose, however, a potential opportunity for Marinduque. We suggest that the island residents, government officials, and educational institutions could develop on Marinduque a center of educational excellence in the southwest Pacific for understanding, assessing, predicting, and cleaning up the environmental impacts of mining. Such a center, if established on the island, could oversee and coordinate assessment and remediation activities. At the same time, it could provide hands-on learning and training opportunities in both technical and research fields about mining-environmental issues. Expertise learned on Marinduque could then be transferred to other places in southwest Pacific and southeast Asia with similar large-scale mining-environmental problems. The center could not only provide education and employment opportunities for local residents, but also attract a large number of students, teachers, and others to the island.

Marinduque provides a unique and logical physical setting for such a center of excellence because a spectrum of mined, river system, and marine environments are in close proximity for easy study. The island's proximity to Manila facilitates collaboration with Philippine government agencies and universities. Collaborative arrangements could also be developed with universities elsewhere in the world that have established mining-environmental programs, but that may lack ready access to field study areas in a near-ocean, tropical setting.

Funding for such a center of excellence could be pursued through the mining industry, world monetary institutions, environmental groups, and a variety of other sources.

Marinduque as a case study

As alluded to in the previous section, Marinduque's mining-environmental issues are not unique within the southeast Pacific.

A number of large-scale metal mining operations across the region are gaining increasing publicity for potentially environmentally damaging practices followed in the last 20-30 years. For example, the Ok Tedi Mine (a porphyry Cu deposit) in Papua New Guinea, disposed of large volumes of tailings into a nearby river (many tens of thousands of tonnes per day) from the early 1980's through the late 1990's (Ellis et al., 1994; Murray et al., 2000). Other examples of riverine and (or) near-shore marine tailings or mine-waste disposal include Porgera and Bouganville (Papua New Guinea), and Atlas (Philippines) (Ellis et al., 1994).

The mining industry appears to be curtailing these types of practices, and government agencies and international funding agencies are increasingly not permitting these activities. However, practices followed in the region in the last 30 years have created formidable environmental and remedial challenges that will persist for many years.

The mining-environmental challenges on Marinduque, whether a result of systems failures (Mogpog and Boac Rivers), or designed practices (Calancan Bay, acid-rock drainage at the Marcopper and CMI mines) present a very useful case study in how other mining-environmental challenges across the region can be better assessed, mitigated, remediated, and, hopefully, prevented in the future.

Acknowledgments

We would like to extend our very great appreciation and thanks to Congressman Edmund Reyes for his great help and support prior to, during, and after our visit. Thanks to his tremendous enthusiasm and tireless energy shown in accompanying us around the island, our visit was both a scientific success and personally memorable for us. Many thanks are also due to Governor Carmencita Reyes, for her help in covering logistics during our visit. Last, but not least, we would like to thank the many People of Marinduque who met with us and provided us with a wealth of information about the mining-environmental issues on Marinduque. Their warmth and hospitality toward us were truly remarkable. We hope to be able to visit the island again and help the Congressman, Governor, People of Marinduque, and Philippine DENR find workable solutions to the many mining-environmental challenges facing Marinduque.

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Glossary

Many of the definitions in this glossary are taken or modified from those in Jackson (1997) and Hudson et al. (1999).

Acid rock drainage - Water which contains free sulfuric acid (and commonly dissolved metals), mainly due to the weathering (oxidation) of pyrite (iron sulfide).

Alteration - Any change in the mineral content or chemical composition of a rock by physical or chemical means.

Absorb - To stick to the surface of solid by weak chemical interactions. Depending on the pH and composition of the water and the solids, dissolved chemicals in water can adsorb onto solids in contact with the water.

Bioavailability - The degree to which a metal or other substance is free for movement into an organism.

Carbonate minerals - Minerals composed of carbonate ($CO_3^{=}$) and a cation such as calcium (calcite), calcium and magnesium (dolomite), manganese (rhodochrosite), or some other metals.

Conductivity - A measure of the amount of ionic species dissolved in a water. Ionic species include, for example: cations such as sodium potassium, calcium, and magnesium; anionic species such as carbonate, bicarbonate, and sulfate; and trace elements such as copper, lead, zinc, arsenic, and selenium. In the United

States, most drinking waters typically have conductivities ranging from several tens to several hundreds of μS/cm.

Element - A substance, all of whose atoms have the same atomic number.

Gangue - The valueless minerals in an ore; that part of an ore that is not economically desirable but cannot be avoided in mining.

Hydrothermal - Of, or pertaining to hot water, the action of hot water, or the products of this action. For example, hydrothermal fluids that circulate in the Earth's crust derive their heat from the cooling and crystallization of magmas, or from the cooling of hot rocks.

Hydrothermal alteration - Alteration of rocks or minerals by the reaction of hot water with preexisting rocks or minerals.

Igneous intrusive rock - A rock formed by the cooling and crystallization (solidification) of a body of magma (molten rock) that has intruded into the Earth's crust.

Invertebrate - An organism lacking an internal skeleton, such as an insect.

Leach test - A laboratory or field procedure that measures the ease with which metals can be taken into solution by rain-, river-, or sea-water from mine wastes, soils, or other earth materials.

Limestone - A sedimentary rock that formed on the ocean bottom, and that is composed of consolidated calcium carbonate mud and carbonate skeletons of dead marine organisms.

Metal - Any class of chemical elements, such as iron, gold, and aluminum, that have characteristic luster, are good conductors of heat and electricity, and are opaque, fusible, and generally malleable or ductile.

Milling - The crushing and grinding of ore in order to help extract the commercially valuable elements in it.

Mineral - A naturally formed solid chemical element or compound having a specific chemical composition and, most commonly, a characteristic crystal form.

Mineralized - A term used to describe a rock that has an unusually high content of metallic minerals and (or) altered rock.

Mineral deposit - A mass in the Earth's crust of naturally occurring mineral material that might, under favorable circumstances, be mined economically.

Mitigation - The process by which the occurrence of potential future environmental problems is minimized by prior prediction, planning, and engineering.

Neutralization - Chemical reactions which consume hydrogen ions in a water sample. Neutralization leads to an increase in the pH and a decrease in the acidity of a water.

Ore - The naturally occurring material from which a mineral or minerals of economic value can be extracted profitably. The term generally but not always refers to Earth materials containing metals, and is often modified by the names of the valuable constituent; e.g., iron ore.

Ore deposit - A mineral deposit of sufficient richness that it can be economically mined.

Orebody - The economically important part of a mineral deposit.

Oxidation - A chemical process involving reaction(s) that produce an increase in the oxidation state of elements such as iron or sulfur.

pH - A measurement of the hydrogen ion content, or acidity, of a water-based liquid. The lower the pH value, the greater the hydrogen ion content and more acidic the liquid is.

Porphyry - A type of igneous intrusive rock characterized by large crystals surrounded by smaller crystals.

Porphyry copper deposit - A type of mineral deposit characterized by the occurrence of iron- and other metal-sulfide minerals dispersed in a porphyry igneous intrusive rock. This type of deposit forms during the cooling and crystallization of a magma body that has intruded into the Earth's crust.

Remediation - The process of correcting, counteracting, or removing an environmental problem.

Rock - Any naturally formed material composed of mineral(s); any hard consolidated material derived from the earth.

Secondary mineral - In mineral deposits, a secondary mineral is one that forms as a result of the weathering of the original minerals.

Sediment - Unconsolidated earth material (such as sand, gravel, mud, etc.) that has been transported by water and deposited from the water by settling out.

Sedimentary rock - Rock formed by the consolidation of loose sediment that accumulated in layers.

Skarn deposit - A type of mineral deposit that formed by the reaction of limestone rock with hydrothermal fluids. Iron-, copper, and other sulfide minerals are common ore minerals. The deposits commonly occur in the sedimentary rocks around porphyry copper deposits.

Silicate minerals - The most common rock-forming minerals that contain, among others, the elements silicon and oxygen.

Soluble - A solid that readily dissolves in a liquid is soluble in that liquid.

Spit - A finger-like extension of beach that extends away from the mainland in the direction of near-shore ocean current flow, and terminates in the open ocean.

Sulfide mineral - A mineral compound characterized by the linkage of the element sulfur with a metal; e.g., chalcopyrite, $CuFeS_2$, a sulfide of copper (Cu) and iron (Fe).

Tailings - The waste materials regarded as too poor in quality to be further processed during the milling of ore. Tailings are usually composed of sand-sized particles of silicate minerals and lesser amounts of sulfide minerals.

Toxicity - How poisonous a substance is to living organisms or plants.

Waste rock - The rock that must be broken and disposed of during mining to gain access to, or to increase the quality of, ore.

The USGS- AFIP team with Congressman Reyes and the pilot who took us on the overflight of Marinduque. From left to right: the pilot, Congressman Reyes, Geoff Plumlee, José Centeno, Jack Medlin, Terry Boyle, and Bob Morton