Porgera Gold Mine

Riverine Tailings and Waste Rock Management
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The Porgera Gold Mine

The Porgera Gold Mine is situated in Enga Province in the central highlands of Papua New Guinea (PNG), approximately 600 km northwest of Port Moresby. The mine is operated by Porgera Joint Venture (PJV) and is owned by Barrick Gold Corporation (95%) and Mineral Resources Enga (5%). Mineral Resources Enga is owned by the Enga Provincial Government and the landowners of the Special Mining Lease (SML) through an equal partnership.

Production began in 1990 and PJV currently operates both open pit and underground mines. In 2009, PJV produced 572,600 ounces of gold with proven and probable mineral reserves identified to date of 8.1 million ounces of gold.

PJV employs 2,500 people plus approximately 500 contractors. The mine’s economic contribution to PNG’s gross domestic product (GDP) is approximately 11% and, over the life of the mine, is expected to constitute about 12% of national export earnings.

The Porgera Gold Mine sits high in mountains (Plate 1) thrust up between the Indo-Australian and Pacific plates. Some peaks rise to more than 4,500 m separated by deep valleys and fast-flowing rivers. Rainfall is high and earthquakes and landslides are common. Large rivers carry high sediment loads to the alluvial lowlands and advancing deltas of the Gulf of Papua to the south.

The tectonic collision zone, which created this dramatic and dynamic landscape, also hosts the gold deposits at Porgera. An obvious question arose early in mine planning: how to engineer the development of the Porgera Gold Mine in such a challenging terrain?

Plate 1 The Porgera Gold Mine open pit at an elevation of 2,700 m

The Planning and Development of the Porgera Gold Mine

Setting

The Porgera Gold Mine is located at an elevation of 2,200 to 2,700 m, in a seismically active highland valley with frequent slope failures. Annual rainfall averages 3,700 mm. The steeply sloping Porgera River drains the Porgera Valley through mountainous terrain with sparse aquatic life. It joins the Lagaip River and flows westward to its confluence with the Ok Om to become the Strickland River. The Strickland River flows out of the highlands and across a vast, sparsely inhabited, ecologically rich floodplain to eventually join the Fly River running southeast to the Gulf of Papua. The mountain section of the river runs for approximately 250 river-km downstream of Porgera, with the lowland section running a further 370 river-km to the Fly River, a total distance of 620 km (Figure 1).

Planning and Alternatives

Planning for the mine in the 1980s examined ways to contain tailings and the large volumes of competent (hard) waste rock and incompetent (soft) waste rock required to be stripped to allow access to the gold orebody. However, none of the potentially feasible full-containment options could cope with the inherent weakness of saturated tailings and incompetent waste rock, nor overcome the instability of storage sites with poor foundation conditions in a seismically active zone. In essence, any structure to store fine-grained and saturated materials that was close enough to the mine to be...
feasible would fail, the only question being when.

After much study, consultation and independent review, the PNG Government approved a hybrid arrangement, the objective of which was to store in Porgera Valley as much waste material as practicable:

- Competent waste rock would be stored in a conventional stable dump configuration (Plate 2).
- The tailings would be treated to precipitate trace metals and detoxify residual cyanide before direct release to the Porgera River1.
- Incompetent waste rock would be placed in erodible dumps in two small valleys near the mine (Plate 3).

The 1988 Porgera Gold Project Environmental Plan noted that the proposed hybrid waste arrangement would eliminate the catastrophic failure risk of engineered storage structures for tailings and incompetent waste rock. This arrangement would also create very high mine-derived, suspended-sediment concentrations immediately downstream of the mine. However, the fast-flowing Porgera River had always been a naturally poor aquatic habitat. The Porgera River had been further degraded by hydraulic small-scale mining in the decades before the mine opened and the valley downstream of the locality of Porgera itself was uninhabited.

Downstream of the Porgera–Lagaip confluence, the Environmental Plan predicted sediment-induced biological impact progressively diminishing from severe-to-moderate to minor over the next 103 km downstream to the Lagaip–Ok Om confluence at the start of the Strickland River. The Environmental Plan also predicted possible minor biological effects between the Ok Om and the water quality compliance point on the Strickland River (SG3) near the Tumbudu River (165 km downstream of the mine), but no biological impacts were predicted from this point to the sea more than 750 km downstream. The impact assessment also found that adverse impacts from metals in the mine waste were unlikely.

The Outcome

The PNG Government commissioned an independent review of the Environmental Plan’s predictions and of international practice (notably USEPA and ANZECC water quality standards). On this basis, the government approved the Environmental Plan, with the condition that PJV demonstrate by monitoring that river water quality at SG3 was meeting ambient quality standards set to protect public health (including drinking water) and riverine ecosystems.

Gold production began in 1990. In 1996, ore production doubled to a nominal 17,700 tonnes per day, with a corresponding increase in waste rock and tailing quantities. Since then, PJV’s long-term annual average inputs to the river system have been estimated at 5 to 6 million tonnes of tailings and 12 million tonnes of sediment from the erodible dumps.

After 20 years of monitoring, the observed effects on fish populations downstream of the Porgera–Lagaip confluence have turned out to be less than was predicted in 1988: some trace metals have increased in some fish and prawns, but fish and prawn populations have been maintained across their full pre-mine range.

The CSIRO Independent Review 1996

In 1995, PJV commissioned Commonwealth Scientific and Industrial Research Organisation (CSIRO)2 to examine the downstream impacts of the mine. The CSIRO-led, multi-disciplinary review team comprised its own and independent international experts and investigated the mine’s effects on the health of villagers living downstream, chemical impacts, sedimentation, the effectiveness of the monitoring program and compliance.

The review found compliance with water quality criteria, that monitoring methods were appropriate and that the original impact predictions had proved to be reasonably accurate.

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1 At start-up (Stage I), high-grade underground ore would be processed and flotation tailings discharged directly to the river system. The small quantity of cyanidation tailings would be stored until the introduction of pressure oxidation within a year (Stage II) and then reprocessed and treated for metals precipitation and cyanide detoxification prior to discharge.

2 CSIRO: Australia’s national science agency.
More specifically, the CSIRO review concluded that:

- Total metals in the river system had increased but the biologically more available dissolved (and hence more toxic) metals had not.
- Total sediment load had increased, but large-scale downstream deposition, other than near the mine, remained unlikely.
- The risk of potential metal impacts to people was deemed to be low.

CSIRO concluded with 48 recommendations to improve the monitoring performance by fully assessing the impact of the January 1996 doubling of the mine’s process plant output and to focus, in addition to meeting regulatory compliance, on the risk to human health of villagers living downstream of the mine.

**Follow Up to the CSIRO Report**

PJV responded to the 1996 CSIRO report in two ways:

- By setting up the Porgera Environmental Advisory Komiti (PEAK), comprising representatives of the PNG Government, PNG national and local NGOs, independent technical experts and PJV (Plate 4). PEAK’s function has been to oversee the implementation of the 48 CSIRO recommendations, to improve public understanding of the mine’s environmental and social issues and to review PJV’s performance and accountability.
- By addressing each CSIRO recommendation in turn. By 2002, 38 had been implemented in full, with the remaining 10 considered either infeasible, no longer relevant or requiring further investigation.

**Downriver Monitoring**

PJV monitors its mining operations and the river and associated off-river water bodies downstream of the mine (Plates 5 and 6). The program gauges downriver health by chemical and biological indicators, and relates changes in the river system to possible causes, such as fluctuations in rainfall or changes in ore type or tailings treatment.

**Monitoring Indicators and Results**

PJV monitors upland river, lowland river and Lake Murray ecosystems using five groups of indicators:

- Dissolved metals – arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, silver and zinc.
- Metals in sediments – arsenic, cadmium, chromium, copper, iron, lead, mercury, nickel, silver and zinc.
- Conductivity, total suspended solids, pH and cyanide.
- Metals in fish and prawn – arsenic, cadmium, chromium, copper, lead, mercury, nickel, selenium, silver and zinc.
- Fish and invertebrate abundance, diversity and condition.

Recent chemical monitoring shows compliance with PNG water quality criteria at SG2, which is 123 km upstream of the formal compliance point at SG3 (165 km downstream of the mine). Box A summarises the specific findings of the 2008 Annual Environmental Report and previous work. The as-yet-unpublished results
for 2009 show a similar picture, the main changes being decreases in cyanide and dissolved copper concentrations attributable to the commissioning of the new cyanide destruction plant in December 2008 (Plate 7).

**Upstream inputs**
- Tailings
- Process chemicals
- Waste rock
- Treated sewage

**Lowland River Section**
- Low levels of metals in fish tissue and dissolved in water.
- Elevated arsenic and lead levels in SG4 and SG5 sediments (but not a trigger for further investigation).
- Elevated cadmium in sediments (but not of mine origin).
- High suspended solids.
- Reduced predators at Bebelubil (see Figure 1); otherwise fish and invertebrates communities as expected.

**Lake Murray**
- Dissolved metals in water low and of no concern.
- Some metals in sediments are elevated (mercury, nickel and cadmium).
- No evidence of anomalous mercury inflows.
- Efficient biomagnification of mercury from naturally low levels.
- Naturally elevated mercury in some fish (not mine-derived).

In broad terms, the findings of PJV’s down-river aquatic biological monitoring program have not changed much over the 20 years since the mine opened.
despite a doubling of tailings output since 1995. For example, Wankipe, some 116 km downstream of the mine and 49 km upstream of the formal SG3 compliance point, still yields catches of fish and prawns in similar numbers, condition and diversity to pre-mining catches (Plate 8). Small year-to-year variations can be seen in a number of variables, but no trends are evident and the fluctuations may be a reflection of the natural variability in a large tropical river system.

Mercury from Small-scale Mining

The material eroded from the mine site and erodible waste dumps feeds particles of gold into the Porgera River that small-scale miners (none of whom are employed by PJV) extract by panning. The small-scale miners then add liquid mercury to amalgamate gold into a concentrate. It seems inevitable that some mercury is spilled into the river. However, PJV’s monitoring shows consistently low total and dissolved mercury values at SG1 and at all stations downstream.

Other Investigations

PJV’s routine monitoring shows major down-river impacts to be localised to the immediate mine area drainage, with small anomalies and fluctuations in dissolved and total metals both downstream of the mine and also at some unaffected reference sites. It is hard to draw ecological conclusions when the trace metal levels are relatively low, the variability is small and there are no apparent trends.

Nonetheless, despite the tailings from the Porgera mine being treated before release, the practice of discharging mine waste into natural rivers will always raise questions that warrant investigation beyond mere regulatory compliance.

PJV has therefore carried out a number of studies in addition to the compliance monitoring written up in the annual environmental report series 1991 to 2008 (Box B). Some have supported applications for regulatory approvals from government. Others have pursued improvements in performance or were special studies seeking to better understand the impacts. The more important work in the latter category is discussed below.

Performance Initiatives

Tailings Storage

Barrick acquired a majority stake in PJV in 2006 and re-opened the case for tailings storage with an investigation of 28 sites within functional proximity of the process plant. The original 1986 study had concluded that a tailings dam could not be safely constructed and the 2006 investigation reached the same conclusion for the same reasons: insufficient storage capacity, excessive pumping heads and distances, and long-term safety risk.

Tailings Re-use

PJV expects to commission a new tailings paste plant in October 2010. The plant will cyclone the tailings and send the coarse fraction mixed with cement to fill voids in the underground mine. The environmental benefits are twofold: the paste plant will reduce the volume of tailings discharged by up to 8%, and the balance of the tailings will be finer and less likely to settle on the riverbed and, hence, more likely to be carried through the river system as washload.

Improved Cyanide Destruction

The residual cyanide concentrations in tailings downstream of the mine have been consistently low but did not meet
the most recent International Cyanide Management Code tailings cyanide standard at the point of discharge. PJV therefore commissioned a new destruction plant in December 2008 (see Plate 7), which has reduced discharge concentrations by up to fourfold to well under the new standard. More significant, however, has been the reduction in dissolved metal concentrations at SG2, with copper, in particular, falling by a factor of five from around 12 µg/L (just above the SG3 compliance limit of 10 µg/L) to around 2 µg/L (Figure 2).

Human Health

Since 2002, PJV has conducted a series of surveys of the health of the people of 20 villages in 5 zones from the Porgera local area through the upland and lowland (Plate 9) sections and downstream as far as Lake Murray. The surveys encompassed water and air quality, vegetation, soil and, most importantly, food, and have paid particular attention to the possible uptake of potentially hazardous trace metals from the environment. The surveys are to be completed shortly, but have so far found no evidence of adverse health effects attributable to the Porgera mine.

Figure 2 Mean annual dissolved copper concentrations at SG2 from 1999 to 2009 (all results in µg/L)

Note: Compliance value at SG3 (123 km downstream of SG2) is 10 µg Cu/L.
Mercury in Lake Murray

Lake Murray is a tributary lake of the Strickland River (Plate 10). It is unusual in that both some of the people living around the lake and some of the fish that they eat have, since the first scientific studies in 1975 (and by logical inference for as long as the ecosystem has existed in its present form), shown unexpectedly high levels of mercury for an unpolluted system. Since floods in the Strickland River reverse the normal flow out of Lake Murray for an estimated 15% of the time, the question arose whether mine waste from Porgera could reach the lake and aggravate the mercury body burden of people via the fish that they eat.

Pre-mining studies had found that this was unlikely, but PJV nonetheless commissioned CSIRO to more fully investigate mercury cycling and bioaccumulation in the lake. These studies found no evidence of anomalously high inputs of dissolved inorganic mercury from any of the inflows into the lake (including the Strickland River), but rather an efficient process of methylation and biomagnification of mercury from naturally occurring low levels in water and sediments up through the food web. The effect raises the mercury concentrations in some barramundi specimens (one of the favoured fish consumed by local people) above the World Health Organisation standard. Since fish form the bulk of their diet, the people also have relatively high natural levels of mercury in their bodies and these are not within acceptable guidelines for human health. However, no clinical effects have been observed in any of the studies to date.

Metal Bioaccumulation by Organisms

Elevated metal concentrations of arsenic, cadmium, lead and zinc in prawns downstream of the mine are not easily explained by the levels in water and sediments, nor by the mine’s contribution of nominally low-bioavailability metal compounds. PJV has therefore sponsored a study to examine the following: the chemical behaviour of trace metals in the rivers; how each metal is partitioned between more- and less-biologically available forms; uptake and purging processes in prawns; and, finally, the prawn population and general ecological significance of the increased concentrations (Plate 11). Sophisticated laboratory testwork involving the use of radioactive metal tracers added to waters and sediments has begun in order to find out how trace metals are taken up by these organisms.

The Next Decade

Based on current ore reserves and gold prices, the Porgera mine is expected to remain in production until at least 2020, and it seems likely that the riverine impacts of the past two decades will continue more or less as they are until mine discharges end and natural recovery begins.

At the same time, innovations in scientific analytical and diagnostic methods have made it possible to search for very subtle environmental effects, which lie outside the scope of the formal compliance framework.

Normal compliance monitoring will therefore be accompanied by special studies to look beyond the zones of ‘impact’ and ‘no impact’ established by statutory monitoring for a better understanding of sub-lethal effects and implications for the population dynamics of the organisms concerned.

PJV will continue its program of specialist studies, which investigate potential impacts of the mine on the downstream environment. This includes the fate of mine-derived sediments and the bioavailability of trace metals. For instance, PJV has recently started a four-year research program in conjunction with CSIRO (Plate 12) to further investigate bioavailable fractions of cadmium, lead and arsenic in lowland river.

Plate 9 Tiumsinwam Village at the confluence of the Tomu River (bottom centre) with the lower Strickland River, 366 km downstream of the mine

Plate 10 Barramundi monitoring at Lake Murray (580 km downstream of the mine)

Plate 11 Deploying a prawn trap in the Lagaip River
Q1: Is river water downstream of the mine safe to drink?
A1: Prior to mining, the rivers downstream of the mine site were highly turbid due to natural causes. Local villagers obtained their drinking water from small, clear-water side streams and not from the main rivers. Today, the situation in the upland rivers downstream of the mine is essentially the same for the same reason: mainstream rivers are still turbid and unpalatable and side streams are clean, ubiquitous, accessible and reliable.

PJV’s monitoring of rivers downstream of the Porgera Gold Mine shows that, provided suspended sediment is allowed to settle prior to consumption, dissolved metal concentrations do not exceed the drinking water criteria of the World Health Organisation.

Q2: Are fish and prawns in the river system safe to eat?
A2: Fish and prawns are routinely monitored by PJV. Analyses of trace metals in fish and prawn tissue samples obtained from all sites downstream of the Porgera Gold Mine show that river fish and prawns are safe to eat with the possible exception of some fish in Lake Murray, which have naturally elevated mercury concentrations.

Q3: What third-party, independent checks are undertaken to give confidence that PJV’s environmental monitoring results are accurate?
A3: All PJV’s samples that require trace metal analyses, including water, sediment and biological samples, are sent to independent external laboratories. The design of PJV’s monitoring program has been independently reviewed by a team comprising the CSIRO and other specialists. All water, sediment and biological samples collected since the baseline prior to mine development and for the past 20 years have been analysed in this manner. The current laboratory used is the National Measurement Institute (NMI) laboratory in Sydney, Australia. A comprehensive quality assurance and quality control (QA/QC) program is conducted by both PJV and NMI to ensure ongoing analytical accuracy. Analyses of pH, cyanide, anions, cations and conductivity are performed by PJV’s on-site accredited environmental laboratory. This laboratory undergoes periodic re-accreditation under the PNG Laboratory Accreditation System (affiliated with Australia’s NATA system) to ensure accuracy is maintained.

Q4: As the Porgera Gold Mine open pit has expanded and its waste rock dumps have grown, less land is available for subsistence food gardens and local residents are forced to cultivate more marginal land in steeper terrain and at higher elevations, both of which are challenging for subsistence food production. What is PJV doing to alleviate this significant negative impact on the Porgera community?
A4: The cash economy that followed the start of the Porgera Gold Mine means that most food consumed by Porgera Valley communities is now purchased from stores and is not grown. For food still grown in traditional food gardens, the floor of the Porgera Valley is elevated (>2,000 m) and, as a result, is close to the altitudinal limit for some subsistence food crops. In addition, in-migration and natural population growth has increased pressure on land for subsistence food gardens. However, despite these limitations, ever since mining operations began at PJV, villagers have been relocated from land required for mining and waste rock disposal as well as for safety reasons. All such relocations have been carried out in full consultation of those involved to ensure that relocated people were satisfied with their respective compensation and relocated house and land packages. Nobody has been forced to move against his or her will or relocated to land that is unsuitable for cultivation. All relocated areas were at similar altitude to the land where the villagers originally resided to ensure their continued ability to grow subsistence food crops.

Q5: The Porgera Environmental Advisory Komiti (PEAK), a multi-stakeholder group that monitors and advises PJV on its tailings and waste rock management program, has identified significant areas of concern in its Strickland River Report Card 2009 and specifically, a high level of concern for ecosystem health due to mine-derived trace metals in the upper portion of the river system. What is PJV’s response to PEAK’s findings?
A5: The area of greatest concern identified in PEAK’s 2009 Report Card was water quality in the Porgera River directly downstream of the mine and to a lesser extent in the Lagaip River below the Porgera confluence down to SG2. Further downstream on the Lagaip River, at SG2 and beyond, some trace metals have increased in the tissues of fish and prawns since 1990, but fish and prawn populations have been maintained across their full pre-mine range over the 20 years of mine operations by PJV.
environments, and whether or not an increased bioavailability is of ecological consequence.

**Closure**

At mine closure, plant and equipment can be sold, but the pit, waste rock dumps and other earthworks will remain. It will be at this point that the raison d’être of the mine waste rock and tailings strategy comes into play. The structures that remain will comprise stable material on stable foundations designed to stand safely in the long term. On the other hand, the structures to contain incompetent and saturated waste have never been built and therefore will not outlive mine closure as a safety and environmental threat into the future (Plate 13).

**Box D  Glossary and explanations**

**Alluvial:** river derived, for example, alluvial deposits comprise material previously transported and then deposited by rivers.

**Barrick Gold Corporation:** operates 26 mines and a pipeline of projects located across five continents. Its shares are traded on the Toronto and New York stock exchanges. Barrick has the world gold industry’s largest production of 7.4 million ounces in 2009 and its largest reserves of 139.8 million ounces.

**Competent rock:** hard and durable rock that can be stacked in a stable dump configuration.

**Confluence:** junction of two rivers.

**CSIRO:** Commonwealth Scientific and Industrial Research Organisation is Australia’s national science agency and one of the largest and most diverse research agencies in the world.

**Detoxify residual cyanide:** the Porgera metallurgical plant was originally designed to reduce residual cyanide concentrations by exposing the final tailings stream to an acid intermediate process effluent. This reduced cyanide levels in the tailings discharge to levels low enough to be non-toxic to aquatic life. The subsequent adoption by PJV of the International Cyanide Management Code mandated a more stringent quality standard, and PJV therefore added a new, dedicated plant to destroy the residual cyanide.

**Dissolved metals:** see ‘soluble metals’.

**EP:** Environmental Impact Plan, the PNG equivalent of an environmental impact statement at the time the Porgera Gold Mine was proposed.

**Erodible waste dump:** designed to temporarily store incompetent waste rock in a river valley while allowing the dump to gradually and progressively fail and some material to be eroded and transported downstream by the river system.

**Food web biomagnification of mercury:** a process in which mercury low down the food chain (say in lake vegetation) passes up the food chain (say to grazing aquatic organisms and then to the predator fish and so on), with the concentration increasing at each stage.

**Incompetent rock:** soft and/or friable geological material.

**Indo-Australian and Pacific plates:** continental plates that move in geologic time according to continental drift.

**Inorganic mercury compounds:** of geological origin (see also ‘methylmercury’).

**Lake Murray tributary lake:** in floodplains where gradients are low, large rivers with high sediment loads like the Strickland progressively deposit material in the levees of the main stream. Levees rising above the level of the floodplain can have the effect of damming inflowing tributaries, thereby forming a ‘tributary lake’.

**Low-bioavailability metal compounds:** compounds that are typically chemically stable and are not readily taken up by plants or animals.

**Methylmercury:** an organometallic compound that may be formed by natural processes in the environment. Methylmercury is typically more bioavailable than inorganic mercury and hence environmentally more problematic.

**PJV:** Porgera Joint Venture.

**Radiosotope metal tracers:** chemically similar to the non-radioactive nuclides, so most chemical, biological, and ecological processes treat them in a similar way. Isotope tracers have a radioactive signature that allows, for example, metal uptake pathways in organisms to be traced.

**Raison d’être:** the most important reason or purpose for something’s existence.

**Saturation:** used here in the non-technical sense of material being ‘full of water’.

**Seismically active:** subject to earthquakes.

**SG1:** stream gauging station number 1, 8 km downstream of the Porgera mine.

**SG2:** stream gauging station number 2, 42 km downstream of the Porgera mine.

**SG3:** stream gauging station number 3 (statutory compliance point), 165 km downstream of the Porgera mine.

**Soluble metals:** operationally defined as passing a very fine (0.45 µm) membrane filter.

**Special Mining Lease:** legal name for the area granted to PJV for mining purposes.

**Sub-lethal effects:** detectable but not necessarily fatal impacts, but possibly deleterious to the point of affecting the population of the organism in question (for example, by inhibiting reproductive function).

**Tailings:** residue that remains after economically extractable minerals and/or metals have been removed by ore processing. Tailings is normally a slurry comprising ground-up rock, water and residual process chemicals.

**Total metals:** the sum of all the various compounds of a given metal in a sample (for example, the combined concentration of organic and inorganic mercury).

**Trace metals:** typically present in the environment in low (i.e., trace) concentrations.

**Tailing:** fine sediment suspended in the water column (as opposed to bedload, which comprises coarser sediment fractions typically transported downriver by saltation, i.e., bouncing along the river bed).

Tailings discharge will stop. The erodible dumps will continue to erode but at rates diminishing from the time that fresh material loading ends. In this respect, they can be expected to mimic the behaviour of the numerous landslides that dot the landscape, which eventually equilibrate and revegetate in due course.

**Plate 13** The rugged and mountainous Porgera Valley