



Centre for Advanced Analytical Chemistry
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TRACING MINE-DERIVED
SEDIMENTS AND ASSESSING THEIR
IMPACT DOWNSTREAM OF THE
PORGERA GOLD MINE

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SUMMARY

In order to better understand the impacts of the Porgera gold mine on the riverine environment downstream of the mine, it is desirable to trace the transit of mine-derived sediments (particularly mine tailings) and locate areas in which they may have been deposited. This report describes investigations to identify geochemical tracers that may be used to determine the fate of mine tailings in riverine and floodplain environments.

Three surveys of the Porgera/Strickland river system and major tributaries were conducted between June and November 2000. The suspended sediments isolated from the samples were analysed for over 50 trace elements using a range of multielemental analysis techniques. Mineral tracers were also initially considered as potential tracers but were not pursued as the high cost of quantitative analysis limits their attractiveness for use in surveys where widespread sample collection is required. The results indicated that particulate lead and silver have the greatest potential as mine tailings tracers as they are typically present at enrichment factors of greater than 45 and 140 respectively in mine tailings compared to natural riverine sediments. Procedures for the tracing mine-derived sediments in river and floodplain environments are discussed. The assumptions and potential problems inherent to tracer methodologies are also discussed.

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1 Introduction

The Porgera gold mine is located at an elevation of about 2,500 metres in the rugged Highlands of Papua New Guinea (Figure 1). The mine, which has been in operation since 1990, discharges significant quantities of tailings and waste rock into the Porgera and Lagaip Rivers which then flow into the Strickland River (Figure 1). The Strickland joins the Fly River at Everill's Junction and ultimately flows into the Gulf of Papua. The river system may be divided into mountain and lowland sections. The mountain reaches are characterised by high flows and turbidities, whereas the lowland section, which begins about 50 km downstream of SG3 on the Strickland River (Figure 1), comprises an extensive, flat floodplain through which the river meanders. The local geomorphology has a significant influence on the fate and transport of mine-derived sediments. The high flow rates and steep-sided channels of the rivers in the mountain section ensure that the majority of mine-derived sediments are transported through this area in suspension with minimal deposition. In the lowland section however, the lower currents and frequent flooding make it more likely that a proportion of the discharged sediments will be deposited. This may involve trapping of particles in riverbed sediments, transport of sediments into off-river water bodies or overbank deposition across the extensive lower Strickland floodplain.

The characterisation of sediment transport and deposition in the lowland reaches of the river system requires the use of a signature tracer which is indicative of the presence of mine-derived sediments. This report summarises chemical investigations carried out to select a tracer the fate of mine-derived metals in the aquatic environment downstream of the Porgera mine. Potential applications of the tracers are described along with the inherent limitations of this type of approach.

2 Selection of a Suitable Mine-DERIVED SEDIMENT Tracer

A suitable tracer should have the following properties:

- A high concentration in mine-derived sediments
- A low concentration in natural riverine sediments
- It is chemically inert with little or no degradation, or a predictable degradation from its original concentration (e.g radioactive decay)
- It is easily measurable at low cost
- A low mobility – the remains associated with the mine-derived sediments with minimal dissolution or migration to other sediment particles
- The concentration in the mine-derived sediments does not vary appreciably with time

Tracers may be used to simply detect the presence or absence of mine-derived sediments or more usefully, used to quantify the amounts of mine-derived material present. The later approach usually requires some modelling of field data and involves assumptions about conservative dilution of mine-derived sediments with natural sediments.

There are several potential types of tracer that could be used to trace mine-derived sediments. These include the following categories:

- The concentration of individual elements which are enriched in the ore body relative to the concentrations found in riverine sediments.
- The concentration of minerals that are present in the ore body, or are formed in the mineral extraction process.
- The concentration of isotopes or the isotopic ratios of elements found in the ore body (e.g lead isotope ratios)
- Organic compounds which are introduced during the mineral extraction process.

A detailed investigation of all of these groups was beyond the scope and budget of this study. The study therefore focussed on examining the concentration of individual elements. By comparison, the accurate determination of trace element concentrations in sediments to trace levels is cost-effective. Some preliminary investigations were conducted on the suitability of jarosites formed during the pressure autoclaving process, however, it soon became clear that this approach would be prohibitively expensive owing to the high cost of quantitative minerals

analysis and the need to preconcentrate jarosites from riverine sediment samples.

3 Experimental

In order to select a suitable elemental tracer, samples of mine-derived sediments and natural riverine suspended sediments were sampled on three occasions and analysed for over 50 elements using a combination of multielemental analysis techniques. The concentration in the tailings relative to the natural sediments was subsequently compared.

3.1 Sample Collection

Large volume water samples (approximately 10 L) were collected by PJV staff at various riverine locations downstream of the mine on three occasions between June and October 2000 (Table 1).

Table 1. Survey dates and sampling locations

Survey	Date	Samples Taken
1	1 June	Lagaip at Wankipe, SG1, SG2, Upper Lagaip,
	6 June	Ok Om, SG3,
	15 June	SG4, Tomu River, Tailings,
2	1 July	SG1, SG2, Upper Lagaip,
	6 July	SG3, Ok Om, Lagaip at Wankipe,
	8 July	Tomu River
	11 July	Tailings
3	1 October	SG1, SG2, Upper Lagaip
	2 October	SG3
	6 October	Ok Om, Lagaip at Wankipe,
	15 October	Tomu River, Tailings

The sites (Figure 1) comprised locations impacted by mine-derived sediment and also tributary rivers.

Sites impacted by mine-derived sediments: Lagaip at Wankipe, SG1, SG2, SG3, SG4 (survey 1 only),

Uncontaminated tributaries: Upper Lagaip River, Ok Om, Tomu River

The uncontaminated tributaries (Upper Lagaip River, Ok Om, Tomu River) were sampled in order to characterise the composition of the natural sediments entering the river system. Tailings samples (ex-pipe) were also collected at the time of each survey. The samples were shipped to the Centre for Advanced Analytical Chemistry, CSIRO Lucas Heights where all subsequent analyses were conducted.

3.2 Sample Preparation

On receipt at CSIRO, the samples were transferred to a cold room (4°C) and left undisturbed for at least 24 hours so that the suspended sediment settled to the bottom of the containers. After this time, the majority of the clear supernatant liquid was removed by siphoning. The remaining sediment slurry was then quantitatively transferred to acid-washed glass beakers, using small amounts of the removed supernatant to rinse the original container. The sediment slurry was then dried in an oven for 24 hours at 100°C. The dried sediment was then homogenised by grinding in an agate mortar and pestle and stored in polycarbonate containers prior to analysis. Samples with very low TSS (Tomu River and Upper Lagaip River) were pre-concentrated by filtration through pre-weighed filter membranes (0.45 µm pore size). The filters were dried in an oven (100°C for at least 12 hours) and were retained for metals analysis. Blank filters were also prepared by filtering appropriate amounts of deionised water.

TSS concentrations were determined on the samples collected in surveys 2 and 3 using standard gravimetric procedures (APHA 1989).

3.3 Sample Digestion and Trace Metals Analysis

One hundred milligrams of dried sample was weighed into a polycarbonate vial and 2 mL of concentrated nitric acid (Normatom) and 4 mL of concentrated hydrochloric acid (Normatom) was added. The samples were allowed to stand for between 2 to 24 hours and were then microwaved in a domestic microwave oven (1100 W) for 20 minutes at 10% power. After cooling to room temperature, the solutions were made up to 100 mL final volume with deionised water. Each sample was prepared in triplicate. In order to provide a check on analytical accuracy, digestion blanks and reference material samples (PACS-2, National Research Council, Canada) were included in the sample batch. Semi-quantitative multielemental analysis using inductively coupled argon plasma mass spectrometry (ICP-MS) was applied to tailings, Ok Om, Tomu River and Upper Lagaip River samples from each survey. Selected trace metal concentrations were accurately determined on all samples from each survey using a combination of inductively coupled argon plasma atomic emission spectrometry (ICP-AES) and graphite furnace atomic absorption spectrometry (GFAAS) (lead and silver).

4 Results and discussion

4.1 TSS Concentrations

The TSS of the samples collected in surveys 2 and 3 are given in Table 2. As expected, the TSS concentrations were highest in samples collected at the monitoring stations downstream of the mine and generally lowest in the tributary rivers unaffected by mine discharges. The TSS concentrations in the OK Om were 1.3 and 3.2 g/L and were comparable to those found at SG2. These values reflect the high natural sediment loads carried by the Ok Om.

Table 2. Total suspended solids (TSS) concentrations (Surveys 2 and 3)

Sample	TSS g/L	
	Survey 2	Survey 3
Tailings	126	185
SG1	7.5	7.5
SG2	2.0	3.2
Lagaip at Wankipe	0.9	2.8
SG3	0.8	2.0
Ok Om	1.3	3.2
Upper Lagaip	0.135	0.163
Tomu River	0.010	0.089

4.2 Trace Metal Concentrations and Tracer Selection

The results of the ICP-MS analyses are given in Appendix 1. This type of multielemental analysis is excellent for screening the concentration of a wide range of trace elements. This data was used to identify potential tracers by calculating the ratio of particulate metal concentration in the tailings sample to that in the suspended sediment collected at Ok Om (the enrichment ratio). Ok Om was chosen for this initial comparison as this tributary of the Strickland River is a major source of natural sediments to the lowland river system. Any element having an enrichment ratio of >10 was selected for further evaluation. The elements fulfilling this initial criteria were as follows:

Survey 1: Ag, As, Au, Cd, Pb, Sb, W, Zn

Survey 2: Ag, As, Au, Cd, Nb, Pb, Sb, U, W, Zn, Zr

Survey 3: Ag, As, Cd, Mo, Pb, Sb, Te, V, Zn

Only Ag, As, Cd, Pb, Sb and Zn met this initial criterion in all three surveys. The enrichment ratio of these elements are given in Table 3. Silver had by far the highest enrichment ratio.

Table 3. Enrichment ratios (Tailings/Ok Om) of the potential tracer elements

Element	Survey 1	Survey 2	Survey 3	Mean \pm standard deviation
Ag	156	167	121	148 \pm 20
As	68	39	50	52 \pm 15
Cd	10	38	54	34 \pm 22
Pb	47	59	28	45 \pm 16
Sb	84	64	50	66 \pm 17
Zn	11	16	11	13 \pm 3

Despite their high ratios, arsenic, cadmium and zinc were eliminated from the list of potential tracers owing to their known mobility in aquatic environments. Previous testwork (Apte et al. 1996) has shown that these elements readily desorb from mine-derived sediments in river water and subsequently re-adsorb onto natural riverine sediments. The mobility of arsenic in deposited sediments has been illustrated in previous studies conducted for PJV (Apte 1995). Using sediment porewater peeper samplers, it was shown that arsenic in mine-derived sediments was potentially mobile under anoxic conditions. This is likely to occur when mine-derived sediments are deposited and mixed with natural benthic sediments. These findings were consistent with the known diagenetic mobility of arsenic in aquatic sediments (Belzile and Tessier 1990).

Antimony had the second highest enrichment ratio and therefore showed promise as a tracer. No previous work has been conducted on the mobility of antimony downstream of the mine. However, considering the strong chemical similarity of antimony and arsenic, it is likely that antimony will be subject to the same migration effects and will be diagenetically mobile in deposited sediments. In view of this possibility, antimony was eliminated as a possible tracer.

The mobility of silver and lead was not studied directly, however there is ample evidence in the literature that lead and silver do not substantially migrate in riverine environments and deposited sediments. This is one of the basic assumptions made when dating of sediments using lead isotopes. Lead and silver were therefore selected as tracer elements.

It should be noted that the measured silver ratios are potentially underestimates. This is because the concentrations of particulate silver in the natural sediments were close to the detection limit and may be subject to some error. In future

tracer applications, it is recommended that the methods for the determination of particulate silver are refined (i.e increase the mass of sediment digested) in order to improve the detection limit. This will be a challenge when dealing with low turbidity rivers such as the Tomu.

4.3 Variation of Tracer Concentrations with Time

An important criterion for trace use is that the concentration of the tracer in the mine-derived sediments does not vary appreciably with time. The actual acceptable level of variability depends on the application of the tracer. As long as the tracer is consistently enriched compared to natural sediments it is still valid as a qualitative indicator of the presence of mine-derived sediments, however, significant variability limits the application as a quantitative tracer. Variability may be compensated for in snapshot studies (see below) by regularly measuring tracer concentrations in mine-derived sediments over the course of the study period. Hydrologically-based sediment transport models may be used to calculate the transit time between discharge from the mine and the site under investigation.

Unfortunately, little data exists on the temporal variability of particulate metals in mine-derived sediments. Monthly PJV monitoring data is not suitable for this purpose as acid-soluble particulate metals are derived by calculation rather than direct determination on particulate matter isolated from water samples. As a result, the existing PJV data will not be directly comparable with the data presented in this study. The variability of particulate lead in mine tailings characterised by CSIRO over a six-month period in 1995/96 (Apte 1996), is given in Table 4. Unfortunately, particulate silver was not analysed in this study. It should also be noted that the waste rock discharged to the river system may also contain quantities of lead and silver. This also needs to be taken into account. Further characterisation of particulate silver and lead concentrations in mine tailings and waste rock is required.

Table 4. Particulate metal concentrations ($\mu\text{g/g}$) in composite tailings samples (1995/6) data (Apte 1996)

Sample	Collection Date	Pb
A	23 June 95	752
B	7 July 95	1140
C	22 July 95	674
D	6 August 95	816
E	22 August 95	697
F	4 September 95	671
G	18 September 95	751
H	3 October 95	525
I	14 December 95	482
J	31 December 95	428
K	14 January 96	541
L	31 January 96	747
Mean		685
Standard Deviation		188
% Relative Standard Deviation		27

5 proposed Tracer applications

The two main applications for the silver and lead tracers are as follows:

- Assessment of the dilution of mine-derived sediments with natural sediments
- Identification of mine-derived sediment deposition on the Strickland River floodplain and associated off-river water bodies.

These applications are discussed in more detail below.

5.1 Assessing In-river Sediment Dilution

In-river sediment dilution refers to the mixing of mine-derived sediment with natural suspended sediments. This is the most important process that determines the concentration of particulate metals in sediments downstream of the mine. The concentrations of lead and silver measured in all survey samples is given in Table 5. The results indicated a consistent decrease in both tracers with distance from the mine. This is a consequence of dilution of mine-derived sediments with natural particulates that are low in metals.

These data were used to quantitatively estimate the dilution of mine-derived sediments by natural sediments. As the contributions of lead and silver in waste rock have not been estimated, particulate silver and lead data obtained at SG1 was used as an estimate of mine-derived sediment concentrations. The following simple dilution model was used:

Tracer concentration at site = [(fraction of mine-derived sediments) x tracer concentration in tailings] + [(fraction natural sediments) x tracer concentration in natural sediments]

where: Fraction of mine-derived sediments = concentration of mine-derived sediments/total suspended sediment concentration

Fraction of natural sediments = concentration of natural suspended sediments/total suspended sediment concentration

The input data were the concentration of particulate metals measured at SG1 and the mean background particulate metal concentration in the natural sediments. Temporal variations of tracer concentrations in mine-derived sediments will occur as different ore types are mined and processed. This may be compensated for by conducting 'snapshot' experiments where samples from all sites are collected over a short time span and the temporal variability of metals in mine tailings and waste rock are adequately characterised over the duration of the study period. The model may also be refined if the lag times

between sediment discharge from the mine site and arrival at the sampling sites are known.

The percentage of mine tailings at each site is shown in Table 5. With the exception of the data for SG3 (survey 2) the agreement between the two tracers is quite good. It should be noted that the data sets are not ideal for this type of application as the sampling sites were sampled at different times over a period of several weeks (Table 1). The general agreement between the two tracers is therefore highly encouraging.

A sensitivity analysis was carried out by systematically varying the concentrations of metals in the tailings and the natural sediments. This indicated that the dilution calculations are not particularly sensitive to changes in the concentrations of lead and silver in natural sediments however they are very sensitive to changes in mine-derived metal concentrations. This emphasizes the need to accurately characterise the tracer concentrations in the mine tailings (and waste rock) inputs and any variations over the time frame of the study. This needs to be taken into account when designing future in-river dilution studies. It is also desirable to study in-river dilution under differing hydrological (and sediment transport) conditions.

Table 5. Tracer concentrations in mine tailings and suspended sediments

Sample	Distance from mine (km)	Ag (µg/g)	Pb (µg/g)	% of mine-derived sediments (Ag tracer data)	% of mine-derived sediments (Pb tracer data)
Survey one					
Tailings	-	15.6	1470	-	-
SG1	8	11.9	700	100*	100*
SG2	42	11.3	618	95	88
Lagaip River at Wankipe	116	10.2	508	84	72
SG3	165	2.4	206	19	27
SG4	360	1.4	92	11	10
Ok Om	143	0.1	31	-	-
Upper Lagaip	-	0.1	21	-	-
Tomu River	366	<0.1	14	-	-
Survey 2					
Tailings	-	16.7	1010	-	-
SG1	8	9.51	614	100	100
SG2	42	9.42	607	99	99
Lagaip River at Wankipe	116	6.59	441	69	71
SG3	165	3.52	444	36	71
Ok Om	143	0.1	17	-	-
Upper Lagaip	-	<0.21	23	-	-
Tomu River	366	<0.21	13	-	-
Survey 3					
Tailings	-	12.1	499	-	-
SG1	8	4.5	357	100	100
SG2	42	2.8	268	61	73
Lagaip River at Wankipe	116	2.6	231	57	62
SG3	165	1.8	164	39	42
Ok Om	143	0.1	18	-	-
Upper Lagaip	-	0.2	15	-	-
Tomu River	366	0.2	32	-	-

*SG1 data used as an estimate of initial mine-derived sediment concentration

5.2 Detecting the Presence of Mine-derived Sediments in Off-river Water Bodies

The principal application of the identified tracers is the detection of mine-derived sediment deposition resulting from overbank deposition during flood events and the associated ingress of sediments to off-river water bodies during flow-reversal events or flooding. An initial investigation of these processes was conducted by Day et al. (1998). Sediment cores were collected along six transects at key points on the lower Strickland River floodplain and in five off-river water bodies of this region. All five off-river water bodies studied showed enrichment of arsenic and lead in surface sediments and all the floodplain sites studied showed a clear enrichment of arsenic, lead and zinc in surface sediments. The gradients of metal concentrations across the floodplain (highest concentrations closest to the river channel) suggest overbank deposition is the source of these metals.

The lead concentrations measured in core sections of benthic sediments collected from an off-river water body located on the Lower Strickland River SWB-3 are shown in Table 6. The clearly shows evidence of lead enrichment in the surficial sediments which are indicative of mine-derived sediment deposition at this location. The lead concentrations with depth (17-40 $\mu\text{g/g}$) were typical of the range found in natural riverine suspended sediments (Table 5).

By conducting high resolution coring (1 cm slices or smaller), and measuring the silver lead concentration as depth profiles, it should be possible to deduce the deposition rates of the introduced sediments. This would allow prediction of mine impacts over the entire mine life to be made. Some confounding factors need to be taken into account when conducting coring studies. The previous floodplain study (Day et al. 1998) noted negative correlations between particulate metal concentrations (including lead) and sediment organic matter content. This indicates a dilution effect of mineral rich sediments with organic matter (mainly plant material) low in metals. Organic matter content should therefore be measured and corrected for. A procedure for organic matter correction is described by Day et al. (1998). Metal concentration can also vary with sediment particle size. Given that the majority of mine-derived particles found in suspended sediments are $<63 \mu\text{m}$, it is appropriate that samples are sieved before chemical analysis (Day et al. 1998).

Table 6. Particulate lead concentrations ($\mu\text{g/g}$) in sediment core sections taken in an off-river water body (SWB-3) connected to the Lower Strickland River (Day et al. 1998).

Sample location	Particulate lead, $\mu\text{g/g}$	
	0-1 cm depth	30-31 cm depth
ORWB end closest to river channel	111	40
Middle	78	17
Far end of OWRB	51	18

6 CONCLUSIONS

There are many potential tracers of mine sediments including specific mineral phases and isotopic ratios of certain elements. This study focussed on the identification of geochemical tracers that are simple and cost effective to measure. Particulate silver and lead were identified as suitable tracers of tailings originating from the Porgera mine. Using these relatively simple chemical tools, it is possible to obtain information on mine-derived sediment dispersion and deposition in an extremely complex aquatic system. The tracers are particularly suited to characterising overbank deposition and in-river dilution of mine sediments with natural riverine sediments. A dual tracer approach is particularly desirable as it provides a simple cross-check of the results from any investigation.

It cannot be overstressed that the scope and limitations of the tracer approach should be fully understood. The proposed tracers are tracers of *mine-derived sediments*. Previous studies by CSIRO (Apte 1996) have shown that several metallic contaminants initially present in mine tailings (e.g. arsenic, nickel and zinc) are highly mobile in river water and will migrate from mine tailings first to the water column and then to natural sediment particles (by adsorption). Direct measurement of these metals in waters, sediments and biota still remains the most effective way of characterising the impacts of these contaminants.

7 Recommendations for further work

1. As a first priority, the tracers elements identified in this study should be applied to characterise the extent of overbank deposition of mine-derived sediments on the Lower Strickland River floodplain, the off-river water bodies of the area and Lake Murray. This will provide important information on the impacts of the mine on the Lower Strickland region.
2. The temporal variability of lead and silver concentrations in natural sediments, waste rock and mine tailings should be characterised. This information is important for quantitative applications of the tracers.
3. Studies similar to the ones described in this report should be carried out to identify suitable tracers of waste rock inputs to the river system.
4. Snapshot measurements of particulate lead and silver in riverine suspended sediments and mine tailings/waste rock inputs should be used in conjunction with hydrological/sediment transport models to estimate the extent of dilution of mine-derived sediments with natural sediments. This will assist with the development of a comprehensive sediment budget for the system.
5. The concentration of particulate antimony is enriched in mine-derived relative to natural riverine sediments. Further studies should be carried out to examine the suitability of this element as a tracer.

8 ACKNOWLEDGMENTS

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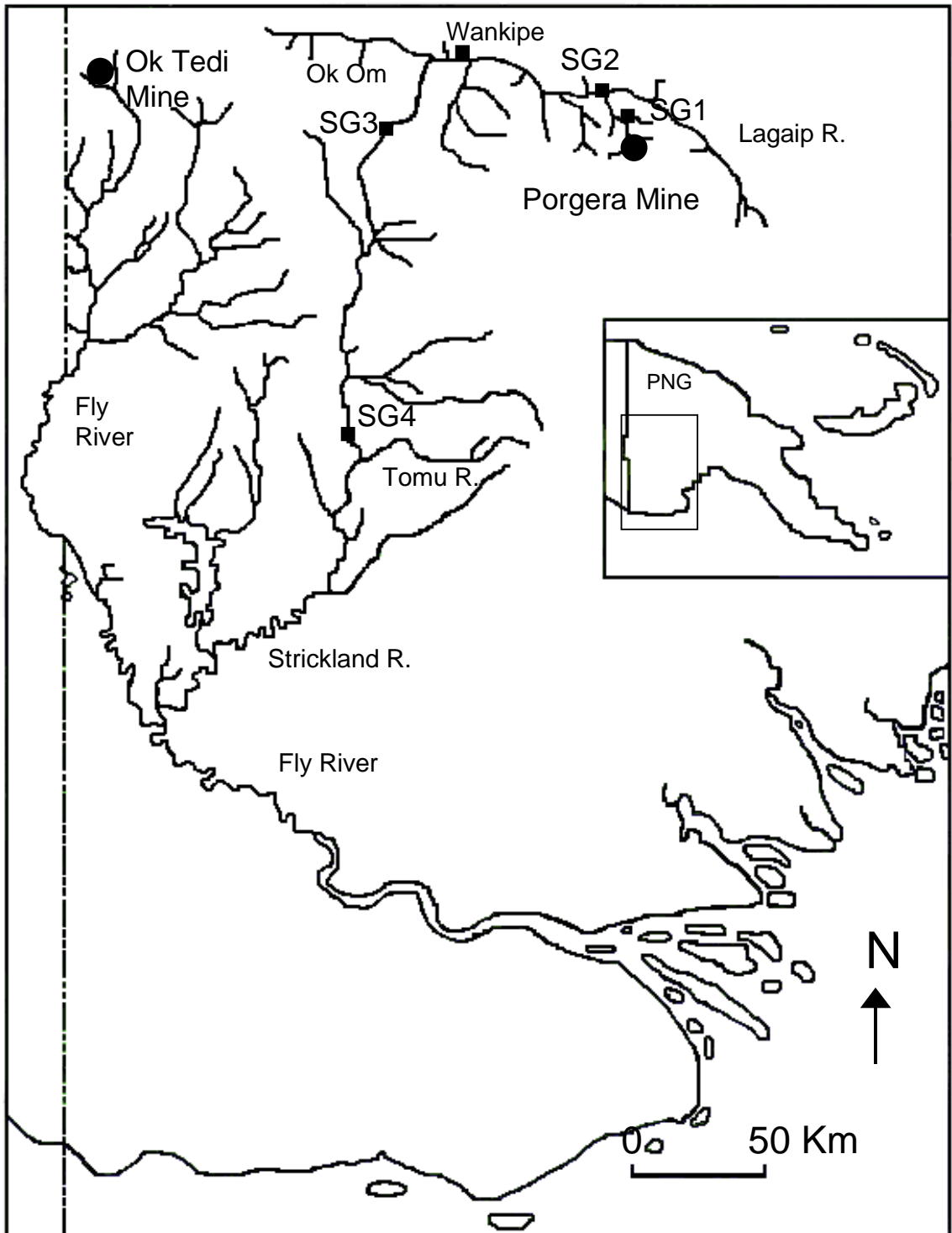


Figure 1. Map of the river system showing the mine location and routine monitoring stations.

APPENDIX

ICP-MS Data: Survey 1

Element	Concentration (µg/g)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank	
Ag	15.6	0.1	0.1	<0.1	<0.1	156
Al	7610	14600	9480	<100	<100	1
As	741	<10	11	<10	<10	68
Au	1.4	<0.1	<0.1	<0.1	<0.1	14
B	<1000	<1000	<1000	<1000	<1000	-
Ba	166	119	90	0.6	0.2	2
Be	<10	<10	<10	<10	<10	-
Bi	0.7	0.5	0.5	<0.1	<0.1	1
Ca	49800	39300	7500	<500	<500	7
Cd	9.8	0.1	1.0	<0.1	<0.1	10
Ce	30.2	11.0	12.8	<0.1	<0.1	2
Co	23.4	17.4	12.8	<0.1	<0.1	2
Cr	49	44	30	3	6	2
Cs	1.1	0.5	0.5	<0.5	<0.1	2
Cu	156	37	22	1	<1	7
Dy	1.9	2.2	2.2	<0.1	<0.1	1
Er	0.9	0.8	0.8	<0.1	<0.1	1
Eu	1.0	0.8	0.9	<0.1	<0.1	1
Fe	69300	46600	36500	<1000	<1000	2
Ga	1.8	2.2	1.4	<0.1	<0.1	1
Gd	2.8	3.2	3.4	<0.1	<0.1	1
Ge	<1	<1	<1	<1	<1	-
Hf	<0.1	<0.1	<0.1	<0.1	<0.1	-
Hg	2.4	<0.1	<0.1	<0.1	<0.1	2
Ho	0.3	0.4	0.4	<0.1	<0.1	1
I	<100	<100	<100	<100	<100	-
Ir	<0.1	<0.1	<0.1	<0.1	<0.1	-
La	16.6	4.8	4.0	<0.1	<0.1	4
Li	<100	<100	<100	<100	<100	-

Element	Concentration (µg/g)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank	
Lu	0.1	0.1	0.1	0.1	<0.1	1
Mg	1850	11900	5920	<100	<100	0
Mn	1370	841	642	<1	<1	2
Mo	6.3	0.4	1.0	<0.1	<0.1	6
Na	1170	<1000	<1000	<1000	<1000	1
Nb	0.4	0.2	<0.1	<0.1	<0.1	4
Nd	14	9	9	<0.1	<0.1	1
Ni	40	45	20	<1	<1	2
Os	<0.1	<0.1	<0.1	<0.1	<0.1	-
Pb	1470	21	31	14	<0.1	47
Pd	<0.5	<0.5	<0.5	<0.5	<0.5	-
Pr	3.5	1.8	1.9	<0.1	<0.1	2
Pt	<0.1	<0.1	<0.1	<0.1	<0.1	-
Rb	17.6	7.3	10.9	<0.1	<0.1	2
Re	<0.1	<0.1	<0.1	<0.1	<0.1	-
Rh	<0.1	<0.1	<0.1	<0.1	<0.1	-
Ru	<0.1	<0.1	<0.1	<0.1	<0.1	-
Sb	16.6	0.1	0.2	<0.1	<0.1	84
Sc	13	11	<10	<10	<10	1
Se	<1	<1	<1	<1	<1	-
Sm	2.6	2.8	3.1	<0.1	<0.1	1
Sn	0.6	0.5	2.0	<0.1	<0.1	0
Sr	185	119	55	0.2	<0.1	3
Ta	<0.1	<0.1	<0.1	<0.1	<0.1	-
Tb	0.4	0.5	0.5	<0.1	<0.1	1
Te	2.2	0.1	0.2	<0.1	<0.1	11
Th	1.9	2.2	1.5	<0.1	<0.1	1
Ti	117	174	52	<10	<10	2
Tl	0.5	<0.1	<0.1	<0.1	<0.1	5
Tm	0.1	0.1	0.1	<0.1	<0.1	1
U	1.1	0.2	0.3	<0.1	<0.1	4
V	166	29	18	<10	<10	9
W	1.8	<0.1	<0.1	<0.1	<0.1	18

Element	Concentration ($\mu\text{g/g}$)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank	
Y	8.0	8.2	10.9	0.1	<0.1	1
Yb	0.7	0.5	0.5	<0.1	<0.1	1
Zn	1760	110	158	<1	<1	11
Zr	<1	<1	<1	<1	<1	-

ICP-MS Data: Survey 2

Element	Concentration (µg/g)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank 1	
Ag	16.7	<0.2	0.1	<0.2	<0.1	167
Al	6900	20600	9400	2100	3.0	1
As	512	<74	13	<63	<10	39
Au	0.84	0.59	0.02	0.44	<0.01	42
B	5.6	81	23	500	55	0
Ba	233	103	108	<6.3	<1	2
Be	1.9	<7.4	<1.0	<6.3	<1	2
Bi	0.5	<0.7	0.3	0.6	0.2	2
Br	186	735	201	1880	200	1
Ca	32600	27200	12100	1250	200	3
Cd	7.6	1.47	0.20	<0.63	<0.1	38
Ce	21.4	6.6	11.1	1.9	<0.01	2
Co	16.8	19.1	11.1	1.9	<0.1	2
Cr	19	66	16	31	<1	1
Cs	2.61	2.94	1.11	0.06	<0.01	2
Cu	106	44	17	13	1	6
Dy	1.8	1.8	1.6	<0.06	0.06	1
Er	0.68	0.51	0.50	0.13	<0.01	1
Eu	0.93	0.37	0.70	<0.06	<0.01	1
Fe	42900	39000	28200	3060	10	2
Ga	1.86	2.94	1.51	<0.63	0.20	1
Gd	2.05	0.74	3.02	0.13	0.01	1
Ge	0.75	0.74	0.60	<0.63	0.30	1
Hf	0.05	0.15	0.05	<0.06	<0.01	1
Hg	9.3	<7.4	<1.0	<6.3	<1	9
Ho	0.21	0.22	0.22	<0.06	<0.01	1
I	<0.93	<7.35	<1.01	6.25	<1	-
Ir	<0.01	<0.07	<0.01	<0.06	<0.01	-
K	4380	1910	1710	250	<10	3
La	13.05	2.65	3.52	1.63	<0.01	4
Li	4.66	36.8	23.1	<6.3	<1	0

Element	Concentration (µg/g)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank 1	
Lu	0.04	<0.07	0.06	<0.06	<0.01	1
Mg	7640	8090	3920	506	39.0	2
Mn	1320	647	332	206	2.0	4
Mo	7.08	1.47	1.01	<0.63	<0.1	7
Na	1400	2210	704	1250	200	2
Nb	1.21	0.37	0.05	0.13	0.02	24
Nd	8.76	5.15	7.24	0.81	<0.01	1
Ni	30	66	18	19	<1	2
Os	<0.09	<0.74	<0.10	<0.63	<0.1	-
Pb	1010	23	17	13	0.2	59
Pd	<0.5	<3.7	<0.5	<3.1	<0.5	1
P	0.74	0.37	0.31	<0.06	<0.01	2
Pr	2.14	0.88	1.71	0.13	<0.01	1
Pt	<0.01	<0.07	<0.01	<0.06	<0.01	-
Rb	20.5	20.6	14.1	1.25	<0.1	1
Re	<0.01	<0.07	<0.01	<0.06	<0.01	-
Rh	<0.01	<0.07	<0.01	<0.06	<0.01	-
Ru	<0.001	<0.01	<0.001	<0.01	<0.001	-
Sb	10.3	0.44	0.16	0.50	0.40	64
Sc	14.9	36.8	11.1	6.3	1.0	1
Se	7.5	14.7	3.0	25.0	11.0	2
Si	8	20	10	3	<10	1
Sm	2.3	<0.7	2.2	<0.6	<0.1	1
S	29800	221	3200	750	60	9
Sn	<0.9	<7.4	<1.0	<6.3	<1	-
Sr	144	88.2	56.3	5.6	0.1	3
Ta	0.02	0.15	<0.01	0.25	<0.01	2
Tb	0.31	0.37	0.33	<0.06	0.01	1
Te	<1	<7.4	<1.0	6.3	<1	1
Th	3.5	1.5	3.5	<0.06	<0.01	1
Ti	79.2	265	37.2	119	<1	2
Tl	0.93	2.06	0.26	2.69	0.66	4
Tm	0.12	0.07	0.04	<0.06	<0.01	3

Element	Concentration ($\mu\text{g/g}$)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank 1	
U	1.49	0.07	0.15	<0.06	<0.01	10
V	167	36.8	29.2	<6.3	<1	6
W	0.93	0.59	0.04	0.25	0.06	23
Y	6.34	5.81	5.13	0.75	<0.01	1
Yb	0.50	0.15	0.19	<0.06	<0.01	3
Zn	1320	169	85	56	3	16
Zr	3.1	3.5	0.08	1.56	0.10	38

ICP-MS Data: Survey 3

Element	Concentration (µg/g)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank	
Ag	12.1	0.2	0.1	0.2	<0.1	121
As	442	<44	<9	<91	<10	49.5
Au	1.2	<0.4	0.3	1.8	<0.1	4.3
Ba	231	120	87	327	<0.1	2.7
Be	1.1	0.9	0.4	<0.9	<0.1	2.4
Bi	0.4	<0.4	0.2	<0.9	<0.1	2.2
Cd	4.8	<0.4	<0.1	5.5	0.2	53.8
Ce	24.0	7.5	10.7	30.9	<0.1	2.2
Co	14.4	17.7	11.6	27.3	<1	1.2
Cr	41	62	26	82	7	1.6
Cs	1.5	2.7	1.3	0.9	<0.1	1.2
Cu	83	40	16	55	<1	5.1
Dy	1.6	1.8	1.9	5.5	<0.1	0.9
Er	0.6	<0.4	0.4	1.8	<0.1	1.6
Eu	0.5	0.4	0.4	<0.9	<0.1	1.1
Ga	3.8	4.4	4.5	9.1	<1	0.9
Gd	1.7	1.3	2.2	2.7	<0.1	0.8
Ge	0.2	0.9	0.2	0.9	<0.1	1.1
Hf	<0.1	<0.4	<0.1	1.8	<0.1	-
Hg	3.5	<0.4	0.7	<0.9	<0.1	4.8
Ho	0.2	<0.4	0.3	<0.9	<0.1	0.7
Ir	<0.1	<0.4	<0.1	<0.9	<0.1	-
La	12.5	4.9	3.8	13.6	<0.1	3.3
Lu	0.1	<0.4	0.0	<0.9	<0.1	0.1
Mo	5.3	0.4	0.3	<0.9	<0.1	19.7
Nb	0.5	<0.4	<0.1	4.5	<0.1	5.4
Nd	9.6	6.6	7.6	22.7	<0.1	1.3
Ni	28	44	19	46	<1	1.5
Os	<0.1	<0.4	<0.1	<0.9	<0.1	-
Pb	499	15	18	32	0.2	28
Pd	<0.5	<2.2	<4.5	<4.5	<0.5	-

Element	Concentration (µg/g)					Ratio
	Tailings	Upper Lagaip	Ok Om	Tomu River	Blank	
Pr	2.9	0.9	1.4	4.5	<0.1	2.0
Pt	0.1	<0.4	<0.1	<0.9	<0.1	1.1
Rb	13.5	17.7	12.5	9.1	<0.1	1.1
Re	<0.1	<0.4	<0.1	<0.9	<0.1	-
Rh	<0.1	<0.4	<0.1	<0.9	<0.1	-
Ru	<0.1	<0.4	<0.1	<0.9	<0.1	-
Sb	8.9	<0.4	0.2	1.8	0.2	50.0
Sc	14.4	35.4	13.4	63.6	<1	1.1
Se	<10	<44	<9	<90	<10	-
Sm	1.6	1.8	1.6	2.7	<0.1	1.0
Sn	0.4	0.9	0.3	3.6	0.3	1.4
Sr	212	124	45.6	146	<0.1	4.6
Ta	<0.1	<0.4	<0.1	<0.9	<0.1	-
Tb	0.3	0.9	0.4	<0.9	<0.1	0.8
Te	2.9	<0.4	<0.1	<0.9	<1	32.3
Th	1.5	2.2	2.9	4.5	<0.1	0.5
Tl	0.5	<0.4	<0.1	<0.9	<0.1	5.4
Tm	<0.1	<0.4	<0.1	<0.9	<0.1	-
U	0.7	<0.4	0.1	0.9	<0.1	7.5
V	88.5	35.4	0.9	109	<1	98.9
W	0.3	<0.4	<0.1	<0.9	<0.1	3.2
Y	6.7	8.8	5.4	18.2	<0.1	1.3
Yb	0.3	0.4	0.2	3.6	<0.1	1.6
Zn	865	155	79	255	2	11.0
Zr	<0.1	4.4	<0.1	45.5	<0.1	-