TECHNICAL MEMORANDUM

DATE: 19 January 2003

TO: **Ok Tedi Mining Limited**
<u>Attention: ARD Coordinator, Environment Department</u>

FROM: Mark J. Logsdon (Geochimica)

SUBJECT: **REVIEW OF THE FY02 ACID-ROCK DRAINAGE (ARD) PROGRAM REPORT -- OK TEDI, WESTERN PROVINCE, PAPUA NEW GUINEA**

cc: **Manager – Environment (OTML)**

EXECUTIVE SUMMARY

At direction of the ARD Coordinator, Environment Department for Ok Tedi Mining Ltd. (OTML), Geochimica, Inc. reviewed the Fiscal Year 2002 (FY02) Acid-Rock Drainage (ARD) Management Program Report.

The principal results of this evaluation of existing information include:

1. ***OTML continue to add to the large body of geochemical and hydrogeochemical data for waste rock and tailing. As recommended in 2001, OTML have substantially supplemented their characterization and understanding of river-sediment system, especially with respect to the dredge sediments at Bige.***

2. ***The sampling strategies, analytical methods, and interpretive reasoning documented in the Environmental Regime FY02 Annual Report are adequate to the spatial and technical scopes of the Ok Tedi Project and the downstream drainages. The methodologies used in the ARD Management Program are at the forefront of best practice in the world for mining, and the level of detail and completeness of the work is a model with few, if any peers in mining geochemistry.***

3. ***Given site history and conditions - including the very large-scale nature of mining at Ok Tedi and both the geologic (lithologic, geomorphic, and tectonic) and climatic/hydrologic conditions – OTML's risk-management options are appropriate and prudent, corresponding to world's best practices for these site conditions. We consider that the Minus-150 NAPP Plan provides the best practicable protection against large-scale acidification in the waste-rock and downstream of the mine. OTML's program to enhance proactive management of potential ARD at the Bige dredge facilities, including engineering alternatives associated with both geotechnical details and hydrology of the facilities, reflects the current state of the art in managing tailing. As they have done with the geochemical site-characterization program, OTML have retained international experts in tailing management to advise them, and the engineers and hydrologists are working very closely with the geochemical consultants. The close and continuing integration of ARD characterization and site-specific engineering activities is a good, specific example of best practice for ARD management.***

4. ***OTML use an empirical model, "OkARD" to predict both the spatial distribution of acid-generating and acid-neutralizing materials in the disposal and riverine systems, and also to estimate the hydrogeochemical consequences (specifically pH and dissolved-copper concentrations) in Ok Tedi and the Fly River. The structure of***

OkARD is logical, and the model continues to undergo refinement and testing, as is appropriate for any predictive tool. The comparison of measured mean values for Net Acid Producing Potential (NAPP) with those predicted by OkARD shows that OTML have a predictive tool that is accurate with respect to average values for this critical measure. The long-term column-leach tests conducted as part of the ARD Management Program show that there are, as expected from theoretical considerations, consistent relationships between NAPP and observed solution chemistry during simulated weathering. Finally, ongoing monitoring of water quality in the Ok Tedi and Fly River systems shows that the laboratory-scale leach tests are consistent with the observed hydrogeochemistry of the field conditions. Therefore, we conclude that OkARD is well posed as a model and provides useful information for OTML planning.

Further development of OkARD should, in our view, continue, especially along three lines:

- *Addressing uncertainty in spatial distributions of NAPP and related system chemistry.*
- *Extending further OTML's efforts to verify and validate the model predictions.*
- *Incorporating the output from the hydrogeochemical model of the mine pit as an additional input to the OkARD model system.*

It should be noted that OTML and their ARD contractor already had identified very similar recommendations.

5. *Geochimica recommends that the ARD characterization program:*

   - *Document the geochemical and hydrogeochemical consequences of OTML's efforts to meet the Minus-150 NAPP Plan.*
   - *Extend geochemical and hydrogeochemical testing of downstream sediments, especially the coupled testing and sampling in point bars and the basic characterization work in the levees and floodplains.*
   - *Continue laboratory-scale column-leach testing, especially for stream sediments, to evaluate the potential for release of dissolved copper.*
   - *Continue developing the hydrogeochemical model for the open cut. When the pit model is sufficiently advanced, it – or at least output from its simulations – should be incorporated into OkARD as a new input component.*
   - *Continue to develop and test OkARD. We recommend specifically that OTML and their geochemical advisors address the impacts of uncertainty in spatial distributions of NAPP and related system chemistry.*

   The principal, near- to mid-term focus of the OTML risk-management activities, in our view, should be:

   - *Implementing the Minus-150 NAPP Plan;*
   - *Continuing to evaluate and implement proactive ARD management alternatives for the Bige dredge sediments.*

6. *The test program and data evaluation described in the FY2002 ARD Management Program Report fulfil our understanding of the objectives of Environmental Regime (a) to characterize the potential impacts of mining due to ARD and (b) to report the results annually to the State of Papua New Guinea.*

INTRODUCTION

General

The ARD Coordinator, Environment Department, on behalf of Ok Tedi Mining Limited (OTML), retained Geochimica, Inc. (Geochimica) to evaluate the Environmental Regime's Fiscal Year 2002 Acid-Rock Drainage (ARD) Management Program Report. The scope of this review is to address the ARD program as it relates to waste rock, tailing, and sediments in and adjacent to the drainages.

OTML produce waste rock and tailing from open-pit mining of the 1.2 million-year-old Mt. Fubilan porphyry copper deposit in the headwaters of the Ok Tedi in Western Province, Papua New Guinea. The Darai Limestone, into which the Sydney Monzodiorite and the Fubilan Monzonite porphyry intruded, is a 300 m to 800 m thick sequence of fresh, massive, dark grey limestone. In some portions of the mined area, the igneous rocks also intrude the Ieru Siltstone, converting the fine-grained clastic sedimentary rock to hornfels near the contact. The mineralised intrusives, and especially the hornfels and skarns near contacts of intrusive and sedimentary rocks, contain elevated concentrations of sulphide minerals, including both pyrite (FeS_2) and chalcopyrite ($CuFeS_2$). The limestone contains only minor chert, and the calcium-carbonate content is very high. The combination of high local relief, active tectonics, and tropical, pluvial climate leads to very high erosion rates. Consequently, substantial amounts of both mine-derived and natural sediments report to the local rivers (Ok Mani, Ok Tedi and Fly River), where the local stream hydraulics affect the distribution of natural and mine-produced sediments. A much fuller description of site and project geology is provided in Geochimica (2001) and the references cited therein.

The principal geochemical consultants for OTML are Environmental Geochemistry International (EGi) Pty. Ltd, Balmain (NSW), Australia. EGi have been the technical lead for the ARD Program studies since they were instituted formally in 1999.

Terms Of Reference

OTML charged Geochimica to provide an independent, scientific review of the current acid-rock drainage (ARD) management program for the Ok Tedi mine based on the FY02 annual report. Geochimica's review is to be presented in a technical memorandum.

For this review, OTML provided Geochimica a set of documents:

- OTML's Annual Environmental Report for FY 2002;
- Nine (9) major reports addressing selected aspects of the ARD characterization and management programs, including:

    a. Mine Pit Geochemistry
    b. Tailings Geochemistry
    c. Ok Mani Geochemistry
    d. Sediments Geochemistry
    e. Floodplain Geochemistry
    f. Leach Columns
    g. Sedimentology of the Mine Area Creeks
    h. Bige Hydrogeochemistry
    i. Bige Dredge Sediment Geochemistry

As appropriate, we also have reviewed additional background material provided to us in 2000 and 2001 as part of an earlier review (Geochimica, 2001). We also have reviewed appropriate work and data from the open literature on mine-waste geochemistry and our previous professional experience.

We relied on the data and other information provided to us by OTML as accurate and complete, although we do discuss the data and their interpretations in light of previous experience and general geochemical principals. We collected no original data for this task, and we performed no detailed quality-assurance evaluations of data provided to us. We have not visited the site.

Disclaimer

Neither Geochimica, Inc. nor Mark Logsdon, its principal geochemist and sole stockholder, has any financial interest in Ok Tedi Mining Limited, its owners/investors, or Environmental Geochemistry International Pty. Ltd.

ISSUES

1. Are the sampling strategies, analytical methods and interpretive reasoning adopted by OTML appropriate in comparison to world's best practice for evaluation of ARD?
2. Are the risk treatment options presently being implemented by OTML appropriate in light of world's best practice for management of ARD?
3. Is the design of the OTML predictive model, OkARD, appropriate, and are the results to date useful?
4. What, if any, changes to sampling, analysis, and interpretive procedures likely would improve OTML's ARD risk-characterization and management program?

TECHNICAL BACKGROUND

Prediction of Acid Rock Drainage

Acid-rock drainage (ARD) is the generation of low-pH drainage from rocks or rock products by reaction of air and infiltrating meteoric water with certain minerals. Such acidic effluents may carry elevated concentrations of dissolved solutes including sulphate and sometimes metals and metalloids. The following material is an abbreviated outline of the theoretical and practical aspects of ARD prediction, described in more detail in Geochimica (2001).

In short, oxidation of pyrite (FeS_2) and other sulphide minerals can produce dilute solutions of sulphuric acid (H_2SO_4, which dissociates in solution to H^+ and SO_4^{2-} ions) through reactions such as:

$$[1]\quad FeS_2 + 15/4\ O_2 + 7/2\ H_2O \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+$$

As H^+ ions are produced, the pH of the solution falls, and a variety of metals, including copper (Cu) may be solubilized and then transported in surface and ground waters.

Reactions between the acidity and mineral phases in the rock can neutralize the acidity released by sulphide oxidation. The most effective minerals for neutralization are carbonates, such as calcite ($CaCO_3$), the principal mineral of limestone. A typical limestone neutralization reaction is:

$$[2]\quad CaCO_3 + 2\ H^+ \rightarrow Ca^{2+} + H_2CO_3\ .$$

The reaction product, H_2CO_3, is the general form for $H_2O + CO_2$, representing dissolution of carbon dioxide into water.

Acid-Base Accounting

The theoretical background of acid production due to pyrite oxidation and acid neutralization by minerals of the gangue and the country rocks suggests a simple approach, used with some local variations all over the world, to predicting the potential for ARD (e.g., Price, 1997; White et al., 1999). In this memorandum we will use the Australasian nomenclature. The conceptual chemical model is that (1) a sulphide-bearing rock has a "maximum potential acidity" (MPA) that could be released if all sulphide were to oxidize, and (2) the rock may have an "acid neutralization capacity" (ANC) associated with the capacity of the sulphide mineral phases to consume H^+ ions. Both MPA and ANC are reported in conventional units of kg $H_2SO_4/10^3$ kg rock). The overall potential for ARD, then, is modelled as the net acid-base balance of the two estimates, and procedures for calculating the balance are called acid-base accounting (ABA).

When values for the MPA and the ANC are available in consistent units, there are two ways to calculate the acid-base balance: by difference or by ratio. The simplest approach is to calculate a Net Acid-Producing Potential (NAPP): NAPP = MPA - ANC. If the value of NAPP is positive, then the MPA > ANC, and one would expect that the rock does not have the capacity to consume all the possible acidity that could be generated by oxidation of pyrite in the sample. On the other hand, if MPA < ANC, then NAPP would be negative, indicating that the rock would be capable of consuming all the acidity that could possibly be produced by pyrite oxidation.

Alternatively, one can evaluate the acid-base account in terms of the ratio of ANC/MPA. At a ratio of 1, there would be an exact balance of ANC and MPA. If ANC/MPA > 1, the acid-neutralization capacity dominates; conversely, if ANC/MPA < 1, then the acid-generation potential is greater. Corresponding to international best-practice, OTML and their ARD contractors use both methods to screen mine wastes for ARD potential.

To interpret ABA test results, geochemists have developed decision rules that are based on (a) the sort of factor-of-safety approach that is common in geotechnical engineering and (b) empirical evidence of bulk acid generation from sulphide ore bodies around the world. The usual method is to define three classes of results:

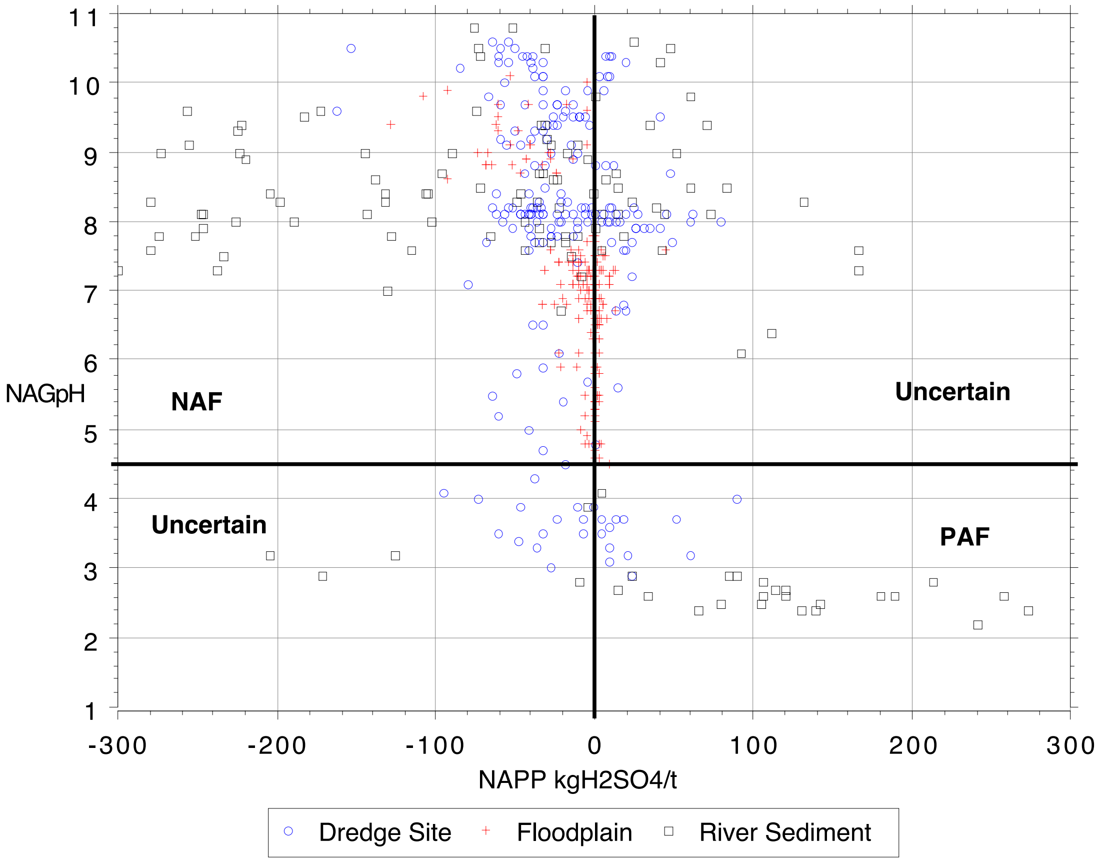
- Potentially acid forming (PAF): NAPP > 0 kg $H_2SO_4/10^3$ kg rock, or ANC/MPA < 1;
- Non-acid forming (NAF): NAPP < - 20 kg H2SO4/10^3 kg rock, or ANC/MPA > 2;
- ARD potential uncertain: 0 < NAPP < -20 kg $H_2SO_4/10^3$ kg rock, or 2> ANC/MPA >1

Although useful and conceptually simple, there are some underlying uncertainties and technical issues associated with the classic ABA procedures. These issues with standard ABA tests led Environmental Geochemistry International Pty. Ltd. (Balmain, NSW, Australia) (EGi) to develop a stand-alone procedure, called the Net Acid Generation (NAG) Procedure, that addresses some of these issues (e.g., Miller at al., 1991; Miller et al., 1997.) Geochemists evaluate static NAG results in two steps. Firstly, one measures the pH of the stabilised solution, and this value is called the NAGpH. Values of pH < ca. 4.5 indicate that the solution has net acidity. Therefore, samples that produce a NAGpH < 4.5 indicate that the sample has the potential to generate net acidic drainage if the sulphides are permitted to oxidize. If samples have a NAGpH < 4.5 and also a NAPP > 0, they are designated as potentially acid forming (PAF). If the NAG solution has a NAGpH > 4.5, the test reactions generated no net acidity, and one generally assumes that such materials would not become acid generating. If such samples also have a NAPP <0, they are designated as non-acid forming (NAF). Secondly, one can form a judgment as to the qualitative level of ARD risk by taking solutions with NAGpH < 4.5 and titrating them with a strong base to determine how much titratable acidity the sample has generated. The titrated acidity of this step is termed the "NAG potential" (or simply "NAG"), and one often will classify samples into "low capacity" and "high capacity" depending on the magnitude of the NAG acidity. This second step may be useful in detailed classification studies and in formulation of engineering procedures for special handling of materials that have the potential to produce high capacities of acidity. The principal, practical advantages of the NAG procedure are that it assesses the net acid-base behaviour of samples in a single test and that it can be performed rapidly and inexpensively, particularly during the operational phases of waste management.

For OTML, as elsewhere, EGi developed a waste-characterization program using NAG testing in conjunction with other acid-base accounting procedures and with an understanding of the lithologies and mineralogies of samples. These conjunctive evaluations allow a project to calibrate the NAG results and provide a crosscheck between independent measures of ARD risk. The ARD Management Program at OTML combines the NAGpH values with the NAPP values for samples, typically illustrating the results with a graph that plots NAGpH on the ordinate and NAPP on the abscissa. An example of such a plot is shown as Figure 1, for samples of Ok Tedi river sediments, floodplain sediments, sand dredge-site samples. This style of diagram represents the state-of-the-art in international practice in acid-base accounting as a tool in characterizing ARD potential.

The static and quasi-static tests are useful screening tools especially for very large mining projects such as OTML, but they do not describe the rates at which ARD might be generated or the leaching rates and fluxes of metals and other solutes generated by sulphide oxidation. To estimate the full-scale behaviour, OTML has commissioned additional studies, including (a) kinetic NAG tests that evaluate the relative reactivities of acid-generating and acid-neutralizing minerals in rock, tailing or sediment samples and (b) slow titration tests to evaluate the rate of alkalinity yield in samples. These tests, originally designed and continuously developed by EGi, are at the forefront of laboratory test methods in the world of mine-waste geochemistry. Furthermore, OTML have commissioned a large number of column-leach tests that simulate field weathering processes by alternating periods of aerobic weathering with periodic rinsing such as would occur as seasonal rains infiltrate the wastes. Temperature is controlled in these tests to improve the simulation of site-specific conditions. Again, the EGi methodology, applied on behalf of OTML, is consistent with world's best practice.

Figure 1 Example of NAGpH – NAPP Plot for Ok Tedi (from OTML/EGi, 2000).



DISCUSSION

1. Sampling Strategies, Analytical Methods, and Interpretive Reasoning

Sampling Strategies and Implementation

The Ok Tedi Mine has a large and growing database of quantitative geochemical testing of overburden, tailing and various types of sediment collected from the drainages, including both channel samples and levee and floodplain sediments collected on traverses outward from the channels.

Waste Rock:

The more than 6,000 sulphur analyses of drill-core samples that are used as the basis of the geochemical block model is among the largest such databases at any mine in the world. Because these samples are tied spatially to the block model for the mine, it is clear that the database is not only large but also represents geologic, lithologic and overall geometric relationships in ways that relate to mine operations and plans. Coupling ARD and other geochemical data to a formal block model used in mine represents world's best practice. OTML continue to extend the number of geochemical tests for ores and waste rocks, however because the initial data set previously developed prior is so large, the number of such mine-related samples increased more slowly than did other classes of materials in FY02. Continued static testing of additional samples, at a modest scale, is an appropriate strategy. Since 2000, OTML have significantly increased the number of dynamic tests of waste-rock columns, a good step toward more complete understanding of waste-rock behaviour, and the current total as of the FY02 Report of 143 column tests of waste rock is a very large number by international standards for mines.

Tailing:

Tailing is a much more homogeneous material (both texturally and mineralogically) than are waste rock materials, so the very large number of samples needed to characterize the nature and distributions of waste-rock geochemistry are not necessary for tailing. Prior to our previous review (Geochimica, 2001), OTML had performed geochemical characterization tests on 450 ex-mill tailing samples, already a large number of coupled ABA and NAG results for tailing by international practice. OTML have almost doubled that total since our last review. Because of potential dispersion of tailing in the fluvial system, additional emphasis on tailing is well placed, raising the new total into the highest range of international practice. Additionally, OTML have very significantly extended the column test program. OTML now have 143 column tests of tailing both (a) to confirm the waste classification based on static testing and (b) to develop data on the potential geochemical evolution of effluents when site materials are allowed to weather. The development of long-term, time-series data on this large set of tailing samples represents world's best practice.

Sediments:

Since our previous review, OTML have significantly increased sampling by OTML of stream sediments. In our view, this is entirely appropriate, and responds to our earlier recommendations (Geochimica, 2001). In FY02, OTML concentrated particularly on the Bige dredge sediments; 68% of the total geochemical-test samples in FY02 were taken from the Bige dredge system. Because earlier data had suggested a potential for ARD associated with a portion of the dredge sediments, we find this emphasis on Bige to be very well posed. In addition to the large number of additional samples for geochemical testing, OTML also have concentrated approximately 60% of the FY02 hydrochemical sampling on contact waters and local groundwaters at Bige. Because such waters represent full-scale field tests of the evolving geochemical system at Bige, OTML's strategy of coupling the geochemical and hydrogeochemical sampling at Bige in FY02 is sound both technically and strategically.

In addition, in 2001 and 2002, OTML has significantly increased its sampling of sediments in the Ok Tedi channel and levee and floodplain sediments along the Fly River. Appropriately, OTML have focussed channel sampling (exclusive of Bige) on bar deposits where field data indicate some localized oxidation of sulphide concentrations. The strategy of collecting hydrogeochemical samples together with geochemical samples in these zones is well posed, as it speaks to the specifically relevant questions of whether the oxidation actually produces acidic waters and to what extent copper is released into and remains in solution. The coordination of geochemical and hydrogeochemical studies, especially together with detailed sedimentological evaluations of the rivers, certainly represents international best practice. Evaluating these results in terms of overall acidification and copper chemistry implies a coordination of the ARD Management Program with the rest of the OTML Environmental Regime, and this technically broad and large-scale focus is the sort of strategy that is needed to develop and sustain long-term human and ecological sustainability on the Ok Tedi – Fly River system.

During FY02, OTML continued developing its database of samples and test results for riverbank levees and floodplain sediments. Because of the identified potential for sulphides to sort hydraulically during fluvial transport, previous reviews had identified hypothetical issues with preferential distributions of sulphides and acid-neutralizing sediments in these zones. Not only have OTML significantly increased the number of samples for both geochemical and hydrogeochemical testing, but the Company also has increasingly developed samples from carefully defined transects. This approach to sampling design is very well posed, as it directly addresses the hydraulic-sorting hypothesis. Again, coupling the sedimentology and fluid dynamics with the ARD evaluation program shows that OTML are developing and implementing strategies for its ARD program that reflect the most modern approaches to site characterization and program planning (Plumlee and Logsdon, 1999).

Hydrogeochemistry of the Open Cut:

OTML has continued to develop its long-term program plan for evaluating the long-term hydrogeochemistry of the open cut. During FY02, OTML sampled pit-wall materials (based on the long-term mine plan) and collected seepage samples over much of the rock–type distribution expected after mining. They have established a monitoring program to evaluate the time-series behaviours of flows into the pit. When coupled, over time, with the numerical model for hydrogeochemistry that is under development for OTML and the finalization of long-term mine plans, OTML will have a data set that is well suited to evaluating the open-cut hydrogeochemistry. Coupling in-pit measurements of waters with mine plans and then projecting the results through equilibrium-based geochemical models represents world's best practice for "pit lakes".

Analytical Methods

OTML's sampling and analysis plans and procedures are compiled and documented in a formal operations manual. The use of this level of documentation is a standard part of world's best practices. We have reviewed the test procedures and the performance of the testing laboratories (Geochimica, 2001). The test procedures are conceptually sound, and both the OTML Environmental Chemistry Laboratory and the contractor facilities of EGi in Australia produce internally consistent data that are reliable for evaluating geochemical processes in Ok Tedi rock, tailing, and sediments. As the developers of the NAG procedures, no one is better qualified to apply and interpret NAG tests than are OTML's lead geochemists at EGi. The basic waste characterization tests are designed to distinguish accurately between classes of possible mine-waste behaviour (i.e., between mine wastes that are likely to become acid generating and those that are not.) The simplicity of the underlying test methods (pyrolysis and automated infra-red spectrophotometry for total sulphur content, pH and simple acid-base titrations for ANC and NAG) provides a high degree of assurance that the accuracy and precision of their static tests will be satisfactory for decision making. EGi have long-term, quality-control data across many, geologically diverse projects on their test procedures, and the analytical laboratories reporting detailed chemical data for the column leach tests have standard quality-assurance plans. The Ian Wark Research Institute conducted mineralogical and other test work for OTML in the course of these investigations. The Institute has a very well qualified professional staff who well known in the international scientific community. They use standard, modern mineralogical techniques, and their instrumental work also is controlled under standard laboratory protocols.

The analytical methods and the manner in which they are related to both sampling and subsequent evaluations, meet all international considerations for best laboratory practice related to mine waste characterization.

Interpretive Reasoning

OTML use technical approaches to evaluating ARD potential that accurately reflect the underlying physical chemistry of sulphide oxidation and the overall mineralogy of the various rocks and sediments. The methods are applied through state-of-the-art laboratory methods and procedures, and the test work was selected and developed by consulting geochemists who are internationally recognized experts with decades of experience, much of which has been developed in Australasian mining systems that are directly relevant to the Ok Tedi experience.

By combining the independent acid-base accounting and NAG tests for waste classification, OTML's program decreases the potential of incorrectly classifying the bulk ARD risk. That is, the joint use of two independent tests decreases the potential for both Type I ("false positive") and Type II ("false negative") errors in waste classification. By using a simple waste-classification scheme (PAF; PAF – Low Capacity; and NAF) OTML can rapidly and accurately distinguish ARD risk. Confirmatory testing and evaluation of metal-leaching rates and fluxes, based on long-term column-leach results, extends the static-test classifications. OTML combine the geochemical test work with field-based data on hydrogeochemistry of contact waters, local pore waters, and ground waters, an approach that is used by the best mine-waste geochemistry programs around the world. Finally, results are combined through empirical models – the basis of which is consistent with theoretical considerations of chemistry, air and water flow, and sediment transport – to provide predictive interpretations. These predictive models are evaluated through an on-going program of verification and validation, using other site-specific results and information from other similar mining sites.

Taken together, OTML's steps in interpretive reasoning reflect good science and engineering and are consistent with world's best practices for evaluating ARD potential and its management.

2. Risk Treatment Options Presently Being Implemented By OTML

The options for managing ARD risk at the Ok Tedi Mine are constrained by a variety of factors:

- The high sulphide content of much of the waste rock and tailing, especially tailing from the hornfels and skarn;
- The large-scale mining and processing methods used for an open-pit mine such as this;
- The instability of slopes in a region of high local relief, seismic instability, and very high rainfall;
- The inability (because of lack of space and slope instability) to establish a conventional tailing impoundment;
- The inevitable process of hydraulic sorting of high-density sulphides during fluvial transport;
- Large climatic variations (associated particularly with the ENSO phenomenon) on time scales of significance to the operations and long-term maintenance of the mine and its downstream impacts.

In judging OTML's strategies for managing ARD risk, the operational, geologic, and climatic contingencies of the site and the Ok Tedi – Fly drainages must be kept fairly in mind. There simply is no merit in comparing ARD management of a very large-scale porphyry copper mine in a high-rainfall tropical setting to, for example, that of small-scale gold mines in arid portions of the Great Basin of the United States or Western Australia. The proper basis for comparison, in our view, is to the principles by which ARD risk can be managed in light of site-specific realities, rather than to specific details that depend on specific matters of operation, mineralogy, and climate. There is no single approach to ARD management that represents a universally applicable international standard.

The basic tool for managing ARD risk at OTML is the "Minus-150 NAPP" mine plan. OTML propose to control the long-term risk of ARD generation during and after the remaining life of mine by controlling the amount of limestone that is mined to protect the acid-base balance of materials at source. This approach is formalised in the ARD management program as the "NAPP Minus-150 Plan", based on a target of 150 kg H_2SO_4/tonne excess ANC in mined materials. Test work to date at the geologically and geochemically analogous Grasberg site in West Papua, Indonesia shows that for limestone addition to be successful at attenuating both acidity and metals release, thorough mixing is required. Layering of limestone and PAF rocks or placing relatively thin (e.g., < 10 m) covers of limestone have very limited utility (and would be impractical as a long-term matter in the waste-rock dumps at Ok Tedi in any event). In addition, significant quantities of limestone (a NAPP of –150 kg H_2SO_4/tonne indicates a 15% excess of neutralization potential) are needed to effectively control the pH condition. This pH control is needed to (a) ensure that acidity is neutralised, (b) control the solubility of metals, and (c) maintain the surface chemistry of the sulphides in a state that favours passivation of the surfaces by armouring with clay minerals.

OTML manage risk through more than an arithmetic model of acid-base accounting. OTML implement the "Minus-150 NAPP Plan" using the continuously updated block model and their empirical geochemical model OkARD (see discussion below) to determine how much additional limestone, i.e., beyond that scheduled in the current mine plan, would be needed to ensure a NAPP of –150 kg H_2SO_4/tonne. Note that the current run-of-mine plan already incorporates some limestone mining because of the geologic structure of the deposit, so the "Minus-150 NAPP Plan" represents an incremental extension of the existing mining program, not an untested hypothesis. Furthermore, OTML also have a significant operational advantage: the deposit has a great excess of limestone beyond that needed to meet the Minus-150 NAPP plan. Therefore, OTML have the option of increasing limestone production yet further if long-term monitoring were to indicate that additional ANC is needed to offset fluvial effects.

The excess ANC implied in the Minus-150 NAPP goal is much greater than likely would be needed were the mine wastes geotechnically stable in situ near the mine and milling facilities, as would be the case for most sulphide mines around the world. The target NAPP of –150 kg H_2SO_4/tonne is based on the need to provide sufficient ANC across all particle-size distributions of waste rock and tailing to be protective against net acid-generating conditions. OTML know from experience and site-specific monitoring that there is hydraulic sorting of particles in the fluvial system down the Ok Tedi and Fly River. Geochemical test work and experience in many other sulphide mines around the world shows that, to be effective, alkaline blending must be thorough across all particle size domains. Detailed test work at the mineralogically, climatically, and operationally similar Grasberg Mine in West Papua Province, Indonesia, shows that a target NAPP of –150 kg H_2SO_4/tonne is sufficient to be protective geochemically against ARD there.

In the last two years, as documented by the FY02 Annual report, OTML also have begun to evaluate engineering alternatives for managing ARD risk at the Bige dredge impoundment. On a track parallel to and using results from the geochemical and hydrogeochemical investigations discussed above, OTML are evaluating the physical hydrology and geotechnical engineering of the dredge sands. The purpose of these evaluations is to evaluate operational and engineering controls that would maintain the water-saturation level at higher levels in the impoundment and that also would reduce the effluent flux that discharges, ultimately back to the Fly River system. The engineers involved in the testing and design work are internationally renowned experts in geotechnical engineering and cover design. OTML's integration of geochemical concerns with geotechnical engineering designs and physical hydrology is now a standard part of best-practice for ARD management programs around the world.

OTML continue to develop the risk-management options by testing predictions against the large-scale, ongoing geochemical and hydrogeochemical monitoring program, discussed above. The willingness to test proposed risk options against real-world, site-specific data is a hallmark of good science and engineering practice generally, and represents world's best practice with respect to ARD management specifically.

3. Design and Results To Date Of The OTML Predictive Model, *OkARD*

OTML and their ARD contractor, EGi, continue to develop the empirical hydrogeochemical model, "OkARD", that evaluates acid generation and solute (particularly sulphate and copper) release in mine materials from the waste-rock stockpiles and tailing downstream through Ok Tedi and Middle Fly River. The OkARD model uses a mass-balance approach for MPA and ANC coupled with a mechanistic model of pyrite oxidation, to track flow and transport of both water and solids and to address the potential for acid generation throughout the fluvial system. Since we last reviewed the status of OkARD (Geochimica, 2001), OTML have begun to incorporate site-specific data from column-leach tests on the relationship of pH and aqueous copper concentrations into the model.

The ability of OkARD to allocate acid-base characteristics down the river system was tested in the FY02 program. Table 3.9.5 of the FY02 Annual Report (reproduced below as Table 1 of this memorandum) presents comparative values of NAPP from the monitoring program with values predicted by OkARD.

Table 1. Comparison of Mean NAPP Measured and Predicted by OkARD (NAPP in kg H_2SO_4/tonne) – after Table 3.9.5, FY02 ARD Annual Report

Depositional Component	**Mean of Measured Values [Std. Dev.]**	**OkARD Predicted Mean**
Mill Tailing	+51 [44]	+47
Waste Rock Dumps	-123 [80]	-88 (Harvey Creek); -151 (Ok Mani)
Ok Tedi River	-181 [355]	-190 (Gorge) -62 (Braided stream)
Ok Tedi Floodplains	-37 [34]	-34
Bige Dredge Sands – Deposited	+16 [29]	+19
Bige Dredge Sands - Discharge	+20 [31]	

The model calibration in FY02 shows that OkARD accurately predicts the <u>average</u> acid-base characteristics of the flow system. This confirms that OkARD appropriately evaluates the general mass-balance characteristics of the system. This should allow OTML to make reasonable judgments about the likely effects of changes in mine plans or other efforts to modify inputs to the system. Because of the large and growing database relating kinetic leaching behaviour in columns to NAPP values, OkARD also can be used to identify the general trends of pH, SO_4 and, ultimately dissolved copper.

However, as discussed in the FY02 Annual Report, the results in Table 3.9.5 show that there is a large dispersion in the measured NAPP values especially along the river system. (Data for which standard deviation exceeds the mean, the ratio commonly called the "coefficient of variation", are considered to be highly heterogeneous.) This implies that whereas OkARD is very accurate, it does not provide results that are precise at the spatial scales of variation in the downstream system. The FY02 Annual Report indicates that future developments with OkARD will attempt to address the matter of spatially ranging distributions of acid-base characteristics. As OTML continue this development, the predictions can be supplemented by using OkARD in a sensitivity mode – i.e., by varying input values and calculating new predictions for locations downstream. In addition, OTML will continue to maintain its ongoing field monitoring and use those results to conduct further calibration tests.

The FY02 report also points out that, to date, OkARD does not include a component for inputs of potentially acidic waters that may be discharged from the open cut after mining. The structure of OkARD is sufficiently robust that it should be a straightforward matter to add that input to the model, once the hydrogeochemical modelling of the open cut has reached the point at which reliable estimates for that new source-term could be made.

In summary, the structure and implementation of OkARD appear to us to be technically sound. OTML are performing calibration tests of the models predictions, as is appropriate for any model, especially an empirical one. The predictive capabilities continue to be developed, as additional column-test data become available. OTML have identified the issue of spatially ranging outcomes that are beyond the current capabilities of the model and are working with their advisors to address that matter. All these steps are appropriate ones for a predictive hydrogeochemical model, so we consider that the model, while requiring continued development, is appropriate and provides useful guidance to OTML at the level of project planning.

4. Recommendations for OTML's ARD Risk-Characterization and Management Program

Based on our review of the FY02 ARD Management Program Report we consider that, in addition to maintaining the proposed monitoring and laboratory-testing programs, the risk characterization program in the next few years should concentrate on:

- Documenting the geochemical and hydrogeochemical consequences of OTML's efforts to meet the Minus-150 NAPP Plan.
- Extending the geochemical and hydrogeochemical testing of downstream sediments, especially the coupled testing and sampling in point bars and the basic characterization work in the levees and floodplains.
- Continuing the laboratory-scale column-leach testing program, especially for stream sediments, to evaluate the potential for release of dissolved copper.
- Continuing development of the hydrogeochemical model (including material and water testing) for the open cut. When the pit model is sufficiently advanced, it – or at least output from its simulations – should be incorporated into OkARD as a new input component.
- Continuing to develop and test OkARD. We recommend specifically that OTML and their geochemical advisors address the impacts of uncertainty in spatial distributions of NAPP and related system chemistry. The simplest approach would be to conduct sensitivity studies of the system using OkARD with ranging inputs to determine the likely range of outputs as a function of downstream location. An alternative approach, which is computationally much more complex, would be to develop an approach that accounts explicitly for the spatial range and distribution of ARD parameters seen within each of the major components (tailing; waste rock; river sediments; floodplains, and dredge sands). Using Monte Carlo simulation or another resampling technique (e.g., bootstrap or jacknife), one can generate models that produce a "probabilistic" estimate of outcomes. Although advocated by some engineers as a general methodology, it is not obvious to us that there are distinct advantages to the "probabilistic" analysis in terms of OTML decision-making that cannot be met with the simpler sensitivity approach more rapidly and at more efficient use of resources.

The principal focus of near- to mid-term OTML risk-management activities, in our view, should be:

- Implementing the Minus-150 NAPP Plan;
- Continuing to evaluate and implement proactive ARD management alternatives for the Bige dredge sediments.

CONCLUSIONS

The principal results of Geochimica's review of the FY02 ARD Management Program Report include:

1. OTML continue to add to the large body of geochemical and hydrogeochemical data for waste rock and tailing. As recommended in 2001, OTML have substantially supplemented their characterization and understanding of river-sediment system, especially with respect to the dredge sediments at Bige. The test program and data evaluation described in the FY02 ARD Management Program Report fulfil our understanding of the objectives of Environmental Regime to (a) characterize the potential impacts of mining due to ARD and (b) report the results annually to the State of Papua New Guinea.

2. The sampling strategies, analytical methods, and interpretive reasoning documented in the Environmental Regime FY02 Annual Report are adequate to the spatial and technical scopes of the Ok Tedi Project and the downstream drainages. The methodologies used in the ARD Management Program are at the forefront of best practice in the world for mining, and the level of detail and completeness of the work is a model with few, if any peers in mining geochemistry.

3. Given site history and conditions - including the very large-scale nature of mining at Ok Tedi and both the geologic (lithologic, geomorphic, and tectonic) and climatic/hydrologic conditions – OTML's risk-management options are appropriate and prudent, corresponding to world's best practices for sites with comparable conditions. Based on our review of the technical data and site conditions and our experience with ARD issues at other mines around the world, the Minus-150 NAPP Plan provides the best possible protection against large-scale acidification in the waste-rock and downstream of the mine. OTML's program to enhance proactive management of potential ARD at the Bige dredge facilities, including engineering alternatives associated with both geotechnical details and hydrology of the facilities, reflects the current state of the art in managing tailing. As they have done with the geochemical site-characterization program, OTML have retained international experts in tailing management to advise them, and the engineers and hydrologists are working very closely with the geochemical consultants. The close and continuing integration of ARD characterization and site-specific engineering activities is a good, specific example of best practice for ARD management.

4. OTML use an empirical model, "OkARD" to predict both the spatial distribution of acid-generating and acid-neutralizing materials in the disposal and riverine systems, and also to estimate the hydrogeochemical consequences (specifically pH and dissolved-copper concentrations) in Ok Tedi and the Fly River. The structure of OkARD is logical, and the model continues to undergo refinement and testing, as is appropriate for any predictive tool. The comparison of measured mean values for Net Acid Producing Potential (NAPP) with those predicted by OkARD (Table 3.9.5 of the FY02 Report) shows that OTML have a predictive tool that is accurate with respect to average values this critical measure not only in the waste materials at source, but also in the downstream portions of the mixed sediment system. The long-term column-leach tests conducted as part of the ARD Management Program show that there are, as expected from theoretical considerations, consistent relationships between NAPP and observed solution chemistry during simulated weathering. Finally, ongoing monitoring of water quality in the Ok Tedi and Fly River systems show that the laboratory-scale leach tests are consistent with the observed hydrogeochemistry of the field conditions. Therefore, we conclude that OkARD is well posed as a model and provides useful information for OTML planning.

5. Further development of OkARD should, in our view, continue, especially along three lines:

a. Addressing uncertainty in spatial distributions of NAPP and related system chemistry.
b. Extending further OTML's efforts to verify and validate the model predictions.
c. Incorporating the output from the hydrogeochemical model of the mine pit as an additional input to the OkARD model system.

It should be noted that OTML and their ARD contractor already had identified very similar recommendations for further development of OkARD.

In summary, based on data and discussions presented in the FY02 Annual Report, Geochimica, Inc. considers that OTML's ARD Management Program is proceeding in a scientifically sound manner that is fully consistent with world's best practices. To maintain its commitments under the Environmental Regime, OTML's ARD management program needs to (a) work with mine planning to fully implementing the Minus-150 NAPP Plan; (b) continue aggressively pursuing its monitoring program, (c) update the OkARD model and simulations as more data become available, and (d) demonstrate, through field sampling and testing, that the limestone blending can maintain alkalinity in the fluvial system.

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