TECHNICAL MEMORANDUM

DATE: 27 February 2001

TO: **Ok Tedi Mining Limited**
Attention: The Manager, Environment

FROM: Mark J. Logsdon (Geochimica)

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

EXECUTIVE SUMMARY

At direction of the Manager, Environment for Ok Tedi Mining Ltd. (OTML), Geochimica, Inc. has reviewed available geochemical data and plans for the acid-rock drainage (ARD) management program. The evaluation included review of documents and data, discussions with OTML's Environmental Staff and the existing project's principal geochemical consultants, Environmental Geochemistry International Pty. Ltd. (Balmain, NSW, Australia), and participation in a two-day workshop in Sydney on the OTML ARD Program.

The principal results of this evaluation of existing information include:

1. ***There is a large body of geochemical data for waste rock and a substantial body of data for tailing. In quantity and quality, we consider that this database is adequate for decision-making and planning. The current ARD management plan will expand the sampling and testing program in both space and time. It is appropriate for OTML to concentrate particular attention on parts of the river-sediment system (e.g., floodplain sediments) that have been sampled and tested to only a limited extent to date.***

2. ***The overburden already in the waste dumps is not acid generating because of the very large excess of limestone that has been mined to date. The Net Acid Producing Potential (NAPP) of run-of-mine waste rock to date is approximately – 400 kg H_2SO_4/tonne. Current tailing is potentially acid generating, having a NAPP of approximately + 50 kg H_2SO_4/t.***

3. ***High flow conditions (under average to above-average rainfall in the drainages) cause hydraulic sorting of sediments based on their effective specific gravity. Pyrite and chalcopyrite have relatively high mineral-grain densities (ca. 5 g/cm^3), compared to alumino-silicates or limestone. Thus, there is a tendency for sulfide-rich sediments to***

accumulate separately from the gangue phases with which they first entered the system.

4. ***Current hydrologic and geomorphic information, sediment mapping, geochemical testing of sediment samples, and observations of in-situ conditions in some reaches of the Ok Tedi indicate that, at least under low-stage stream flows (e.g., during El Niño conditions), there are accumulations of hydraulically-concentrated sulfides in fluvial sediments that are actually acid generating when they are exposed to air. These accumulations, to date, are sufficiently small and localized that they have not led to widespread lowering of river pH and release of copper at elevated concentrations. Geochemical test data also indicate that the dredged sediments stockpiled at Bige contain some materials that are Potentially Acid Forming. Ongoing testing of these sediments is appropriate, and OTML should develop a program to manage the dredge spoils in such a way that oxidation is controlled and risk of ARD minimized.***

5. ***Future drainage from overburden, tailing and mixed sediments in the river depends on the acid-base balance of materials, both as placed and after transport through the Ok Tedi – Fly River system. OTML has developed an alternative mine plan, called the "NAPP Minus-150 Plan", that is expected to control the acid-base balance of waste rock across all size fractions at a level that would protect the waste-rock dumps and Ok Mani storage areas from acid generation. It is very likely that the continued introduction of excess limestone in the headwaters also will provide aqueous- and solid-phase alkalinity to the river, floodplain and dredge sediments, but such benefits have not been quantified at this time. The plan depends on mining larger than previously expected volumes of limestone to maintain the acid-base balance of the bulk-mined rock. The excess alkalinity from this material is expected to be adequate, in conjunction with the alkalinity of the Ok Tedi and Fly River, to offset the net acid-generating capacity of future tailing.***

6. ***Limestone blending, to be successful chemically, requires intimate co-mingling of the limestone with the other rock types. At another mine in very similar rocks, careful limestone blending effectively controls the chemistry of effluents from waste rock (at bench and test-pad scales). Intimate co-mingling of limestone and PAF rock is required: layering and thin covers are ineffective at changing chemical behavior of acid-generating, sulfide-rich sediments.***

7. ***The ability of OTML to successfully blend limestone with the PAF rock at operational scale remains to be demonstrated. At this stage in the ARD management program, OTML's focus is to control ARD generation in the waste dumps and the Ok Mani storage zone. This is the area of the project and the downstream fluvial systems in which OTML can most directly and efficiently intervene in the system to control geochemistry. As part of the ARD management program, OTML and its contractors have developed a mass-balance geochemical model that has the capability of tracking acid loads and acid-neutralization capacity dynamically down the river system. Currently, many of the parameters used in the model are assumed or estimated for the***

purpose of model development, and OTML will need to pursue its ongoing program of field studies to better quantify ARD risk and risk management in the fluvial system.

8. ***Alternative mine plans can have major impacts on projected effluent chemistry and loading rates by changing the NAPP of bulk mined rock. Because there is a very large excess of limestone at the site, OTML has the option (at cost) to control the NAPP of long-term waste rock and tailing by increasing the limestone fraction mined. Based on available data and an assumption that the NAPP Minus-150 Plan can be successfully executed by OTML, it appears very probably that OTML can mine the remainder of the scheduled mineralization without adverse chemical impacts in the rivers in either the near- or long-term.***

9. ***OTML's ARD management plan includes a geochemical / hydrological model of the pit at end of mining. Based on current data, it seems likely that there will be a permanent body of water in the pit after mining ceases. EGi recently initiated a hydrogeochemical evaluation for OTML of the future pit. Their approach, which is based on a geochemical mass balance coupled with equilibrium thermodynamic modeling of the mixed-water results, follows the worldwide standard approach to such studies. Because such models are relatively simple (though not necessarily easy to design and execute), it should be possible for the EGi modelers to consider several cases, allowing OTML to evaluate the hydrogeochemical effects of alternative approaches to closing the pit. Although it is too early to determine the chemical outcome of such modeling effects, it is apparent that the ARD management program is addressing the issue through an appropriate program of study.***

INTRODUCTION

General

The Manager, Environment, on behalf of Ok Tedi Mining Limited (OTML), retained Geochimica, Inc. (Geochimica) to evaluate the company's acid-rock drainage (ARD) program at its Ok Tedi mining operation in Western Province, Papua New Guinea. 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 Ok Mani, Ok Tedi and Fly River drainages. The memorandum also will comment briefly on the proposed program for evaluating long-term water quality in the open pit after mining.

Waste rock and tailing currently are produced from the open-pit mining of the Ok Tedi ore body. Because of high natural erosion rates, a very substantial amount of natural sediment reports to the local rivers, where the local stream hydraulics affect the distribution of natural and mine-produced sediments.

The principal geochemical consultants for OTML are Environmental Geochemistry International (EGi) Pty. Ltd, Balmain (NSW), Australia. EGi has 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. Geochimica's review is to be presented in a technical memorandum.

For this review, OTML provided Geochimica a set of documents (designations in parentheses are the citation forms that will be used subsequently in this memorandum):

- "OkARD 1.1" ***[EGI, 1999a]***
- "ARD program update." Memorandum from S. Miller (EGi) to D. Michelson (OTML) dated 29 November, 1999. ***[EGi, 1999b]***
- "ARD management program – Site visit report." EGi contractor report 2404/446 to OTML, dated May, 2000. ***[EGi, 2000a]***
- "ARD management program – Site visit report, June 2000." EGi contractor report 2404/449 to OTML, dated July, 2000. ***[EGi, 2000b]***
- "Review and update of ARD Issues at Ok Tedi." Memorandum from S. Miller (EGI) to R. Higgins and B. Bolton (OTML), dated 18August, 2000. ***[EGi, 2000c]***
- "Proposal for a study to predict pit water quality in the final void at the Ok Tedi Mine." Letter proposal from J. Jeffery and S. Miller (EGI) to D. Newton (OTML), dated 23 August, 2000. ***[EGi, 2000d]***
- Meeting notes and handouts, prepared by EGi for the ARD workshop in Sydney, Australia, 06-07 November, 2000. ***[EGi, 2000e]***

- "Consequences of ARD at Ok Tedi". Memorandum from S. Miller and C. Rumble (EGi) to J. Veness and B. Bolton (OTML), dated 21 November, 2000. ***[EGi, 2000f]***
- "Final Meeting Minutes, Ok Tedi Mining Ltd. (OTML) Environment Department, ARD Workshop, Novotel Hotel, Sydney, 6-7 November, 2000." Meeting minutes taken by P. Chapman, Chair of Peer Review Group and subsequently revised by him based on input from participants, date 01 December, 2000. ***[PRG, 2000]***
- "Summary report of ARD Workshop 6-7 November, 2000". Memorandum prepared by OTML Environment Department and EGi, dated December, 2000. ***[OTML and EGi, 2000]***

We also have reviewed information in the open literature pertaining both to Ok Tedi geology and to general issues in the geochemistry of acid-rock drainage. Additionally, we have briefly reviewed the Cui-Parker sediment transport model and its review by Professor T.R. Davies and a summary report of the CSIRO modeling of copper geochemistry and transport in the Fly River system (Apte et al., 1995). We participated in the two-day workshop in Sydney that is described in some detail in PRG (2000) and OTML and EGi (2000).

We have relied on the data and other information provided to us as accurate and complete, although we do discuss the data and their interpretations in light of previous experience and general geochemical principals. We have 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. As Geochimica is a U.S. corporation, this report will use standard U.S. spelling and construction (e.g., "sulfide" instead of "sulphur"; minimization of passive voice). We use SI units and the term "tonne" (abbreviated as "t") to represent metric ton (10^3 kg).

Disclaimer

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

ISSUES

1. How comprehensive and how reliable is the existing knowledge of the potential for acid-rock drainage (ARD) and metals leaching?
2. For the major geochemical classes and current geographic loci of disposal, what is the potential for generation of ARD and release of elevated fluxes of metals [especially copper (Cu)]?
3. What is the potential for ARD and metals release if OTML were to successfully implement the "-150 NAPP Mine Plan"? What are the most important uncertainties facing OTML in implementing the "-150 NAPP Plan"?
4. What are the potential geochemical consequences of long periods of inactivity on stockpiles and of extended "El Nino"-type drought cycles?
5. What are the geochemical issues for closure of the open pit, and how are these to be addressed by OTML's ARD Program?

TECHNICAL BACKGROUND

Geology and Mineralogy

The following, very brief description is drawn primarily from Jones and Maconachie (1989), Sillitoe (1993), and Corbett and Leach (1998). Most information in Sillitoe and Corbett and Leach appears to be derived from Hewitt et al. (1980) and Rush and Seegers (1990).

The Ok Tedi mine is the developed portion of the Mt. Fubilan porphyry copper deposit in the headwaters of the Ok Tedi in Western Province, Papua New Guinea. The mine is located at 2000 m above mean sea level, at which elevation mean annual precipitation exceeds 10 m. The mine site is at approximately 5 ° S. latitude and approximately 300 km from the ocean. The combination of high local relief, active tectonics, and tropical, pluvial climate leads to very high erosion rates of both mine-derived and natural sediments.

The ore body is a polyphase, shallow stock and hypabyssal complex of high-potassium, calc-alkaline igneous rocks (Sydney Monzodiorite and Fubilan Monzonite Porphyry) that intrude sedimentary rocks, primarily carbonates, but also including some siltstones. Intrusive relations include both stocks and sills. No coeval volcanic pile is present, but volcaniclastic sediments of the Birim Formation may represent associated extrusive activity. The igneous activity is associated with the Tertiary development of a still-active foreland fold-thrust belt that has developed as the Australian craton collides with an island-arc terrain to the north. In the region, igneous activity extends as much as 30 m.y., but detailed dating studies indicate that the Ok Tedi mineralization is only 1.2 m.y. old, making Mt. Fubilan one of the youngest porphyry copper deposits known.

The ore deposit is classified as a high-gold, porphyry copper based on tectonic setting, intrusive style, ore and gangue mineralogy, and hypogene alteration; near the contacts between the intrusion and the sediments, there is an extensive zone of structurally controlled Cu-Au skarn. The hydrothermal alteration of the intrusives includes an early potassic stage that is centered on the axis of the intrusive complex. Along with the potassium-silicate introduction, including biotite and potassium feldspar, the core of the deposit is characterized by quartz stockworks and sheeted quartz veins and veinlets that produce highly silicified zones. There are late-stage (presumably retrograde) phyllic and locally argillic overprints. There is no significant advanced argillic alteration and (presumably because the intrusions are in carbonate, rather than volcanic superstructure) no propylitic alteration. Sulfate and carbonate phases are locally present in late-stage veinlets. The skarn alteration shows an early, zoned, isothermal structure that is overprinted by metasomatic and retrograde assemblages. The paragenesis of veins in the skarn extends from early garnet-pyroxene assemblages to magnetite-rich veins, then chlorite-sericite-quartz veins, and finally carbonates. The magnetite-skarn zone includes not only massive magnetite with accessory sulfides, but also localized zones of massive sulfide mineralization, including both pyrite and pyrrhotite.

The principal hypogene copper minerals are chalcopyrite and bornite; the bornite to chalcopyrite ratio generally decreases with depth. Pyrite is subordinate to the copper sulfides in the core of the intrusives, but is common in the higher and more lateral phyllic and argillic alteration zones and in portions of the skarn. Magnetite is common in the deeper parts of the core and in portions of the skarn, but, overall, Ok Tedi is not a high-magnetite porphyry system (as, for example, is Grasberg). Marcasite is a common phase, especially from higher levels in the phyllic alteration zones; this may be a retrograde sulfide phase.

The tropical, pluvial conditions of the district are an ideal environment for supergene alteration. Sillitoe (1993) has commented on the general lack of significant supergene enrichment zones in the gold-rich porphyry copper deposits of the Southwest Pacific Rim. Perhaps because it is too young for extensive erosion of the high-level portions of the deposit (and perhaps because Ok Tedi was initially somewhat higher in pyrite than some other such deposits), Ok Tedi is notable for its supergene alteration, including both a high-copper (chalcocite - digenite) enrichment zone and a leached cap that is depleted in Cu, but enriched in Au. [The association of residual pyrite with chalcocite may support the proposition that pyrite was relatively more common at Ok Tedi than at some other deposits where leached zones are absent.] In the leached zones, silicates are highly leached, predominantly to kaolinite, magnetite is partially converted to hematite, and hypogene anhydrite is either hydrated to gypsum or has been entirely removed.

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 gray limestone. In the vicinity of the intrusions, the thickness appears to be less, but thrust faulting probably controls this. Near the intrusives, the limestone is partially altered to marble. The limestone contains only minor chert, and the calcium-carbonate content is very high. The Ieru Siltstone is a fine-grained, clayey siltstone containing clay minerals and residual feldspar and quartz. Near intrusive contacts, the siltstone has been converted to hornfels, with detrital clays and feldspars generally reduced to kaolinite.

The supergene alteration zone and the presence of karst in the limestone indicate that there was a rapid decline of water table in the site. This presumably was related to rapid tectonic uplift in the region.

Prediction of Acid Rock Drainage

Acid-rock drainage (ARD) is the generation of acidic 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 sulfate and sometimes metals and metalloids. The following material is an outline of the theoretical and practical aspects of ARD prediction.

In short, oxidation of pyrite (FeS_2) and other sulfide minerals can produce dilute solutions of sulfuric acid through reactions[1]such as:

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[1] The parenthetical annotations *(s)* and *(aq)* indicate that the chemical species to which they are attached are present in the solid phase or the aqueous phase, respectively. For simplicity of presentation, we have omitted the phase annotations for oxygen (O_2) and water (H_2O). The chemical component H_2CO_3 (aq) represents "dissolved CO_2" and does not distinguish between the various aqueous species in which CO_2 may be present, depending on the pH of the bulk solution.

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

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

$$[2]\ CaCO_3\,(s) + 2\,H^+\,(aq) \rightarrow Ca^{2+}\,(aq) + H_2CO_3\,(aq)$$

Acid-Base Accounting

The theoretical background of (a) acid production due to pyrite oxidation, on the one hand, and (b) acid neutralization by minerals of the gangue and the country rocks, on the other hand, suggests a simple approach to predicting the net acid-generation potential of rocks, i.e., the potential for ARD. The conceptual chemical model is that (1) a sulfide-bearing rock has a "maximum potential acidity" (MPA, sometimes called acid-generation potential, or AGP) that could be released if all sulfide were to oxidize, and (2) the rock may have an "acid neutralization capacity" (ANC[2]) associated with the capacity of the sulfide mineral phases to consume $H^+(aq)$ ions. The overall potential for ARD, then, is modeled as the net acid-base balance of the two estimates. The procedures for calculating the balance are called acid-base accounting (ABA) .

The MPA is calculated by determining, first, the sulfide-sulfur content of a representative sample of rock. Then, from the stoichiometry of Reaction 1 above, the sulfide-sulfur concentration can be used to compute the total number of moles of H^+ ions that could be produced per unit mass of rock if all the pyrite were oxidized. The ANC is measured by adding a known, excess amount of strong acid to a standard rock sample, and then back-titrating with strong base (usually NaOH) to determine how much of the original acid was consumed by the rock.

To calculate the net acid-base account, both the acid-generation potential and the acid-neutralization potential must be reported in common units. It is possible for the common unit to be given in terms of a base or an acid. In North America, the conventional unit is in terms of $CaCO_3$ (equivalent); in Australasia, the conventional unit is in terms of H_2SO_4[3]. In both cases, again by convention, the coefficient of the term is parts-per-thousand (e.g., kg $CaCO_3/10^3$ kg, or kg $H_2SO_4/10^3$ kg rock). Procedures for calculating the MPA and ANC from measured values are discussed in standard references in the technical literature on methods and procedures and on approaches to evaluating the ABA results, including Sobek et al. (1978), Coasttech (1989), Price (1997) and White et al. (1999).

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[2] In North America, the acid-neutralization parameter is called acid-neutralization potential (ANP, or sometimes simply NP), instead of capacity. In this memorandum we will use the Australasian nomenclature, as OTML and EGi use that.

[3] Because the gram-formula weights of $CaCO_3$ (100 g/mol) and H_2SO_4 (98 g/mol) are nearly the same, the numerical values of the MPA and ANC are very nearly the same in either set of conventional units. One can, therefore, compare results calculated from the two approaches without, necessarily, having to undertake laborious re-conversions.

When values for the MPA and the ANC are available in consistent units, there are two ways to calculate the acid-base balance: by addition or by ratio. The simplest approach is to calculate a Net Acid-Producing Potential (NAPP)[4]: 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 ANP dominates; conversely, if NP/MPA < 1, then the acid generation potential is greater. North American geochemists use the ratio method more commonly than do those in Australasia; all practicing geochemists today use the NAPP (or NNP, in North America) approach as at least part of their evaluation.

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 sulfide ore bodies around the world. The usual method is to define three classes of results:

- Likely acid generating (NAPP > 0 kg $H_2SO_4/10^3$ kg rock, or ANC/MPA < 1);
- Unlikely to be acid generating, or potentially acid consuming (NAPP < - 20 kg H2SO4/10^3 kg rock, or ANC/AGP > 3);
- ARD Potential Uncertain (0 < NAPP < -20 kg $H_2SO_4/10^3$ kg rock, or 3>ANC/MPA >1)

In the first case, experience as well as the arithmetic of the ABA implies that one should expect that the rock would be acid generating if allowed to weather. In the second case, there is a factor-of-safety of 20 kg H_2SO_4 excess neutralization potential using the NAPP method (or a ratio of 3 using NP/MPA). Experience indicates that rocks with these factors of safety rarely, if ever, generate significant ARD. If the factor of safety increases well above 20 kg $H_2SO_4/10^3$ kg rock (or above a factor of safety of 3 in the ratio method), the rocks may have sufficient available alkalinity to be able to consume excess acid from other parts of the waste-management system.

However, when the MPA and ANC are nearly in balance, the uncertainties of the analysis and of the kinetics of the field reactions are sufficiently great that most geochemists consider that the static ABA tests alone are not an adequate basis for decision-making. When a significant number of samples fall into this zone of uncertainty, most geochemists recommend that selected samples be tested using kinetic tests such as humidity cells or columns tests. These tests leach

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[4] Equally, one could calculate a Net Neutralization Potential (NNP): NNP = ANC - MPA. This convention is traditional in North America. As expected, when NNP is used in lieu of NAPP, the decision-making criteria are reversed in sign.

larger samples of intact rock through a simulated, accelerated weathering test under variably saturated conditions using artificial precipitation that allows both the acid-generating and the acid-neutralizing capacities of the rock to work together. Generally, such tests run for periods of not less than 20 weeks (and often much longer), with test effluents sampled periodically for a range of chemical parameters used to assess not only net acid generation, but also metals and other solutes that report to the aqueous phase. As one would expect, such tests are both time consuming and expensive, so they must be (a) carefully designed and executed and (b) applied to well-selected subsets of samples. Because of the elapsed time of kinetic tests, they are not suitable for use in operational waste-management decisions, which must be made on time scales of one to a few days to match the handling schedules of an operating mine.

Net Acid Generation (NAG) Test And Prediction Of ARD

The static acid-base accounting (ABA) procedures outlined above are conceptually simple and easily related to the underlying processes of acid generation and neutralization, and they are very widely used. There are, however, both theoretical and practical limitations to the static procedures:

- The laboratory performs the two tests, for MPA and ANC, separately, on different splits of a sample. The acid-base account is an arithmetic construct of two, operationally independent estimates. Thus, the acid-base account does not represent an integrated estimate of the behavior of a rock that contains both sulfide minerals and solid phases that are able to neutralize acidity.

- The static ABA tests do not account for any kinetic effects, either limitations on the rate of oxidation of pyrite or limitations on the reactivity of acid-neutralizing phases. Such limitations may be either physical (e.g., some pyrite or carbonate may occluded in other minerals), or chemical (e.g., intrinsic oxidation rates of pyrite and reaction rates of neutralizing phases). In effect, both tests provide bounding estimates, and one makes a judgment on bulk behavior by balancing the two estimates. This is the reason for the common use of factor-of-safety approaches.

- The static ABA tests do not account explicitly for the actual mineralogy of samples. Because not all sulfides react at the rate or following the stoichiometry of pyrite, and because the ANC estimate is calculated as an equivalent mass of $CaCO_3$ (when no calcite may be present), the tests and, particularly their arithmetic combination, represents a model. This model has the limitations (as well as advantages) of other models: predictions are apt to be most accurate when the field conditions correspond closely to the underlying assumptions and less so when conditions range widely from the assumptions.

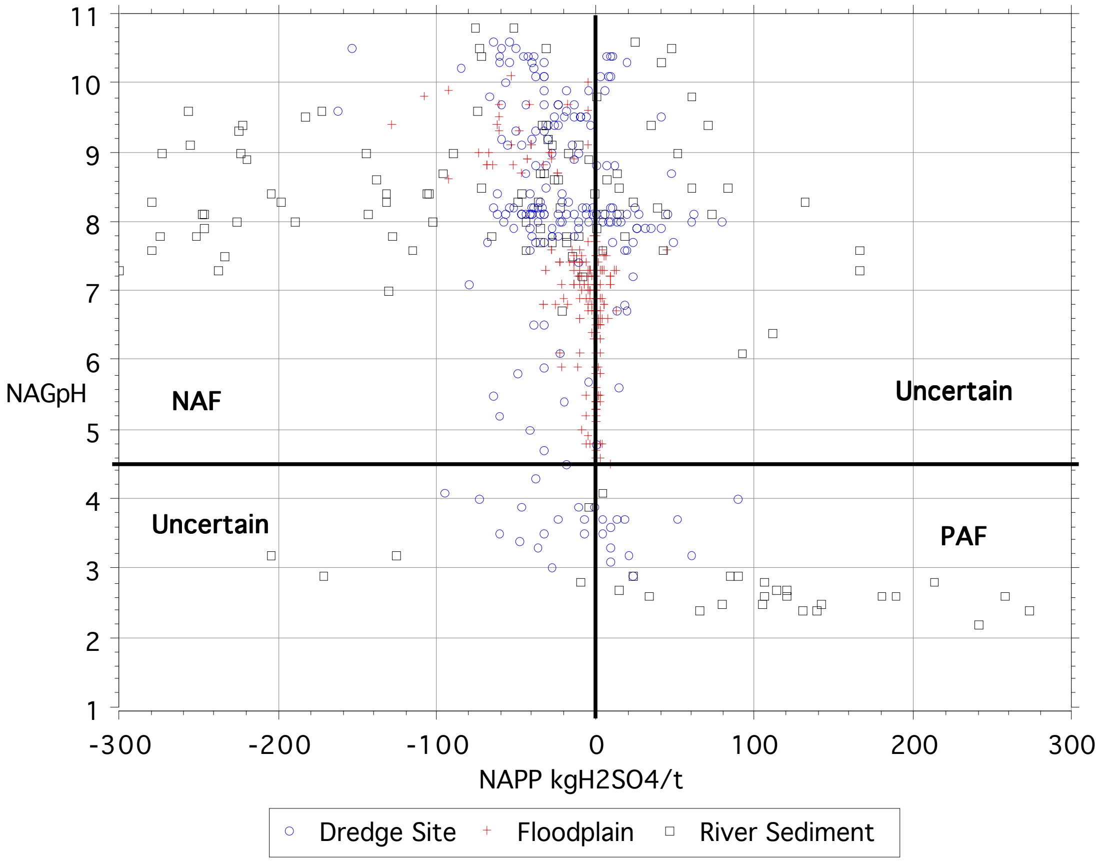
- The sample handling, preparation, and analytical burdens of the analyses are such that there often are rather long turn-around times on the results. This limits the usefulness of the static procedures for operational waste management.

These issues with standard ABA tests led Environmental Geochemistry International Pty. Ltd. (Balmain, NSW, Australia) (EGi) to develop a stand-alone procedure that addresses some of these issues. The EGi procedure, called the Net Acid Generation (NAG) Procedure, is a rapid, low-cost, and simple procedure that adds hydrogen peroxide (H_2O_2, a very strong oxidant) to a sample of waste rock, tailing, or sediment (e.g., Miller at al., 1991; Miller et al., 1997). The hydrogen peroxide solution rapidly oxidizes available sulfide phases to produce sulfuric acid. Because the NAG-procedure sample is a "whole-rock" assemblage, the acidity released by sulfide oxidation may react with the available neutralization potential of the sample. The result is a net solution after reaction that reflects coupled acid generation and acid neutralization in the sample under the test conditions. The net effluent may be either acidic or non-acidic, depending on both the acid-generating and the acid-neutralizing reactions that occur in an integrated sample of natural material. Note that this test makes no assumption about the mineralogy or reactivity of either the sulfide phase or the acid-neutralizing minerals; the test is entirely empirical.

Geochemists evaluate static NAG results in two steps. Firstly, one measures the pH of the stabilized 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 sulfides 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 behavior of samples and that it can be performed rapidly and inexpensively, particularly during the operational phases of waste management.

EGi always develops 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. For Ok Tedi, EGi combined 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.

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



OTML/EGi TECHNICAL APPROACH

Waste Classification

For environmental (and eventually also for mine-planning) purposes, OTML and EGi define three geochemical types of materials on the basis of their potential to generate acidic drainage. These types are defined in terms of their acid-base balance using a set of characterization procedure developed by EGi. The EGi characterization procedures include both (a) an acid-base account (ABA) using maximum potential acidity (MPA) and acid neutralization capacity (ANC) and (b) the Net Acid Generation (NAG) test developed by EGi.

Broadly speaking, EGi distinguishes samples as ***Non-Acid Forming (NAF)*** (i.e., samples that are unlikely to generate net acidity, and which may have sufficient excess ANC from limestone to be acid consuming); and two subclasses of ***Potentially Acid Forming (PAF)*** (i.e., samples with significant potential to form acidity during weathering if the sulfide is allowed to oxidize). OTML use these designations variously for waste rock, tailing, and mixed sediments from the river systems. The OTML mine-planning classification scheme includes:

1. **Non-Acid Forming.** NAF materials can contain minor sulfide sulfur, but also has sufficient ANC from the limestone to neutralize the potential acidity from the inherent sulfide. Note that the limestone *per se* has an acid-neutralizing capacity (ANC) approaching 1,000 kg H_2SO_4/t, which is equivalent to 100% $CaCO_3$ equivalent.
2. **Potentially Acid Forming – Low Capacity (PAF-LC).** PAF-LC materials typically have a NAG-pH in the range of 3.5 to 4.5 and NAG values of < 15 kg H_2SO_4/t. The low NAG values indicate that such materials, even when allowed to oxidize freely, generate a low capacity of acidity.
3. **Potentially Acid Forming PAF.** PAF materials have NAGpH values < 4.5 and NAG values > 15 kg H_2SO_4/t. Such materials are expected to become acid generating if allowed to oxidize, although there may be a lag period before net acid generation occurs. PAF materials may generate significant fluxes of acidity.

The OTML mine-waste classification system is not conditioned explicitly on mineralogic or petrologic descriptions. However, EGi is working through the Environment Department with OTML's geologists, and there will be an effort to coordinate geochemical block modeling with OTML's geologic block modeling. Additionally, Professor Roger Smart (Ian Wark Research Institute, University of South Australia) has begun detailed mineralogical analyses of samples from test columns and field materials, using x-ray, optical, electron-beam and wet chemical extraction techniques to evaluate weathering products.

At this time, the geochemical and geologic block modeling efforts have not yet proceeded to the point at which it is possible to correlate the copper content and the ARD classification. When this is complete, it may be possible to elaborate the existing, tripartite ARD classification into additional components that also address potential for copper loading.

The ARD potential of the intrusive rocks is largely a function of the sulfide-sulfur concentration. All of the hydrothermally altered igneous rocks have low to very low ANC values (generally < 10 - 20 kg H_2SO_4/t), which is typical of the altered igneous rocks of porphyry copper deposits except in propylitically altered zones (which are absent at Ok Tedi). Such low values of ANC generally are related to silicate minerals and have limited availability, especially during the early stages of acidification. In Geochimica's experience, very low values should be considered negligible and not relied on as quantitatively important in the overall acid-base balances. (The multiplication of a low ANC value per unit rock mass times a very large mass of total rock can lead to the conclusion that there is a significant total ANC, but in many siliceous rocks the availability of the ANC is so low that this apparent ANC is actually misleading.) It is reasonable to consider that the ANC of the limestone to be readily available, based on both (a) mineralogical identification of calcium-magnesium carbonates and (b) column and field-monitoring data showing the availability of carbonate alkalinity and base-titratable cations Ca^{2+} and Mg^{2+} in leachates from limestone-bearing overburden and in the Ok Mani and Ok Tedi flows. [Carbonate alkalinity and alkaline-earth cations also are present at discernible levels on the Fly River, but as much of its flow originates from clastic terrains, the alkalinities and Ca-Mg concentrations are lower than those of rivers directly draining the limestone highlands in the upper reaches of the Ok Tedi drainage.]

Geochemical Testing and Evaluation

There is a large and (since initiation of the new ARD management program in 1999) rapidly growing database of ABA, NAG and multi-element whole-rock chemical test work for the Ok Tedi overburden. OTML bases its geochemical block model on comprehensive ABA, NAG, and chemical testing of diamond-drill hole samples collected in 1999 - 2000. The OTML ARD team coordinated sample selection with the OTML geology department so that the spatial distribution of the 1999- 2000 samples would optimize the reliability of the geochemical block model. In addition, since OTML initiated the current ARD program, the mine uses NAG tests on a routine basis for operational waste classification. When OTML completes the current waste-characterization program in early 2001, the database will include approximately 6,000 sets of ABA data that are tied into the quantitative OTML mine-planning block model.

In addition to the waste characterization of ores and overburden, OTML has performed geochemical tests on ex-mill tailing, on samples collected from the Harvey Creek and upper Ok Mani waste-rock stockpiles, and from river sediments along the Ok Mani – Ok Tedi – Fly River drainages. The sediment samples include a spatial range of hydraulic mixtures of mine-derived and natural sediments, but in all cases these represent samples of in-situ materials. There has been a special campaign by OTML to sample and test the dredge spoils at Bige. As of the end of November 2000 the number of samples in each of these classes is summarized in Table 1:

Table 1 Summary of OTML Geochemical Testing (Through November, 2000) [C. Rumble, EGi, personal communication, January, 2001]

Component	**Material**	**Total S**	**ANC**	**NAG**	**Leach Column**	**ABA Characterization By Size Fractions**	**Additional Tests Planned ***
Tailing	Ex-Mill	450	450	450	3		
	Ore-Type	7	7	7	7		
Waste Rock	Drill-Hole	450	450	450			
	Rock Type & Blends	6	6	6	10		
	Block Model	6000	1040				
Waste-Rock Dumps**	Harvey Creek	2	2	2		2	158
Ok Mani Storage	Fluvial Deposits	2	2	2		2	
Mine Reach	Channel-Belt Deposits	2	2	2			
Upper Ok Tedi (Gorge)	Channel-Belt Deposits	27	27	27	1	1	
Middle Ok Tedi (Braided)	Channel-Belt Deposits	5	5	5	4	5	
Bige Dredge Site	Ex-dredge	107	107	107			
	Stockpile	228	228	228	1		
Lower Ok Tedi (Meander)	Channel-Belt Deposits	1	1	1	1	1	
Lower Ok Tedi (Floodplain)	Floodplain Deposits	7	7	7			
Middle Fly (Meander)	Channel-Belt Deposits	2	2	2	2	2	44
Middle Fly (Floodplain)	Floodplain Deposits	295	295	295			

* Additional tests from field-survey samples currently being collected. Will include static ABA and NAG tests. Selected samples may be chosen for additional leach columns and size-fraction characterization.
** Taranaki Dump cannot be sampled due to instability.

To date, the floodplain samples have been coordinated with sediment and ecological sampling already required by the Government of PNG (i.e., samples collected from the "APL" sites). Based on PRG (2000) and OTML and EGi (2000), it is expected that there will be changes to the sampling plan for floodplains to better reflect the flood plain hydrology and geomorphology, as suggested by Professor Dietrich of the PRG.

EGi and OTML have initiated evaluation of the geochemical evolution of effluent during weathering of Ok Tedi overburden, tailing and sediment types through a long-term program of both bench-scale column tests and site-wide water-quality monitoring. As of November 2000, EGi had initiated column-leaching tests on 29 samples. Geochimica understands that that additional leaching columns and sequential and kinetic NAG tests will be commissioned by the

ARD management program in 2001 from the 202 additional samples of waste rock and river sediment that are currently being collected by the OTML Environment Department.

OTML routinely collects water-quality data from streams and seeps/springs at site. Water-quality monitoring demonstrates that there is a major and on-going addition of alkalinity from the active mining and processing areas, as shown in Table 2:

Table 2 Alkalinity Capacity and Loads Along Ok Tedi [mean values, January, 1987 – January, 2000] (EGi, 2000c)

Location	Alkalinity (mg $CaCO_3$/L)	Average Flow (m^3/s)	Load (kt $CaCO_3$/day)
Bukrumdaing * (upstream of mine)	80	34	0.20
Ok Tedi Bridge	480	112	2.14
Ningerum	279	307	9.21
Konkonda	163	969	13.07
Fly River at Kiunga* (upstream of confluence with Ok Tedi)	58	1229	5.80

* Bukrumdaing catchment contains some mineralized rock. Ok Munga, another tributary to Ok Tedi, has alkalinity near 100 mg CaCO3/L. Kiunga is affected by other land uses where the samples are collected, upstream of the town and port.

Alkalinity and flow measurements are maintained now in a project database that allows OTML to track total alkalinity loads through the mass-balance model, OkARD, down the river system as well as to evaluate changes (if any) to the system over time.

Table 2 shows that there is a very large increase in alkalinity down gradient of the mine compared to background values. The mine-derived alkalinity is a significant buffer to pH in the streams. It is likely that this buffering would continue for some time after mining ceases, but it is not currently possible to determine how long and to what extent the incremental alkalinity would be effective.

In 1999 and 2000, OTML staff and contractors initiated a program to map and estimate volumes of mine-waste deposits at critical locations along and adjacent to the Ok Tedi and Fly River. As indicated in Table 1 above, more than 200 additional samples of mine wastes and mixed sediments also will be subjected to geochemical tests. OTML will coordinate the geochemical results with surface-water quality sampling to establish the short-term responses of mine-derived materials and surface-water chemistry. It is expected that this new mapping initiative can be coordinated, at least semi-quantitatively, with earlier OTML sediment studies and with sediment-transport modeling using the Cui-Parker model.

Finally, in memoranda issued in June,1999, November, 2000 and December, 2000, EGi (1999a and 2000g and OTML/EGi, 2000) documented the development of a hydrogeochemical model

("OkARD") that evaluates acid generation and solute (particularly sulfate and copper) release from the waste-rock stockpiles 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. Site-specific data on the relationship of pH and aqueous copper concentrations (as well as broader information from the geochemical literature) will allow OTML to evaluate release of copper in terms of both potential sources and areas that may be affected.

Material Characteristics and Production Schedule

Since the initiation of the ARD Management program, OTML has recognized that the fundamental control on ARD generation in the system is the acid-base balance of materials that are placed in (e.g., waste-rock dumps) or are transported to (e.g., point-bar deposits) vadose-zone locations downstream of the mine. The nature of the heterogeneous materials in the system depends on the initial materials and on the production of various materials by the mine. Tables 3, based on approximately 450 waste-rock samples tested for ANC and NAPP, summarizes ABA results for the major rock types that are mined at Ok Tedi.

Table 3 Acid-Base Characteristics of Waste-Rock Types (EGi, 2000e and S.D. Miller (EGi), personal communication, 05 Feb, 2001)

Rock Type	Total Sulfur (wt%)	MPA (kg H_2SO_4/t)	ANC (kg H_2SO_4/t)	NAPP (kg H_2SO_4/t)
Limestone	<0.01	Nil	810	-810
Siltstone	0.79	24	10	14
Monzonite	0.49	15	18	-3
Monzodiorite	0.57	17	12	5
Endoskarn	1.26	39	10	29
Skarn	5.1	156	5	151
Oxide Porphyry	<0.01	Nil	56	-56

Table 4, based on approximately 450 tailing samples, summarizes ABA characteristics for ore types that report to tailing.

Table 4 Acid-Base Characteristics of Tailing Types (EGi, 2000e and S.D. Miller (EGi), personal communication, 05 Feb, 2001)

Source Ore Type	Total Sulfur (wt%)	MPA (kg H_2SO_4/t)	ANC (kg H_2SO_4/t)	NAPP (kg H_2SO_4/t)
Sulfide Monzonite	0.39	12	10	2
Sulfide Monzodiorite	0.67	21	9	11
Oxide Porphyry	0.54	17	10	7
Mineralized Siltstone	0.96	29	3	26
Sulfide Endoskarn	1.93	59	10	49
Sulfide Skarn	8.92	273	5	268
Oxide Skarn	8.01	245	10	235
Limestone	<0.01	nil	850	-850

As with river-alkalinity data, OTML updates and maintains the database for acid-base accounting results on waste and tailing types, and the updated information can be incorporated into ongoing evaluations and plans, including the mass-balance modeling. The values in Tables 2 to 4 can be considered representative of current conditions and projections in the short- to medium term.

In addition to mine-derived materials, the high erosion rates of the Ok Tedi region deliver substantial loads of non-mineralized rock to the rivers. EGi (1999b) summarized acid-base data for such materials:

Table 5 Acid-Base Characteristics of Eroded Materials and Natural Sediments (EGi, 1999b)

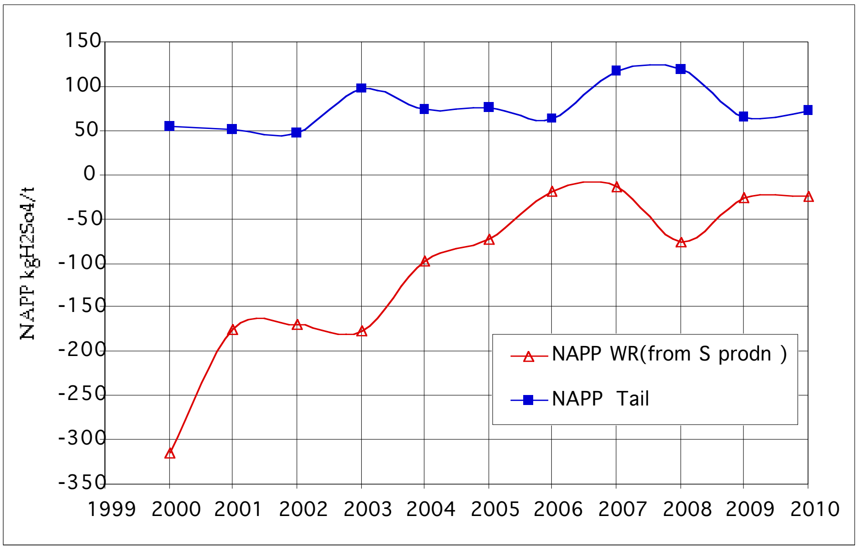
Material Type	Total Sulfur (wt%)	MPA (kg H_2SO_4/t)	ANC (kg H_2SO_4/t)	NAPP (kg H_2SO_4/t)
Vancouver Slide	0.5	15	20	-5
Harvey Valley Erosion	0.5	15	20	-5
Natural Sediments	0.1	3	80	-77

The data in Table 5 are based on only about 10 samples each and should be taken as initial estimates only. OTML currently is sampling across the system to increase the database on the natural materials.

To date, the natural progression of the open-pit mining has ensured that there always would be a significant excess of limestone production in the waste rock, as pushbacks for the pit always include large quantities of unmineralized limestone that surrounds the intrusive bodies and their contact-zone skarns. To date, the average annual waste rock production has had NAPP lower than –400 kg H_2SO_4/t due to the large excess of limestone that has been mined. Because the pure limestone is unmineralized, there is very little limestone in tailing. Consequently the average NAPP for tailing has been approximately +50 kg H_2SO_4/t.

During future mining, there would be less limestone production than there has been to date. Over the same future mining periods, the proportion of sulfide skarn to be mined also will increase. These trends affect the expected NAPP of both waste rock and tailing. If mining and milling proceeded without geochemically guided planning to mitigate risk of ARD, it should be expected that the NAPP of both waste rock and tailing would increase. The projected NAPP for such a "run-of-mine" planning case is summarized in Figure 2.

Figure 2. Predicted NAPP for Waste Rock and Tailing (Assuming Run-of-Mine Production)



The "NAPP Minus-150 Plan"

Because Ok Tedi mines the Mt. Fubilan porphyry copper / skarn deposit, it is clear that the ore body contains substantial amounts of pyrite and chalcopyrite. However, unlike many North and South American porphyry copper deposits, Ok Tedi also mines very large amounts of limestone. OTML, based on conceptual plans developed by EGi, has developed a mine-planning sequence that takes advantage of the available limestone in the deposit to mitigate the risk of ARD generation through the planned remainder of the life of mine. This plan is called the "NAPP Minus-150 Plan" because it sets as the mine-planning basis the generation of an average acid-base balance (reported as Net Acid Production Potential, NAPP) of –150 kg H_2SO_4/tonne. That is, by controlling limestone production, the bulk mined rock would have the capacity to neutralize an excess of 150 kg H_2SO_4 per tonne of rock produced beyond the maximum potential acidity due to the pyrite content of the bulk rock itself. The highly negative NAPP ensures a very high factor-of-safety against acid generation. In fact, a NAPP of –150 kg H_2SO_4/t indicates that the bulk rock should be strongly acid consuming. The "NAPP Minus-150 Plan" couples the mine's geochemical database (through the new and still evolving geochemical block model) with OTML's standard computerized geostatistical modeling. The combination provides an overall mine-planning tool that will ensure pit development and ore processing that will both (a) meet production goals for copper and gold and (b) produce waste rock that is highly certain to not generate ARD. Recent enhancements to the OkARD model allow OTML to track the acid-base balance of sediments through the Ok Tedi and Fly River drainages (OTML/EGI, 2000). These model predictions can be "ground-truthed" (and the model subsequently upgraded) through OTML's on-going programs of sediment mapping and geochemical / mineralogical testing.

The geochemical bases of the "NAPP Minus-150 Plan" are both the theoretical principals of acid-base accounting and, more particularly, the empirical evidence of EGi's long-term (> 5 year) program of geochemical testing of limestone blending at P.T. Freeport Indonesia's high-gold, porphyry copper / skarn deposit, Grasberg, in West Papua (Irian Jaya), Indonesia. The Grasberg deposit is very similar geologically and mineralogically to Ok Tedi. At Grasberg, EGi has developed and documented test work of limestone blending at both bench and pilot scales (up to 500 tonne test pads at site), and the mine (with input and ongoing review by EGi and other consultants) has recently initiated a full-scale blending test. The test program includes both chemical and mineralogical examination. In the pilot-scale and the new field-scale tests, the geochemical investigations are closely tied to hydrological evaluations to ensure that the dynamic system being modeled can be related to the climatic and meteorological conditions of the full-scale mine.

EGi's test work at Grasberg has shown that to effectively control ARD, there must be blending across all size fractions that produces a NAPP sufficient to control the oxidation of pyrites. The Grasberg work shows that NAPP of –150 kg H_2SO_4/t in bulk rock produces negative NAPP values in all size fractions, and this has controlled ARD generation in the Grasberg field tests for the full 3.5 years that the tests have been running to date. Because of the mineralogical and geological similarities between Grasberg and Ok Tedi, EGi has advised OTML that the planning basis for Ok Tedi also should be a NAPP of – 150 kg H_2SO_4/t to ensure adequate blending at all size fractions.

As part of three other peer-review efforts (one for the Government of Indonesia), Geochimica has reviewed EGi's limestone blending test work in detail since the initiation of the field tests in 1996 through results from mid-year 2000. For two of those reviews, we visited the Grasberg site and inspected the field installation and the testing laboratories in both Irian Jaya and Australia. We have convinced ourselves, through these inspections and detailed review of raw data, that EGi's results concerning limestone blending are as described to OTML. Although we have not been to the Ok Tedi site, the peer-reviewed geological literature on the porphyry copper deposits of the southwestern Pacific Rim makes clear that the two deposits are very analogous in terms of mineralogy, genesis, and detailed geologic setting. The ANC values for limestone from the two sites are very similar (both > 800 kg H_2SO_4/t), and the regional geology makes it clear that the depositional environment of the limestones must be very much the same.

DISCUSSION

1. Adequacy of Geochemical Data

General

The Ok Tedi Mine has a large and growing database of quantitative geochemical testing of overburden. The 6,000 sulfur 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 tailing is a much more homogeneous material (both texturally and mineralogically) than are waste rock materials, a total of 450 ex-mill tailing samples also is a large number of coupled ABA and NAG results for tailing. The current 29 long-term column leach tests (of which 10 are leach tests of tailing) is a substantial number of kinetic tests that can be used 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. Based on OTML plans for the ARD management program, the current database will increase in both number of samples tested and in duration of the time-series tests on individual samples.

The general approach to geochemical characterization is very standard and comports with best international practice. We have reviewed (as part of another study) the test procedures and the performance of the testing laboratories. The test procedures are conceptually sound, and the labs 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. As noted in the OTML Peer Review Group's minutes of the November 2000- ARD Workshop in Sydney (PRG, 2000), the basic waste characterization tests are designed to distinguish accurately between classes of possible mine-waste behavior (i.e., between mine wastes that are likely to become acid generating and those that are not), but the factor-of-safety approach geochemists use to classify the test results does not require that there be great precision in the input values of MPA and ANC themselves. 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. The simplicity of the underlying test methods (pyrolysis and automated infra-red spectrophotometry for total sulfur 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 has 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 has a very well qualified professional staff, and they use standard, modern mineralogical techniques, and their instrumental work also is controlled under standard laboratory protocols.

We also satisfied ourselves that the OTML environmental and mine-planning teams are both competent and interested in incorporating modern geochemical data into mine planning tools. The planning basis for the ARD management program since 1999 includes substantial additional monitoring and characterization of river sediment materials. This appears to reflect an appropriate understanding by OTML that the ARD management program requires not only mine planning, but also monitoring of geochemical conditions in the rivers.

To date, the major focus of geochemical characterization has been on source materials (waste rock and tailing). This is a necessary step, particularly for OTML, as it forms the basis for evaluating future mine plans that have prospects of successfully controlling ARD and its geochemical consequences. However, in our view, the source-characterization program needs to be supplemented by additional sampling of in-situ waste materials in waste dumps and river sediment. These additional samples are needed to more fully document geochemical conditions in the mine-area waste-disposal zones and where fluvial processes (especially hydraulic sorting of the heavy-mineral fraction that contains pyrite) may have locally changed the acid-base balance of materials compared to the as-mined (or as-milled) condition. Such additional sampling currently is scheduled as part of OTML's ARD management program.

Geochemical Block Model for Ok Tedi and Implications for Sediments

OTML is in the process of developing a detailed geochemical block model for the existing ore body. At this time, all sulfur data (6,000 data points) have been incorporated, and OTML is completing the final steps of adding the 1024 measured values of ANC. Pending full development of a quantitative model, it should be borne in mind that essentially all overburden except limestone, oxide skarn, and oxide porphyry is expected to be acid generating; tailing also is expected to be acid generating in the long-run if it oxidizes.

TOTML and the EGi geochemists have not yet analyzed kinetic leach tests and field samples to estimate intrinsic oxidation rates (e.g., Ritchie, 1994). Based on data from other porphyry copper sites, it seems likely that rates for Ok Tedi, when developed, will fall into the category of moderate to high (i.e., $\geq$ approximately 10^{-8} kg $O_2/m^3/sec$). This implies that lag times for acid generation (i.e., for those samples with + NAPP) are expected to be relatively short, i.e., probably on the order of months, not years, of exposure to oxygen. Assuming that OTML continues to place waste rock at a NAPP of $\leq$ -150 kg H_2SO_4/t, it is very unlikely that the waste rock and the sediment disposal areas of the mine reach (in which little or no hydraulic segregation is likely to occur) would become acid generating. Lower in the fluvial system, it is possible (even likely) that some sulfide concentrations will occur, as OTML has already documented such occurrences. In these reaches, the acid-generating reactions are likely to be driven by access of the sulfide phases to oxygen. So long as the sediments are fully saturated, the solubility of molecular oxygen in water is sufficiently low that little oxidation can occur. A dissolved oxygen concentration of 10 ppm (near the water-saturation limit) can generate only about 17 mg/L dissolved sulfate, and the oxygen flux in saturated sediments is controlled by diffusion to very low rates of re-supply. In contrast, the oxygen content of air is approximately 200,000 ppm (by volume), and in the vadose zone air can move through sediments by advection as well as by diffusion, rapidly replenishing oxygen lost by reaction with sulfides (or other oxygen sinks).

Given the likely range of oxidation rates of the Ok Tedi pyrite and the subsequent lag-time for onset of acid generation, the principal geochemical vulnerability would be the distribution of sulfide-rich lenses in sediments that are stranded above the water table for extended periods of time during which large surface areas of sediments may be exposed (increasing the total flux of oxygen into the sediments due to diffusion). There are two loci in the Ok Tedi – Fly River system where this might occur. Firstly, pyrite-rich accumulations might occur in bar deposits of braided-stream segments (including in sediments that OTML currently dredges from the stream channel at Bige). As the fluvial structures are apt to be dynamic under normal stream-flow conditions, the exposures of principal concern would be bar deposits during long-term droughts, in which the sediments might be exposed to unsaturated conditions for time periods sufficient to overcome the lag period for onset of ARD. [The stockpiled dredge spoils at Bige constitute a special, anthropogenic class of such stranded sediments.] Secondly, it is conceivable that sulfides could be incorporated into channel-bank deposits of the lower river under high-flow conditions and then stranded in the banks when river stage falls. To the extent that sulfides in the bank deposits are commingled with other, especially fine-grained, sediments, the risk of oxidation would be mitigated. Geochimica considers that the risk of ARD in floodplain deposits is limited for two reasons. The high specific gravity of sulfides suggests that they would not be uniformly distributed across floodplains, but rather would tend to be concentrated in coarser-grained deposits within or near principal channels. Additionally, to the extent that very fine-grained sulfides were distributed to the floodplains, they would be incorporated along with other very fine-grained sediments. Fine-grained sediments have high matric (suction) potentials and tend to remain at high saturation states longer than do coarse-grained sediments. High moisture contents mitigate risk of ARD by controlling the flux of oxygen,

A $pH>7$ is needed to control Cu solubility and promote sorption of Cu-ions onto sediment surfaces such that the concentration of dissolved Cu will be maintained at low levels (e.g., to concentrations of dissolved Cu < 0.010 mg/L). To achieve such a pH, overburden and sediments need to contain a significant mix of limestone. As discussed above, to date, very substantial volumes of limestone have been mined from the Ok Tedi pit, and this appears to have fully controlled ARD on the waste dumps and the Ok Mani sediment storage zone. OTML will use the block model in its mine-planning program to control the NAPP of future waste rock and river-deposited material to levels that are expected to control net acid generation. As discussed above, the mine operations also will continue to provide aqueous alkalinity to the river waters.

2. Current Understanding of ARD Potential of Existing Conditions

Existing monitoring data and field inspections show that, to date, there has been little ARD generated in the system, despite the large total mass of pyrite that has been mined and disposed to the alluvial system. The status of the major segments of the system can be summarized as follows:

- The large amount of limestone that has been mined to date provides the waste-rock dumps and the upstream portion of the Ok Mani sediment storage zone with a very large surplus of acid- neutralization capacity compared to the maximum potential acidity due to the pyrite content of the waste rock. To date, the annual average waste rock has had a NAPP of approximately – 400 kg H_2SO_4/tonne, indicating that the materials would not be acid generating. In fact, such materials have significant potential to be acid-consuming were extraneous sources of acid (i.e., localized areas of massive sulfide in the magnetite skarn zone) present in that portion of the system.

- Tailing discharged to the river system is potentially acid generating, having NAPP values of approximately + 50 kg H_2SO_4/tonne. As the sand- to silt-sized tailing particles move in the river flow, there is a tendency for particles to separate hydraulically, based on their specific gravity (i.e., effective particle density defined by the mineral grain density and the particle diameter). Because the acid-generating sulfides have high densities (pyrite has a density of 5.01 g/cm^3), sulfide particles behave hydraulically is if they were larger particles of more typical rocks (which usually have density near 2.6 g/cm^3). Therefore, there is a tendency for heavy mineral particles (magnetite and sulfides) to be preferentially concentrated in certain energy domains in the stream flow. Similarly, as large fragments of waste rock break down during mass wasting and subsequent river transport, the heavy-mineral fractions will tend to separate hydraulically from the lower-density gangue. OTML has recognized heavy-mineral concentrations in channel deposits at various point in the Ok Tedi, and, under low stage conditions, OTML has identified that there has been localized oxidation of sulfides, with low pH pore waters and secondary salts formed in the vadose zone. OTML, EGi, and the Ian Wark Research Institute currently are investigating the mineralogy of heavy-mineral concentrations in channel deposits to try to distinguish contributions of tailing (entirely liberated sulfide grains) from waste rock (evidence of residual, locked sulfide-gangue assemblages).

  Although the monitoring program has not been in effect long enough yet to be definitive, it seem likely that much, and perhaps nearly all of the observed sulfide oxidation in river sediments occurred during the 1997 El Niño event. Long-term water-quality monitoring data indicate that the pH of stream water at all sampling locations always has remained above pH 7.5, so it is clear that the impacts of sediment oxidation remained local and ephemeral when water levels rose high enough to inundate the localized areas of acid generation.

- OTML has recognized for several years that sediments are accumulating in the stream channel near Bige in quantities sufficient to cause increased frequency of flooding and subsequent stress to vegetative communities bordering the river. To address this issue, OTML dredges the river in the vicinity of Bige, stockpiling the dredge spoil out of the river channel. This program also reduces total sediment available for transport to the lower Fly River system. Sampling and testing of the Bige dredge materials by EGi indicates that a portion of these materials, perhaps on the order of 25%, is designated as PAF when tested by static acid-base accounting and NAG procedures. Were these sediments to remain in the river system and move downstream to deeper water, there would be relatively little risk of actual acid generation because the sulfide fraction of the sediments would remain fully saturated and unavailable to oxygen. However, as the dredged sediments are removed from the river and stockpiled on the banks, the previously saturated sediments will drain, allowing some of the material to be exposed to air in the long run. The lag time for onset of acidity in a portion of these sediments is likely to be on the order of a few years or perhaps even longer, because the sediments need to dewater before the kinetic controls on pyrite oxidation come into play and pyrite oxidation begins to deplete the ANC of the mixed sediment. Although net acid generation is not imminent, so long as OTML dredges the river sediments, this will continue to be a point of potential geochemical vulnerability.

- Riverbank deposits and floodplain deposits in the Lower Ok Tedi and the Middle and Lower Fly River drainages also may receive sulfide minerals as part of the sediment flux. Sampling and testing of bank deposits is very limited to date, but the available sampling (295 tests) of floodplain deposits indicates a very limited risk of acid generation based on underlying mineralogical controls and the acid-base balance of the sediments in those samples. A plot of NAGpH against NAPP for floodplain samples shows no samples that fall into the PAF category, and only a few that would be classified as "uncertain" based on low, but positive NAPP (EGi, 2000e).

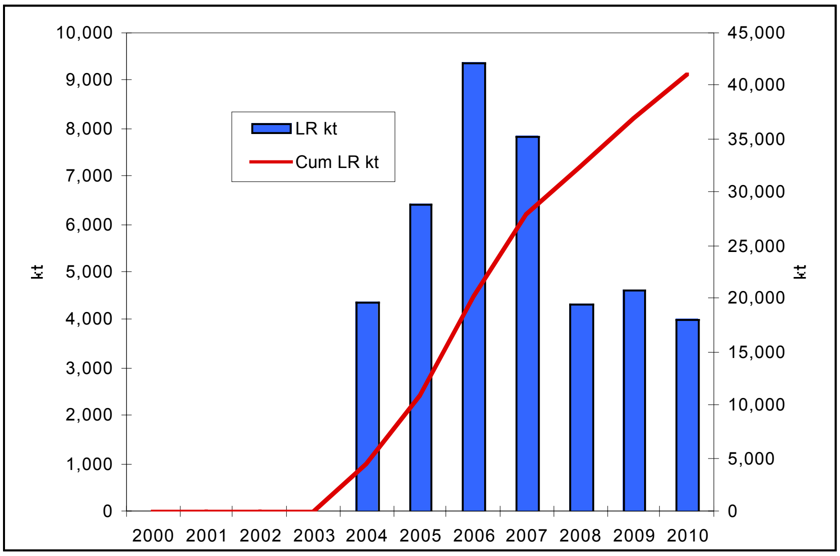
In summary, based on currently available data, the principal area of concern for ARD is the stockpiled dredge samples near Bige. As the Bige dredge samples represent channel sediments, it may be reasonable to infer that geochemically similar materials exist in the channel samples that remain in the system elsewhere, especially farther upstream. Thus, there may be a longer-term risk of localized ARD generation in areas of heavy-mineral accumulations during low-stage flows, such as can be anticipated under future El Niño conditions in Papua New Guinea.

3. NAPP Minus-150 Plan and Potential Impacts If Blending Were Not Successful

OTML proposes 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 formalized 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 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 neutralized, (b) control the solubility of metals, and (c) maintain the surface chemistry of the sulfides in a state that favors passivation of the surfaces by armoring with clay minerals.

EGi has used the current block model and their geochemical model OkARD 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. The additional limestone mining needed to provide the ANC for the "NAPP Minus-150 Plan" is summarized in Figure 3.

Figure 3 Incremental Limestone Mining for NAPP Minus-150 Plan [LR: Limestone Requirement] (EGi, 2000e)



Note that the current run-of-mine plan already incorporates some limestone mining, because of the geologic structure of the deposit. Therefore, the "NAPP Minus-150 Plan" is not a totally radical departure form OTML plans, but rather represents an incremental mining approach that can be incorporated into the mine plans using available equipment and personnel. The current run-of-mine plan includes producing 54 Mt limestone from 2000 to 2010. Therefore, as shown in Figure 3, the additional requirement for the NAPP Minus-150 Plan would be 41 Mt, beginning in 2004.

Test pad data at Grasberg and experience elsewhere in the mining industry show that ineffective blending (e.g., covers, layering, or limestone blends that are too lean) will lead to effluents that are low in pH and high in Cu and some other metals in materials that are allowed to oxidize. For the Ok Tedi deposits, this risk would include post-2000 materials in the waste-rock dumps, the Ok Mani sediment storage area, and subaerial portions of the channel deposits, including Bige dredge spoils. Even blends that are successful at controlling acidity, pH, and metals concentrations may produce sulfate concentrations on the order of several hundred to perhaps 2,000 mg/L, because the sulfate concentration of the effluent will be controlled by gypsum solubility after reactions between the high SO_4^{2-} solutions and the high Ca^{2+} solids.

There are two principal risks in the NAPP Minus-150 Plan for OTML:

- Operations cannot sustain the NAPP Minus-150 production over the life of the mine. Based on current knowledge, there is nothing in the deposit geology or geochemistry that should cause this, so such a situation would have to be caused by engineering or economic factors that are outside the geochemical domain.

- The design-basis NAPP of the blended material will not be maintained across all particle sizes when the rock becomes part of the active fluvial system. In a sense, this would constitute an "un-mixing" of the originally blended materials. At this time, there is no operating mine of the scale of Ok Tedi that intentionally blends limestone with PAF rock and then disposes the mixed materials into a high-energy river system. Thus, there is a physically plausible failure mechanism (hydraulic sorting), and there is no demonstration that the proposed system can be effectively implemented in the long run. On the other hand, OTML has been blending limestone in the waste rock for a number of years, and this has successfully controlled ARD in the waste-rock dumps and Ok Mani storage area. The NAPP Minus-150 blend is lower in limestone than the historic average at Ok Tedi, but it still represents as very substantial excess of acid-neutralization capacity.

Furthermore, OTML also has a significant operational advantage: the deposit has a great excess of limestone beyond that needed to meet the NAPP Minus-150 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.

4. Geochemical Issues of Massive Sulfide-Skarn Zones

For blending to be successful with reasonable proportions of limestone, the maximum Sulfur concentration of rock reporting to the waste-rock dumps probably should be kept under approximately 5 wt% Sulfide-Sulfur in the zone of active bulk dumping and under about 2.5 wt% on final surfaces and open slopes at the end of mining. [It is understood that the "final surfaces" at the end of mining may not be stable at Ok Tedi, however, it still would be prudent to finish the waste rock dumps with relatively low-sulfur rock if this can be done practicably.] OTML will integrate the Sulfur block model, which is near completion at this time, into the OTML mine-planning tools. When this is complete, OTML should be able readily to quantify the tonnages and a production schedule for massive sulfide-skarn materials and then develop a specific plan for mining and managing such materials.

The blending requirements for rock with >10% Sulfide-Sulfur would be very large. This signifies that OTML may have to develop a qualitatively different disposal plan for the very high sulfide zones that will be encountered locally. Geochimica recommends that OTML and EGI, in conjunction with the mine geologist and engineering planners, consider the possibility that such high-sulfur rock would be "special handling" overburden that may need to be placed and encapsulated in a waste-rock dump (or another special storage area) in such a way that oxidation and generation of leachate is very unlikely. To date, such "special handling" materials have not been mined in large volumes from the Ok Tedi open pit, and no "special handling" procedure has been developed yet.

5. Geochemical Consequences of Long Periods of Inactivity on Stockpiles

Available field data from other porphyry copper deposits and theoretical considerations suggest that prolonged exposure of large (especially high) waste-rock stockpiles could allow advective air flow to become established within the dumps. Because pyrite oxidation rates are relatively low (e.g., $-d[py]/dt = 10^{-6.0 \pm 0.5} [O_2]$ (mol/m^2/s), Kamei and Ohmoto, 2000), pyrite must react for some time before large heat fluxes, capable of driving convection, can be generated. Therefore, significant potential for convection in waste-rock dumps arises when stockpiles are inactive for some number of years, as after mine closure or following long periods of inactivity.

If the limestone blending were effective at preventing pyrite oxidation (as EGi have suggested may be the case for blended rock at Grasberg), then there would be little or no excess heat generated in the waste rock. In this case, the only advective flow would be that due to air-pressure differential (e.g., wind against long dump faces), and the issue would be negligible. However, if the limestone blended were not effective at preventing sulfide oxidation, then pyrite oxidation in the vadose zone of the waste rock could generate heat within the pile sufficient to cause thermal convection. This would greatly (by probably an order of magnitude or more) increase the proportion of the waste rock that would subject to oxidation compared to that which would oxidize under purely diffusive conditions. Larger volumes of overburden subject to oxidation, in turn, would increase acid generation, leaching of metals, and total solute loadings to surface or ground waters.

The likelihood of this issue becoming a true problem is less at Ok Tedi than in some other systems because of the metastable nature of the waster rock and the very high precipitation regime. If the NAPP Minus-150 Plan were successfully implemented, the risk of advective/conductive air flow would be greatly reduced by controlling the potential for rapid and extensive pyrite oxidation. However, we have not yet seen an analysis that shows the matter has been evaluated quantitatively, and we consider that it would be well for OTML's ARD management program to address this question.

6. Geochemical Aspects of Closing the Mine Pit

OTML's ARD program includes a geochemical / hydrological model of the pit at end of mining (EGi, 2000d). Based on current data, it seems likely that there will be a permanent body of water in the pit after mining ceases. EGi recently initiated a hydrogeochemical evaluation for OTML of the future pit. Their approach, which is based on a geochemical mass balance coupled with equilibrium thermodynamic modeling of the mixed-water results, follows the worldwide standard approach to such studies. Because such models are relatively simple (though not necessarily easy to design and execute), it should be possible for the EGi modelers to consider several cases, allowing OTML to evaluate the hydrogeochemical effects of alternative approaches to closing the pit. Although it is too early to determine the chemical outcome of such modeling, it is apparent that the ARD management program is addressing the issue through an appropriate program of study.

CONCLUSIONS

The principal results of Geochimica's evaluation of existing information include:

1. There is a large body of geochemical data for the overburden and a substantial body of data for tailing. In quantity and quality, we consider that this database is adequate for decision-making with respect to the current situation at site and to allow prudent planning for future mining. The geochemical testing program is closely coordinated with OTML's mine planning. OTML is using the operational geochemical data to

construct a block model for the existing overburden stockpiles. In addition to the large static-test database, OTML has 29 long-term column leaching experiments. OTML's geochemical contractor, EGi, has combined the geochemical data with other environmental and mine-planning data to formulate a predictive model of mass loading for the Ok Tedi – Fly River system ("OkARD"). The principal shortcoming of the current database is that there are relatively few samples of river sediments. OTML's ARD management program addresses the limited river data by proposing an active program of sediment mapping and sampling that already is underway. The data that will be generated from this sampling program, together with the long-term water-quality monitoring of OTML, will allow the company to calibrate the OkARD model.

2. The overburden already in the waste rock dumps and the upper Ok Mani sediment storage area is not acid generating and does not release substantial loads of sulfate, copper and other solutes into the river systems. The control of ARD is due to the very high ANC of the limestone present in the waste materials. Currently, waste rock has a Net Acid Producing Potential (NAPP) of approximately – 400 kg H_2SO_4/tonne. Because the milling process concentrates sulfides (the source of the copper and gold) and minimizes the diluting effect of gangue minerals, tailing has a different geochemical nature. Current tailing at Ok Tedi is Potentially Acid Forming, with a NAPP of approximately + 50 kg H_2SO_4/tonne.

   OTML has identified localized areas of sulfide concentration in channel sediments of the Upper and Middle Ok Tedi, and some of these zones show evidence of incipient oxidation. Under low-stage conditions, OTML has identified low-pH pore water and secondary salts in partially saturated sediments. Water-quality monitoring indicates that the effects of these zones are limited and ephemeral to date. Sampling and testing of dredge sediments for Bige show that a discernible fraction of these sediments, perhaps as much as 25%, is Potentially Acid Forming and may become a source of poor-quality drainage in the future if the dredge stockpile is allowed to oxidize.

3. Future mine plans call for mining less limestone and more sulfide skarn than OTML has done to date. These changes would be expected move the waste rock and the tailing toward higher NAPP values. Near the margins of the Ok Tedi intrusives, there is a zone of skarn containing massive-sulfide mineralization. In this zone, the sulfide concentrations may be sufficiently high that limestone blending of such materials is impracticable or ineffective. Geochimica recommends that OTML consider whether the high-sulfide skarn requires a selective mining and placement strategy.

4. To limit the risk of ARD developing in the future, OTML and their geochemical advisors, EGi, have developed a mitigation plan, called the "NAPP Minus-150 Plan". The NAPP Minus-150 Plan is an alternative mine plan that calls for intentional mining of additional limestone to produce a bulk waste rock that has a Net Acid Producing Potential of – 150 kg H_2SO_4/tonne. OTML and EGi have set the target of –150 kg H_2SO_4/tonne to ensure that there will be negative NAPP values across all particle-size fractions of the Ok Tedi rock in the waste-rock dumps and the Ok Mani storage zone. This target was developed by EGi on theoretical arguments and also on the basis of

empirical evidence from a similar porphyry copper / skarn deposit (Grasberg, West Papua (Irian Jaya), Indonesia).

Limestone blending, to be successful chemically, requires intimate co-mingling of limestone with PAF rocks at ratios of ANC to MPA that are adequate to ensure that net acid generation will not occur. We recommend that OTML determine whether rocks higher in sulfur than 5% should be selectively mined and disposed under conditions of special handling that may need to be designed for Ok Tedi.

5. At bench and test-pad scales in the Grasberg testing program, blending with limestone controls the chemistry of effluents effectively when the NAPP of the mixture is < -150 kg H_2SO_4/tonne. Intimate co-mingling of limestone and PAF rock is required: layering and thin covers are unlikely to be effective at changing chemistry under dynamic weathering conditions in the field. The effects of hydraulic sorting in the Ok Tedi and Fly River on maintaining the design-basis limestone blend needs to be evaluated. Further development of the OkARD mass-balance model and ongoing sampling and testing activities in river-deposited materials will allow OTML to evaluate this issue.

6. Although advective / conductive air flow is not seen today and is not anticipated in the waste rock dumps at Ok Tedi if the NAPP Minus-150 Plan is effective, we recommend that OTML consider the potential for convection to be established and determine whether any additional aspects of waste management are needed to control this hypothetical risk.

7. Alternative mine plans can have major impacts on projected effluent chemistry and loading rates. OTML has a major advantage over most porphyry copper mines in the world in the excess limestone of the site. If monitoring and testing show that the currently planned level of limestone mining is not adequate to control ARD, the mine has additional limestone that can be used. There are, of course, costs to such additional mining, and it should be invoked if and only if monitoring data shows that the protection anticipated from the NAPP Minus-150 plan is not being achieved.

8. EGi recently initiated a hydrogeochemical evaluation of the future pit. Their approach, which is based on a geochemical mass balance coupled with equilibrium thermodynamic modeling of the mixed-water results, follows the worldwide standard approach to such studies. It should be possible for the EGi modelers to consider several alternatives for pit closure, allowing OTML to evaluate the hydrogeochemical effects of alternatives. Although it is too early to determine the chemical outcome of such modeling effects, it is apparent that OTML's ARD management program is addressing the issue through an appropriate program of study.

In summary, based on available data and an assumption that the NAPP Minus-150 Plan can be successfully executed by OTML, it appears very probable that OTML can mine the remainder of the scheduled mineralization without adversely affecting the chemistry (e.g., by generating low-pH /high dissolved copper) of the Ok Tedi – Fly River system generally in either the near- or long-term. To confirm this overall conclusion, OTML's ARD management program will need to aggressively pursue its monitoring program, update the OkARD simulations as more data become available, and demonstrate, through field sampling and testing, that the limestone blending can maintain alkalinity in the fluvial system.

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