Benefits of timely and valid geochemical characterisation of mine waste for Life of Mine and Closure Planning: A case study of Newmont Boddington Gold Mine in Western Australia

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1. Abstract

The extraction of minerals often involves the removal and storage of large quantities of waste in the form of waste rock and tailings. These waste materials may have the potential for acid or metalliferous drainage. Many of the long-term environmental impacts associated with mining arise from the geochemical characteristics of these wastes. A significant proportion of mining costs and liabilities is linked to the storage of these wastes during the life cycle of the mine, especially at the closure and post-closure stages.

While geochemical characterization is usually conducted in the early stages of mine planning and continues during operations, in many cases the process is driven by the need to assess relevant mineralogical composition that has economic value, with less emphasis on the key environmental elements that affect the long-term storage and impacts of waste materials during the life of mine, closure and post-closure.

There are many examples in the mining industry where the misclassification of potentially acid forming and non-acid forming materials, have had significant adverse operational and environmental implications during the life of mine. Environmental aspects of the geochemical characteristics of waste, particularly in terms of acid generation and other metalliferous drainage potential, are also very important during closure and post closure and need to be given sufficient attention early in project design and development, and as the process progresses.

Acceptable environmental performance at mine closure and post-closure is critical for the continuation of mining companies' social licence to operate, and regulatory agencies in many countries now require a detailed closure plan that includes potential post-closure performance indicators, or closure criteria, prior to mining approval and development. Closure and post-closure costs and performance go beyond the physical life of a mine and in many cases must be dealt with in perpetuity. Unfortunately, most long-term environmental issues associated with mining arise from geochemical characteristics of the waste in storage, which may not have been given sufficient attention during the early stages of mine planning and development.

At Newmont, an important element of closure planning now involves detailed assessment of geochemical parameters of mine waste that affects closure performance. This paper discusses the significant benefits of designing and implementing a geochemical characterization program for life of mine, closure and post-closure planning. To illustrate this, a case study of a Western Australian mine site that has the potential to store over one billion tonnes of waste is discussed. Key risks and opportunities for understanding the specific and subtle issues critical for making management decisions are also discussed.

1. Introduction

Newmont Boddington Gold (NBG) operates a gold mine, located 17 km northwest of the town of Boddington, and 120 km southeast of Perth, in Western Australia. Open pit mining of an oxide gold resource operated between 1987 and 2001, along with a small underground mine and small volumes of basement ore. In 2006, NBG undertook an expansion program that will take gold production to one million ounces per annum. The project was commissioned in 2009 and production is at the ramp up stage. Associated with an expansion program involving large open cut pits, is the requirement to store the large amount of waste rock and tailings materials in an environmentally sound and sustainable way. Numerous investigations have been conducted at various stages since the feasibility stage to ensure the economic and environmental sustainability of the operation.

During the early operational phase, NBG is undertaking further studies to refine and update the feasibility investigation findings and also to develop new innovative approaches for investigating and managing the significant quantities of waste generated from the operation. Central to these ongoing studies is the need to develop an integrated life of mine and closure plan that will ensure efficient and cost effective operation of the mine both in the short and long-term. In achieving this goal, the geochemical characteristics of the mine waste materials were considered critical, as this is a major factor that influences the storage performance of waste rock and tailings facilities, as well as groundwater and surface water quality. Furthermore, Newmont recognises that a significant proportion of mining costs and closure liabilities is linked to the storage of these wastes during the life cycle of the mine, and at closure and post-closure stages. Globally, Newmont's closure liabilities amount to several hundred million dollars (Dowd, 2002; Dowd and Slight, 2009). This proportion of closure liability is also within the range for almost all mining companies of its size and above (ICMM, 2005).

To mitigate the closure liabilities, Newmont's internal closure guideline has strict requirements for the development and review of closure plans at all stages from feasibility as well as periodic reviews of closure plans during operations to ensure consistency with life of mine planning, changes in operations, stakeholder expectation, regulatory requirements and their impact on costs. The aim is to develop a company-wide system, where closure planning is embedded in the day to day activities throughout the life cycle of all mining operations.

In the case of NBG, the size of the operation and the potential for future expansion requires a thorough reassessment of the key closure assumptions and approaches at this early stage of operations in order to:

- Identify key components of the current closure plan that can have significant impact on future liability.
- Ensure that current and future life of mine activities and operational decision are consistent with progressive closure requirements and closure criteria.
- Provide the necessary input for the development of a realistic closure liability / cost estimate.
- Understand and manage potential environmental impacts of the mine expansion that are likely to require attention at the closure stage.

2. General site description

Newmont Boddington Gold mine is located about 120 km south of Perth in Western Australia (Figure 1). The site experiences a Mediterranean type climate, characterized by mild to hot dry summers with occasional storms between November and April and cool wet winter months (May to October). Maximum summer temperatures are typically in the 30's (degree Celsius), while overnight winter temperatures are typically less than 10 degrees Celsius. Average annual (1984-2009) precipitation for the site is 765 mm, of which 75% occurs in winter. Total annual evaporation is always higher than rainfall and has an annual average of 1,400 mm, with 80% of evaporation (1,046 mm) occurring in the period from the start of October to the end of March. Although the site experiences annual net positive evaporation, average precipitation exceeds average evaporation in the winter months.

The NBG site is located within the Saddleback greenstone belt at the southwestern border of the Yilgarn craton. From a geochemical point of view, the most common sulphides across the deposits are chalcopyrite, pyrrhotite and pyrite. Less common sulphide occurrences are molybdenite, arsenopyrite and sphalerite. The sulphur (S) distribution with the deposit varies over a wide range. At the southern part (of Wandoo North Pit) total Sulphur/Copper (S/Cu) ratios are low and coincident with chalcopyrite. In the northeast direction, the ratio increases and most sulfur in these zones is inferred to be related to pyrite and arsenopyrite. A comparable trend is evident in arsenic distributions, with higher arsenic concentrations coinciding with higher S/Cu ratios in the northeast.

In summary, where sulphides occur in the andesite and diorite waste rocks, they are invariably associated with sulfur values less than 0.5%, and $CaCO_3$ contents less than 1%. Weathering of these types of waste rocks therefore corresponds to the oxidation of trace amounts of sulphides in a groundmass where circum-neutral buffering rests chiefly with the fast-reacting calcites initially, followed by the slower-reacting primary silicates.

Figure 1 Boddington Mine location map

3. Geochemical characterization of mine waste materials

Geochemical characterization of mine materials usually forms an integral part of mine development from exploration through feasibility and mine planning and continues during operations stages. While environmentally related testing is conducted as part of this process, in many cases the process is driven by the need to assess relevant mineralogical composition that has economic value and the key environmental elements that affect the long-term waste storage are given less importance than they deserve. The environmental aspects of the geochemical characteristics of waste, particularly in terms of acid generation and other metalliferous drainage potential are very important during closure and post closure performance and require sufficient attention early in project design and development and throughout operations stages.

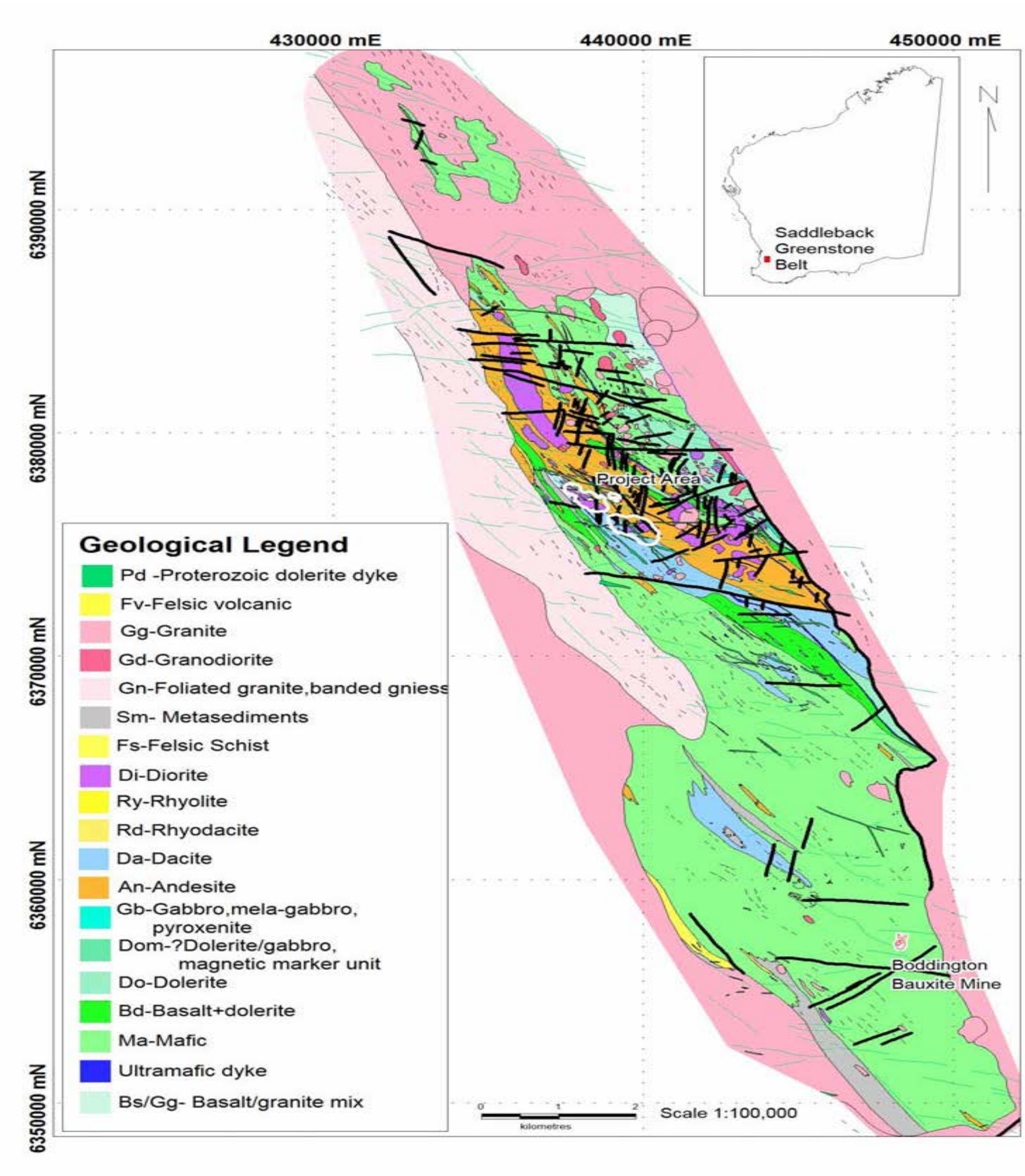

Figure 2 Geological characteristics of the site

3.1 Static tests

The most common approach for assessing the acid-forming tendencies of mine waste materials employs static tests based on the conventional Acid Base Accounting (ABA) methodology. Common indices developed from this approach to quickly classify materials include Maximum Potential Acidity (MPA), Acid Neutralisation Capacity (ANC), Net Acid Producing Potential (NAPP), and Net Acid Generation (NAG). ABA classifications for mine-waste samples are generally divided into three categories including Potentially Acid Forming (PAF), Non Acid Forming (NAF) or Uncertain (UC). Some of the empirical relations used in interpretation include the ANC / MPA ratio, and the NAPP (which is determined by MPA – ANC). If the ANC / MPA ratio is greater than 2, then the tested sample is generally considered to have low potential to acidify, and so may be classified as NAF. This ANC / MPA ratio of 2 applies especially when the ANC is dominated by the dissolution of carbonates like calcite.

The attractiveness of this approach is that static tests are relatively quick, and inexpensive to perform. In terms of management decision making, the interpretation of the results from static tests is generally straight forward. However, this is not the case for the results of NBG waste rocks tests, because of the contribution made to circum-neutral buffering by primary silicates which is not fully accounted for in the conventional suite of static tests employed in ABA assessments. This is particularly important where the rates of sulphide oxidation are slow, since there is, in fact, a sizeable reserve of alkalinity forms in NBG waste rock, arising from the hydrolysis and dissolution of primary silicates, which is effective in maintaining circum-neutral-pH. The net outcome from static testing may then be that a mine waste sample (containing trace sulphides) is classified as PAF when it will actually never acidify as its weathering proceeds to the full decomposition of the sulphides.

Misclassification of PAF and NAF varieties of mines wastes is not uncommon, and can lead to significant adverse operational and environmental implications during the life of mine and beyond. Generally speaking, it is more often the case that a given lithotype may be classified initially as NAF, but is actually PAF, and so becomes a source of acidic drainage. A common situation here is where the ineffectiveness of strongly ferroan forms of carbonates (e.g. siderites) may result in ANC values being significantly overestimated, so that an invalid NAF classification ensues. Given the significant quantities of waste rock materials at NBG, it is important that mine waste classification is valid for effective life of mine planning.

Although a conservative approach to geochemical classification of mine wastes is environmentally sound, this should not be taken to the extreme. Misclassification through over application of the precautionary principle may lead to significant storage costs that could be avoided (for example mine wastes may be incorrectly classified as PAF, despite being NAF). In this case, instead of there being a large quantity of PAF materials requiring isolation, there would be a large quantity of NAF materials suitable for use in other, cost effective operational and progressive closure works. This is a key challenge facing mine waste management at NBG, and reflects the trace occurrences of sulphides in the andesite and diorite waste rocks which contain only trace amounts of calcites.

3.2 Kinetic tests

To ensure the full benefits of geochemical classification, testing is often extended to include kinetic tests. By subjecting samples to simulated ambient weathering conditions, the rates of sulphide oxidation, carbonate depletion, acid generation and metal leaching may be determined to assess the dynamics of weathering in a way that cannot be predicted from static tests alone (Bradhum and Caruccio, 1995). Results of NBG kinetic testing are discussed in the following sections.

4. Geochemical characteristics of NBG waste materials

The need to ensure environmental compliance of the significant volumes of waste material was recognised at the early stage of the NBG expansion project. Hence, detailed geochemical characterization of the various lithologies was conducted early in the feasibility stages. Comprehensive information on static geochemical data which defines acid generation potential for all of the major materials was developed using drill core samples. In general, NAPP data derived from Total-Sulphur values are more common than ANC or NAG data. The ANC and NAG data indicate that the content of fast-reacting alkalinity forms (such as carbonates) is typically low, and reflects the logging of only trace amounts of calcites (at most) in the andesite and diorite waste rocks. This low buffering capacity, due to reactive carbonates, was highlighted by a program of kinetic test work conducted over a two year period (McNeil and Nichols 2003). The kinetic results also highlighted several minor elements which have the potential to report to waste rock facility seepage at elevated concentrations under certain pH conditions.

Singularly, the key finding from the earlier investigations on the acid forming characteristics of NBG waste rocks was the inability to validly account for circum-neutral buffering from primary silicates which thereby biased the ABA assessment overall. Based on the static testing results, the majority of samples were classified as UC (uncertain) in terms of acid formation potential. The kinetic test work by McNeil and Nichols (2003) showed that NAF-Composite samples could produce acidic leachates. Accordingly, the earlier investigation resulted in almost all of the waste bedrocks (those below the regolith profile) at NBG being classified as PAF. This equates to approximately 60 % of the total mine waste volume (includes waste regolith and waste bedrock volumes). The majority of the re-classified waste bedrocks would be characterized by Total-Sulphur values less than 0.3 % (or 3,000 mg/kg), as shown by the histogram of Total Sulphur distribution at NBG (Figure 3).

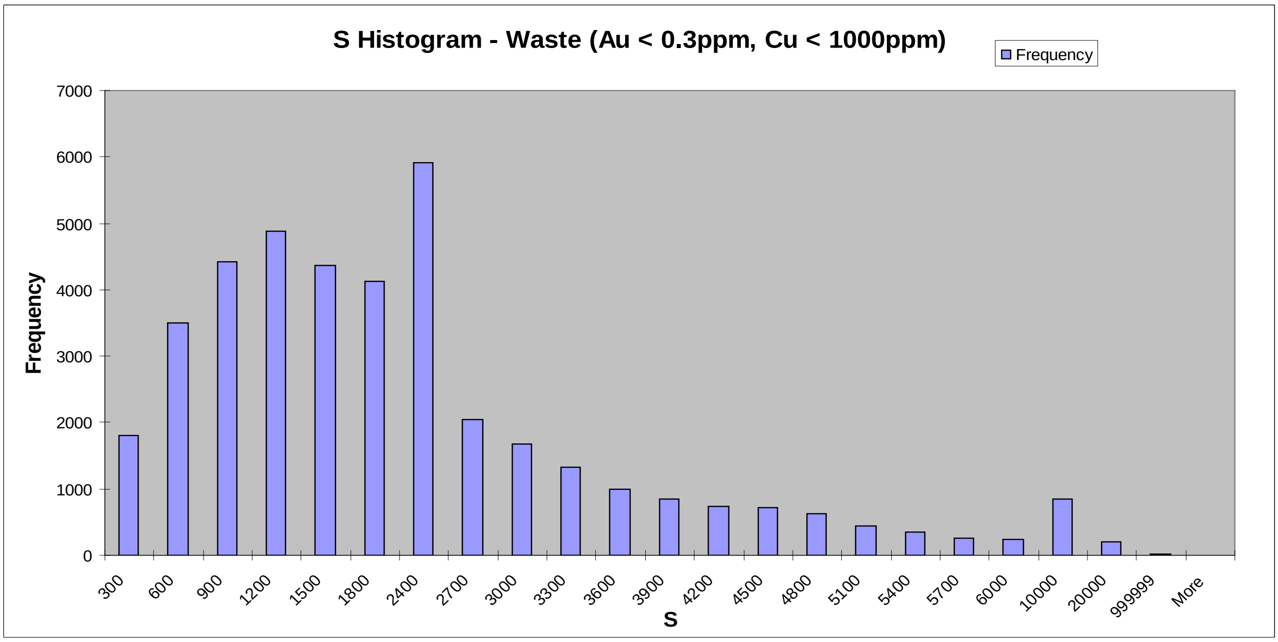

Figure 3 Total Sulphur distribution in waste (parts per million)

4.1 Operational approaches for dealing with geochemical uncertainties

The feasibility era classification led to a mine waste management plan which necessitates the careful control of material segregation throughout operation. Static testing is undertaken during the blast hole sampling process and this information is used to carefully schedule and direct truck movements to control material placement. With over 60% of the entire mine waste inventory for the project classified as PAF, this is a significant undertaking. Although appropriate for environmental protection, such requirements impose significant limitations and inflexibilities on mine planning as areas planned for storage can become quickly consumed with the consequent cost impost. Hence, it was prudent to ensure that the classifications were appropriate. The geochemical uncertainties resulting from historical testing pose a dilemma for operational management at NBG, since the unilateral classification of all of the basement waste rock as PAF places significant constraints on waste storage options, and ensuring implications for project costs.

5. Critical appraisal of historic geochemical investigations and characterization

Coincident with the closure plan review, Newmont commissioned a suite of investigations to more fully characterise the geochemical nature of the waste bedrocks at NBG. Identifying the sources of uncertainties in the historic mine waste classification, and their underlying likely causes, was central to the follow-up work. A program of database interrogation and material testing was commissioned and several consultants with expertise in various technical disciplines were engaged. The geological resource database consisting of tens of thousands of sulphur and other elemental assays that were compiled by the mine planning department was examined.

The investigation also included a reinterpretation of earlier kinetic testing in the light of the design of the kinetic testing programme (similar to that described in the AMIRA (2002) document), and the slow rates of the hydrolysis and dissolution reactions of primary silicates at circum-neutral-pH. Since calcite only occurs as a trace component, its dissolution kinetics may also be suppressed, due to surface-chemical interactions arising from intimate associations between calcite and silicate grains.

An example of conflicting outcomes between predictions and observations is shown in Figure 4 for the kinetic testing of a NAF-Composite sample of waste rock from the South Pit (McNeil and Nichols, 2003). Although this sample had a Total-Sulphur value of approximately 0.1 % was classified as NAF, variable leachate-pH values were recorded during the two years of kinetic testing, and could be as low as 3.8 (Figure 4 below), but only during the summer months.

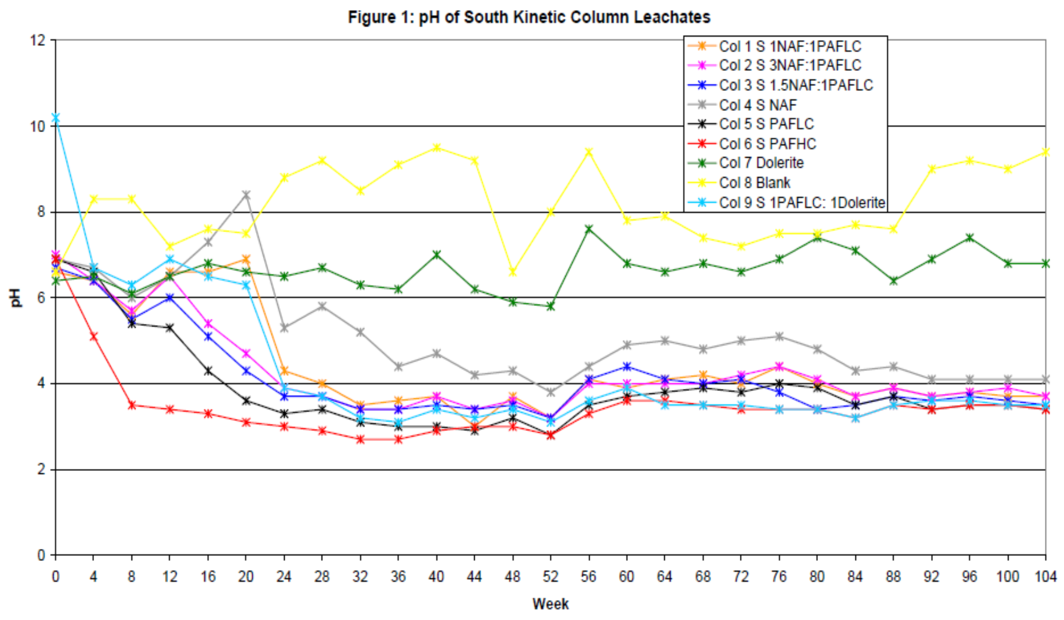

Figure 4: Anomalous kinetic test results for non-acid-forming wastes from South Pit (McNeil and Nichols, 2003)

In a recent review of these kinetic results, the sulphide-oxidation rates (SORs) were estimated, and their variations plotted as a function of weathering history, together with the leachate-pH values (Figure 5). An inverse, and seasonal, trend is evident between the SORs and leachate-pH values, and is interpreted as reflecting both the use of a non-constant temperature room for the kinetic testing, and the particle size range (less than 9 mm with minimal fine earth fraction of less than 2 mm) of the drill core derived samples. Use of flood lamps (AMIRA, 2002) during the daytime to dewater the columns for five days each week meant that the diurnal temperature regime of the columns varied seasonally during the two years of kinetic testing. The coarseness of the waste rock samples meant that the columns drained almost to completion within a matter of minutes following commencement of the flushing step (every four weeks) using deionised water. At the slower winter SORs, the short residence times of the flushing step was sufficient for the leachate-pH values to be greater than 5. Leachate-pH values of 6+ would likely have been recorded if the residence times had been several hours (c.f. minutes), thereby allowing the opportunity for circum-neutral buffering by the traces of calcites, and the primary silicates. By similar reasoning, at the faster summer SORs, leachate-pH values near 4 were recorded.

It is therefore proposed that the observed acidic summer leachates are not representative of the true weathering pH regime, since the residence times of only minutes in the flushing steps were too short. This reinterpretation of the kinetic results reported by McNeil and Nichols (2003) is to be confirmed, or refuted, in the follow-up programme of kinetic testing currently being planned. It should be noted that, from a pragmatic modelling viewpoint, the use of a non-constant-temperature room for kinetic testing has the advantage that seasonal variations in ambient temperature allow direct assessment of the temperature dependence of SORs, and so is useful for modelling purposes, as required.

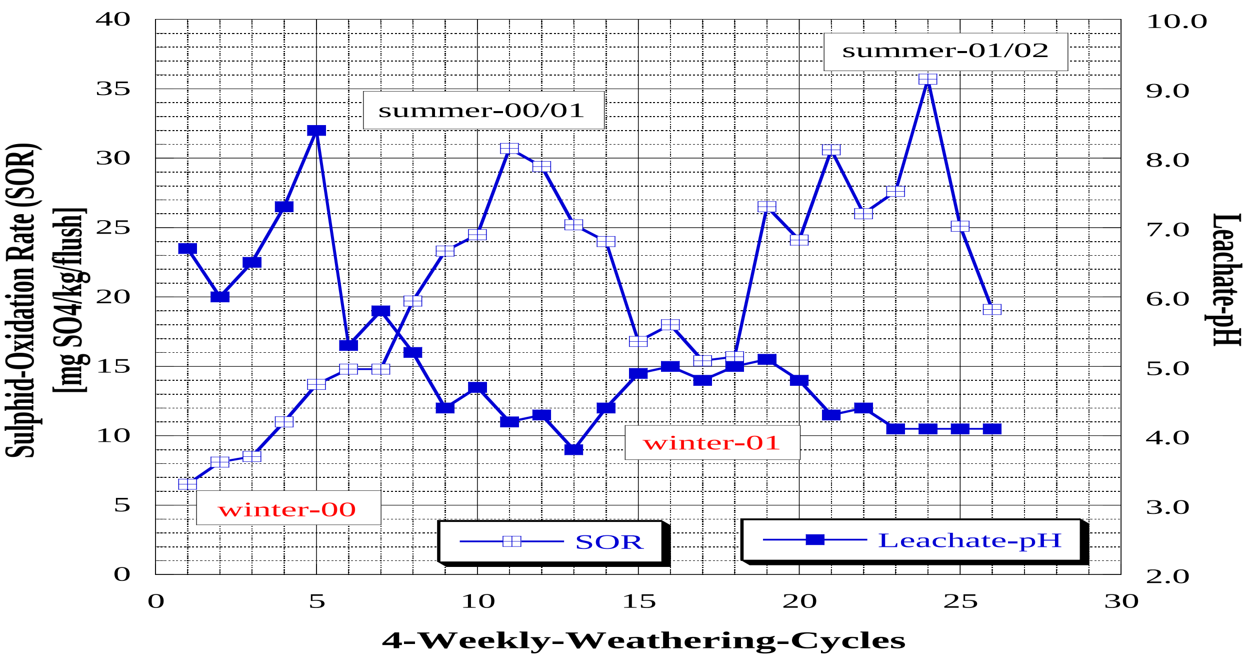

Figure 5 **Variation in sulphide-oxidation rates and leachate-pH values for non-acid-forming sample (Col 4 S NAF)**

The study tasks currently in hand at NBG include:

- Comprehensive review of existing geochemistry data, including analysis of the very considerable static testing database generated since operations commenced;
- Detailed review of the key findings which underpin the earlier geochemical classification, specifically the outputs of a suite of kinetic testing undertaken since 2001;
- Preliminary testing to further understand the nature and behaviour of the material from current as-mined materials, rather than drill core samples tested previously; and,
- Design of comprehensive set of medium to long-term tests to measure a wide range of geochemical signatures/attributes specific to the materials on this site.

The current geochemical investigations focus on the nature of the sulphide forms, and groundmass-buffering properties of the NBG waste rocks (chiefly diorites and andesites), and thereby provide a better understanding of the long term weathering and leaching behaviour. Both conventional testing methods and novel approaches relevant to this low sulphide and low buffering capacity materials, are being employed. The findings from the laboratory testing (both static and kinetic testing) will ultimately be extended by moving to large scale field trials on dumped waste rock materials in situ.

6. Benefits of critical review and follow-up geochemical characterisation

The discussions above highlight that the benefits from conducting careful and detailed geochemical characterization cannot be overemphasized. With the limitation of storage space and the need to minimise waste rock dump sizes for short and long term cost implications, it is clear that valid refinements to classifications are significant for both life of mine and closure planning. This reclassification process currently being undertaken is estimated to result in less than 40% of total waste materials being classified as PAF compared with 60% previously estimated. When dealing with a mine the size NBG where an estimated 1 billion tonnes of waste rock material will be stored over the life of the mine, such a reduction in PAF materials is highly significant in all respects.

The benign component of waste rock material could be used for both progressive and final reclamation purposes and can also be placed in areas allocated for general dumping which will significantly mitigate the cost impost of the various management constraints required for PAF material. The resulting cost benefits during mine planning and the reduction in closure liabilities are in the order of tens of millions of dollars over the life cycle of the mine.

The timing of such investigation to reclassify the materials is very important for the operation of the mine, the life of which is currently around twenty years with potential for future extension. With such reclassification, the waste rock can be managed in a cost effective, environmentally responsible manner that reduces constraints on mining operations and closure liability.

7. Conclusions

A significant proportion of mining costs and liabilities is linked to the storage of waste rock during the life cycle of the mine, especially at the closure and post-closure stages. A considerable proportion of these storage costs arise from the geochemical characteristics that impose environmental restrictions on storage methods. Therefore giving the required attention to geochemical characterisation at an early stage is extremely important for the operations and closure of mines. This paper has outlined, through a case study, the significant benefits of conducting a detailed, accurate and timely assessment of geochemical parameters of mine waste that affects life of mine closure performance.

The findings from this paper support the conclusion that assessment of geochemical characteristics should not be limited to a single approach such as static tests and its interpretation based of ABA methodology. Because of the complexities involved in assessing and understanding the geochemical weathering processes and the inter relationship between, weathering history and specific chemical weathering processes such as sulphide-oxidation rates, tests should necessarily include kinetic tests of various materials and should be done at the early stage of mine planning and continued throughout operations. Such an approach increases the potential for capturing the subtleties involved in the acid forming characteristics of mine waste materials and their potential environmental impacts.

Furthermore, mine waste material classifications should be constantly reviewed and new findings used in adjustment of life of mine and closure planning. An integrated approach will save mining operations significant cost, facilitate life of mine planning process, reduce in environmental harm and minimise closure liabilities.

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