ACID- BASE: ACCOUNTING, TECHNIQUES AND EVALUATION (ABATE):

Recommended Methods for Conducting and Interpreting Analytical Geochemical Assessments at Opencast Collieries in South Africa

This document provides a summary of methodologies that have been researched and developed as part of a project entitled:

On-site and Laboratory Investigations of Spoil in Opencast Collieries and the Development of Acid-Base Accounting Procedures

Report to the Water Research Commission

by

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On-site and Laboratory Investigations of Spoil in Opencast Collieries and the development of Acid-Base Accounting Procedures

The Steering Committee for this project consisted of the following persons:

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Executive Summary of Detailed Report

1. Introduction

Acid mine drainage is a widespread phenomenon affecting the quality of water at many South African collieries. Techniques to determine the likely leachate quality are numerous and have, thus far, been applied without uniformity. This report outlines the research conducted on acid mine drainage and the standardisation of methodologies to be followed to quantify the potential and magnitude of acid mine drainage under South African opencast mining conditions.

As such, this study was focussed on the following aspects:

- To investigate the applicability of existing global Acid-Base Accounting technologies to South African opencast coal mines.
- To refine Acid-Base Accounting methodologies for local conditions through experimentation.
- To establish a creditable database, detailing results from this investigation for future reference.
- To select and recommend Acid-Base Accounting methodologies to be used in South African opencast coal mines.

Acid mine drainage occurs when sulphide minerals in rock are oxidised, usually because of exposure to moisture and oxygen. This results in the generation of sulphates, metals and acidity that can have manifold environmental consequences. It is therefore of utmost importance to the mining industry to know the characteristics/capacity of waste rock, overburden, pit walls, pit floor and tailings to produce acid mine drainage.

1.1 ABA and ABATE

Acid-Base Accounting (ABA) is a first order classification procedure whereby the acid-neutralising potential and acid-generating potential of rock samples are determined, and the difference (net neutralising potential) is calculated. The net neutralising potential, and/or the ratio of neutralising potential to acid-generation potential, is compared with a predetermined value, or set of values, to divide samples into categories that either require, or do not require further determinative acid potential generation test work.

Although the project has been abbreviated as the Acid-Base Accounting (ABA) project, the project aims are to define a suite of acid-drainage prediction, applicable to South African opencast coal mine conditions. The result is that a new acronym, ABATE (derived from **Acid-Base**: **A**ccounting, **T**echniques and **E**valuation), has been defined to include all these methods. This also prevents any confusion from

arising in the use of the term ABA, since most people associate ABA with the static test component of drainage chemistry prediction, rather than the entire suite of tools. Figure i shows the relationship ABA has to the overall ABATE concept and illustrates the different components needed to accurately predict mine drainage quality, depending on the objectives and onsite conditions.

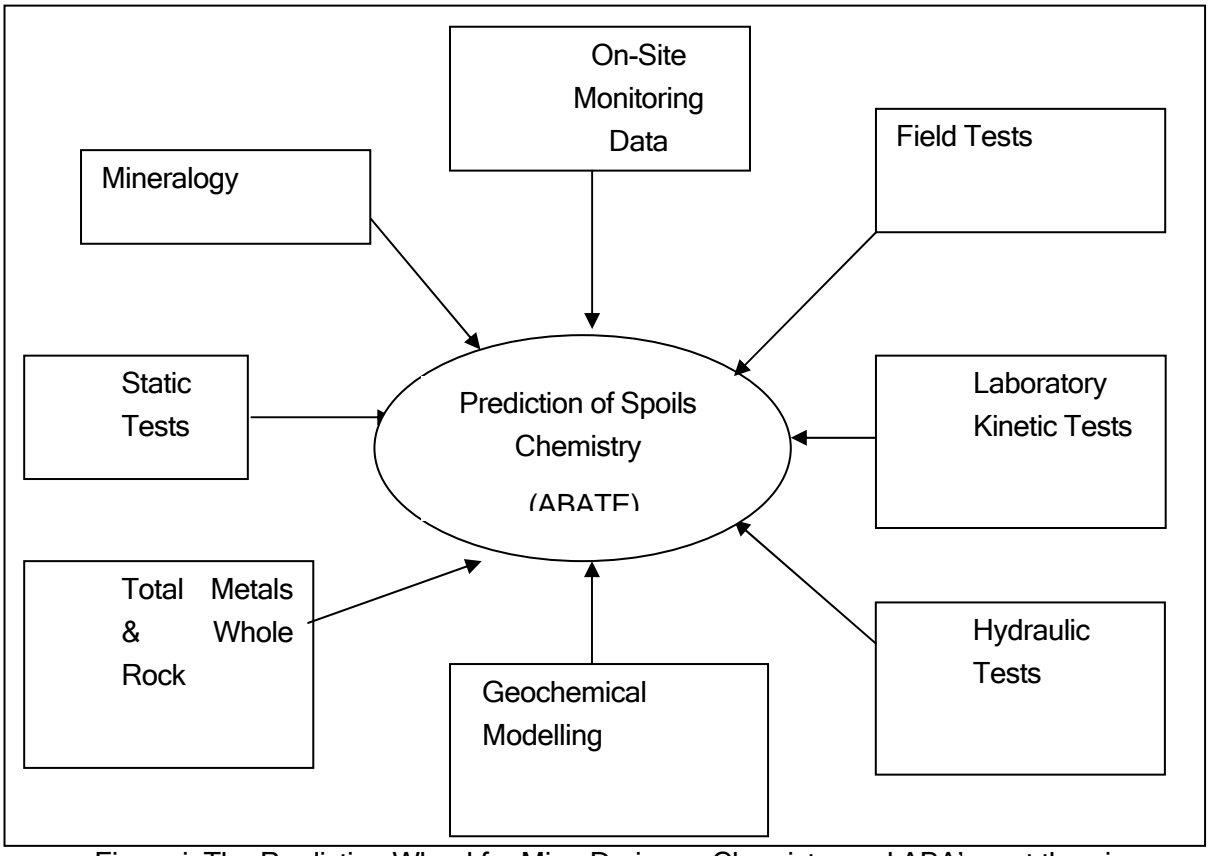

Figure i. The Prediction Wheel for Mine Drainage Chemistry and ABA's part therein (after Morin and Hutt, 1999).

2. Method of investigation

The research for this project was achieved by doing the following:

- Extensive literature review of relevant documents, journals, guidelines, websites and theses.
- Selection of appropriate ABA methods to test.
- Evaluation of different static test methodologies.
- Extensive long-term kinetic testing using several methodologies.
- Discussion with all relevant role players in South Africa in the form of personal meetings and a Specialist Workshop outlining findings and progress.
- Evaluation of modelling methods.
- *In situ* testing of spoil material through test pits.

- Application of ABA to case studies to compare ABA with the field situation.

3. Prediction Methods

Accurate prediction potentially offers the most cost-effective means of reducing the impact of AMD on the environment and the associated costs by allowing advanced planning for prevention and control. The objective of a prediction program is to reduce uncertainty to a level at which potential risk and liability can be identified and effective extraction, waste handling and, where necessary, mitigation and monitoring strategies can be selected (Price, 1998).

The scope of a prediction program will depend on site-specific conditions and factors. Some programs might comprise a few simple tests requiring only a relatively short period and a modest budget. Others can involve extensive testing and analysis lasting several months or even more than 1 - 2 years, with much higher costs. The approach required might include some or all of the following :

- Initial assessment and site reconnaissance.
- Sampling.
- Chemical, mineralogical and physical analyses.
- Short-term leaching tests.
- Geochemical static tests (Acid-Base Accounting).
- Geochemical kinetic tests.
- Mathematical models.

4. Static Methods (Acid-Base Accounting)

Generally when Acid-Base Accounting is referred to it is the so-called static methods, which are involved. These are screening methods to determine the difference between the acid-generating capability and the acid-neutralising potential of a particular sample.

4.1 ABA Terminology

- AP (Acid Potential) = S% x 31.25
- NP (Neutralisation Potential) = the capacity of a sample to consume acid
- NNP (Net Neutralising Potential) = NP – AP
- NPR (Neutralising Potential Ratio) = NP: AP

Units: Usually kg of $CaCO_3$ equivalent of net neutralisation potential per ton of rock

4.2 Types of static test

The following procedures are the most commonly used static test methods:

- Paste pH.
- Peroxide methods.
- Static Net Acid Generation (NAG) procedure.
- BC Research Initial test.
- Sulphur content.
- BC Research Confirmation Test.
- COASTECH modified biological oxidation test.
- Sobek Neutralisation Potential method.
- Carbonate NP determination.
- Modified Acid-Base Accounting procedures for Neutralising Potential.
- Lapakko Neutralisation Potential test procedure.
- Calculated NP.
- Net Carbonate Value (NCV) for Acid-Base Accounting.

4.3 Considerations, Advantages and Limitations of Acid-Base Accounting

Acid-Base Accounting is often a first or second step in determining the mine drainage chemistry. It has been used very widely with success, locally and internationally. It is however important to point out that, although it can be used very fruitfully, particularly in classifying samples into potentials for acid generation, there are several factors to consider.

The principal advantages of ABA are:

- They are relatively cheap
- Interpretation is based on decades of international research/experience
- Methods of interpretation are clear and well established
- Results are obtained quickly
- Correlation to field has been shown by case studies (local and abroad)

The limitations of ABA are thus the following (most of these also apply to several other methods used):

- It only provides a possibility of occurrence.

- Reaction rates are ignored. (ABA generally tests the fast reacting species; slow reacting neutralising species will usually not prevent acidification).
- It assumes instant availability of reactive species. (However, nearly all rock samples lacking carbonates which are fast reacting and thus instantly available, or not of dunite composition (predominantly olivine + serpentine) have insufficient NP to be classifiable as 'not potentially acid-generating' if the minimum limit for this category was to be set at, for example, 20 kg CaCO3 equivalent/tons of material (Errington, 1991)).
- Simple reaction stoichiometry is assumed.
- Size effects are ignored (Limestone particles of greater than 6.4 mm are coated with precipitates and are only 20% utilised when acid conditions are in evidence (Scharer *et al.*, 2000). However from this paper it is clear that if a 4:1 NPR is used then only 10% fines is required for the system to react as expected. From the trenches dug in the spoils, a > 10% fines ratio is a valid assumption in South African conditions, therefore in spoils this limitation is a minor consideration).
- Extrapolation to the field is uncertain when volumetric calculations cannot be made.

4.4 Suggested Methods

Based on the research at the IGS, the following are the suggested methods for Acid-Base Accounting:

1. Paste/Initial pH and solution products.
2. Acid potential using hydrogen peroxide or Leco furnace.
3. Oxidation products analysed (when using H_2O_2).
4. Neutralising potential using sulphuric acid.

From this project the following are considered important:

a. Acid-Base Accounting is an excellent first-order tool to determine whether mine waste has the potential to form acidic drainage.

b. The methods developed as part of this project are in agreement with methods used internationally.

c. Modifications that have been made and suggested are all scientifically justifiable.

d. Well-established criteria exist for the classification of individual samples as potentially acid-generating or neutralising.

e. When samples are obtained at specific locations with depth, the use of depth normalisation and volumetric calculations provides an established methodology of evaluating ABA results for an entire spoil area.

f. Initial pH-methods in the laboratory yield similar results. A standard ratio of 1 g sample:10 g water is suggested since it compares well to traditional paste pH-values, yet provides sufficient supernatant for analysis of naturally available leachable elements.

g. Where material is to be used for neutralisation, acid leachable metals should be determined since these levels may be extremely high if acidification was to occur.

h. The hydrogen peroxide acid potential method and the Total S, determined using a Leco analyser, should provide similar assessment of acid potential.

i. The hydrogen peroxide method, however, provides additional information such as an indication of oxidised pH (which can provide an indication of NNP and therefore acts as a form of quality control) and the levels of different potential contaminants, which can be released. Only reactive sulphur species are determined, thereby removing confusion over total S, sulphate S and organic S contributions.

j. The neutralisation method recommended is a modification of the Sobek method that uses sulphuric acid, no fizz test and a twenty-four hour measurement period. Its use is justified since sulphuric acid rather than HCl reacts in the field, the results compare very well, the removal of the fizz test leads to greater consistency and the twenty-four hour period negates the siderite temporary buffering. The recommended methods are discussed fully with supporting evidence in the report.

4.5 Assessment of recommended Static methods

The proposed static test methods compare to those used internationally. The modifications suggested to the methods are all justified and should result in a more consistent application of the methods in South Africa.

These methods can thus be used with great certainty and success for the screening and placing of waste rock in the coal mines of Southern Africa.

4.6 Screening Criteria

One of the major advantages of static tests is that well-defined sets of screening criteria have been developed to interpret these tests. Although these criteria can sometimes provide slightly contradictory interpretations, their combined use can lead to good classification of tested samples into classes of non-acid-generating to acid-generating, with a slight grey area inbetween. It has been suggested that the

criteria should be area/site specific. The researchers agree with this sentiment but feel that until there is a large enough, comparable Acid-Base Accounting database in South Africa, international criteria should be used.

The criteria are the following:

4.6.1 Net Acid-Generating Test (NAG) pH

This set of criteria is based on the final pH obtained in the NAG test. These subdivisions are slightly arbitrary and these can serve as a rough guideline but not as stand-alone criteria in categorising the samples.

Final pH in NAG Test	Acid-generating Potential
> 5.5	Non-acid-generating
3.5 to 5.5	Low risk acid-generating
<3.5	High risk acid-generating

The 5.5 upper limit is derived from the carbon dioxide/pure water equilibrium pH of 5.69. Any sample tested with deionised water commonly used in laboratories requires this value to be used as reference rather than a theoretical neutral pH of 7.

4.6.2 Net Neutralising Potential (NNP)

The use of NNP often leads to uncertainties. The reason for this is that research and experience have shown that there is a range from -20 to 20 kg/t $CaCO_3$ where the system or sample can either become acidic or remain neutral. However, when used in conjunction with the other criteria, this uncertainty can be resolved.

Where Net Neutralising Potential (NNP) = Neutralising Potential (kg/ton CaCO3) - Acid-Generating Potential (kg/ton CaCO3)

The criteria are as follows:

If NNP = NP – AP < 0, the sample has the potential to generate acid.

If NNP = NP – AP > 0, the sample has the potential to neutralise acid produced.

More specifically any sample with NNP < 20 is potentially acid-generating and any sample with NNP > -20 might not generate acid.

4.6.2.1 Neutralising Potential Ratio (NPR)

Guidelines for screening criteria based on ABA (from Price *et al.,* 1997b).

POTENTIAL FOR ARD	INITIAL NPR SCREENING CRITERIA	COMMENTS
Likely	<1:1	Likely AMD generating
Possibly	1:1 - 2:1	Possibly AMD generating if NP is insufficiently reactive or is depleted at a faster rate than sulphides
Low	2:1 - 4:1	Not potentially AMD generating unless significant preferential exposure of sulphides along fracture planes, or extremely reactive sulphides in combination with insufficiently reactive NP
None	>4:1	No further AMD testing required unless materials are to be used as a source of alkalinity

The criteria above can also be plotted to give a visual indication of the potential.

4.6.2.2 % S and NPR

A set of rules, which has been derived based on several of the factors calculated in ABA, was reported by Soregaroli and Lawrence (1998). It has been shown that for sustainable long-term acid generation, at least 0.3% Sulphide -S is needed. Values below this can yield acidity but this is likely to be only of short-term significance. Using this fact and the NPR values, another set of rules can be derived:

1. Samples with less than 0.3% Sulphide-S are regarded as having insufficient oxidisable Sulphide-S to sustain acid generation.
2. NPR ratios of >4:1 are considered to have enough neutralising capability.
3. NPR ratios of 3:1 to 1:1 are considered inconclusive.
4. NPR ratios below 1:1 with sulphide-S above 0.3% are potentially acid-generating.

4.7 Reporting

It is recommended that all results be reported in units of kg/ton rock. All the ABA results should be expressed in units of kg/ton $CaCO_3$ for standardisation. It is recommended that one of two formats be used; either the ABACUS tool or the WISH format.

4.8 Integrating the criteria

In order to be consistent with the application of criteria, a simple Excel-based tool called "Acid-Base Accounting Cumulative Screening tool" or ABACUS has been developed. This tool applies all the rules outlined above and incorporates several of the graphical presentations. It is felt that this will assist both the practitioners and regulators in obtaining consistent application and interpretation of the rules associated with ABA. The tool is very simple and is menu/button driven, with macros programmed to guide the user and lead them to the correct interpretation.

5. Field methods

Detailed fieldwork is suggested. This should include the following:

- Water sampling and ongoing monitoring.
- Representative sampling of spoil material, preferably through boreholes so that volumetric and depth determinations can be made.
- *In situ* profiling of water.
- Test pits in established spoils to determine areal and age variation.

Until there is a sufficiently large database for the South African coalfields, it is recommended that statistical methods be used to determine the number of samples required. Methods with illustrations of their application are given in the report.

Their suggested inclusion is due to the fact that these measurements:

- Provide the best kinetic reactor there is (As Morin and Hutt (1997) state "Undoubtedly the most valuable and representative kinetic test that can be operated at a minesite is the full-scale operation of minesite components").
- Give the most reliable measurements.
- Help to determine current situation.
- Provide understanding of controls on chemistry.
- Allow comparison to ABA.
- Act as an early warning system.
- Assist in decision on appropriate control measures.

6. Kinetic Tests

For material where the potential for acid generation is uncertain or rates of reaction are required, kinetic test work is performed to attempt to define acid generation characteristics. The term kinetic is used to describe a group of test work procedures wherein the acid generation (and metal solubilisation and transport) characteristics

of a sample are measured with respect to time (Mills, 1998g and Chemex labs, 1997).

The following list shows different categories of tests:

- Humidity cells
- Column tests
- Accelerated biological oxidation tests
- Field tests
- Specialised test apparatus

The most popular kinetic test is the humidity cell test. Therefore, this type of test formed the focus of the kinetic testing research in this project. The test simulates accelerated weathering of the sample. This is done by passing moist air followed by dry air through the sample chamber; moist air for three days, followed by dry air for three days and distilled water on the seventh day. This one-week cycle is typically run for 20 weeks, according to the ASTM standard.

As part of this project, 24 kinetic tests were run on various samples. In addition to the usual reasons for doing these tests, the objectives were to obtain repeatability, determine the influence of different methodologies and compare traditional tests with other methods. From tests done in this project, the following findings are the most important:

- The humidity cell procedure used in this project was repeatable. Cells run with duplicate samples yielded results which were very similar.
- Good correlation was found between standard humidity test methodologies and more simplified methods. Three sets of duplicate tests illustrated that cheaper and less labour intensive test protocols could yield similar results.
- The ABA results and the results from the kinetic tests were in good agreement. This provides verification for both methods.
- Humidity cells can provide reaction rates for different samples. Reaction rates for all the cells tested could be obtained.
- Increasing the humidity causes an increase in the reaction rate, in agreement with international research.
- The rates of flushing were sufficiently high to prevent secondary mineral precipitation.
- Humidity cells may not provide an indication of acidity for samples that are uncertain, according to the static test results.
- Standardised tests should be used, wherever possible, to build up a database of rates for the coalfields.

- Where the influence of any particular aspect, e.g. the effect of a cover, is to be proved using a kinetic test, a standard test should be done as reference, for comparison.
- The degree and rate of NP depletion can be determined from these cells.
- The theoretical depletion of NP correlated very well with the pH-development in the cells that acidified.
- A modified NAG/kinetic test showed that under highly oxidising conditions acidification of large boulders will occur due to reactions at the surface of the boulders. This acidification implies that the neutralising potential of the rock may be overestimated by any static NP determination.
- The $Ca+Mg/SO_4$ ratio appears to be an excellent early indicator of imminent acidification.
- Humidity cells should be able to provide "threshold" values for acid and neutralising potentials. This will greatly enhance the usefulness and likely success of the prediction of acidity.
- The usefulness of these cells for direct translation to field rates is, as yet, unclear, from this research and that done worldwide.
- The variability observed in most spoils as far a mineral, rock/fine size and distribution and depth of soil cover makes the determination of sufficient kinetic tests for spoils an unfeasible task.
- The suggested ASTM test period of 20 weeks is shown to be insufficient, by the research done in this project. This makes standardisation of the procedure extremely difficult.

Detailed methodologies for the operation of humidity cells and the interpretation thereof are given in the report.

7. Modelling

Computer models are another approach to the prediction of acid generation. As part of the development of the ABATE methods, a short review of geochemical modelling was included. Although this does not pertain directly to ABA, geochemical modelling is increasingly seen by many in South Africa as the method of choice for the prediction of long-term drainage from mines.

This section highlights the advantages, requirements and limitations for geochemical modelling. Each modelling code or method has particular advantages and disadvantages as far as availability, cost, ease of use and inherent assumptions and weaknesses. In each case, the appropriate code or method must be used based on the type of answer required. By highlighting the usefulness of these models and their basic data requirements, along with the uncertainties

involved in geochemical models, the user/researcher will, it is hoped, be in a position to select an appropriate model method and geochemical modelling code. This section provides guidance in terms of the uncertainties, requirements and output from geochemical models.

Geochemical models need several input parameters, which have been accurately determined. Without accurate data, the uncertainties increase and the models can then only be used to highlight the most important processes and show what the influence of different variables are.

- Selection of appropriate model tool is vital.
- There are numerous models that can be used for geochemical modelling. The applicability of each model needs to be assessed according to the on-site conditions, availability of data and objectives of the modelling.

The advantages of geochemical models are that they:

- Provide long-term (+100 years) estimates of changes/trends in ARD quality.
- Enable a comparison between different options in terms of:
- Discard dump design.
- Operational procedures.
- Rehabilitation scenarios.
- Provide the basis for comparing the risk and costs associated with each option.
- The models are often associated often associated with large uncertainties.

Illustration using simulations of simplified hydrogeochemical systems, showed how relatively minor variations (relative to the uncertainty of most of the data used in the models) can yield significantly different results. Several different simulations were done to illustrate a particular aspect.

The applicability of modelling was tested by comparison to the humidity cell outflow. Using methodologies discussed in the report and knowledge of the mineralogical make-up, ABA results and outflow volumes, it was possible to simulate the cells satisfactorily. The simulations did, however, show how sensitive the outcome is to slight changes in input parameters.

Geochemical modelling is regarded as an advanced step in the ABATE process.

Despite these limitations, geochemical modelling can be a very useful tool in the prediction of drainage quality, when used in conjunction with data appropriate to the objectives.

8. Case studies

Three case studies showed the application of ABA to a field scale. Fieldwork included test pits dug at the different mines to obtain an *in situ* determination of the acidification and on-site conditions. The most important findings from the case studies are summarised below.

- All of the studies showed a good correlation between static ABA and observations in the field.
- The spoils are extremely heterogeneous. Great variation in particle size, moisture content and type of material was observed in test pits dug in the spoil.
- The depth of soil cover has no apparent impact on the spoil water chemistry. Oxygen and moisture penetrate into the system, regardless of the thickness of soil cover.
- Temperatures in the dug pits can be very low at surface in winter. A rapid increase in the spoil temperature with depth is present in most pits and at 3 m, temperatures around 20°C have been recorded. In several of the dug pits, elevated temperatures ranging from 25 – 50°C have been recorded.
- There are localised areas of acidification; these are due to specific optimal microclimates. It seems that mineralogical composition plays a more important role than age of the spoils.
- Mine A showed how several of the components in the ABATE process could be used to determine the likely quality emanating from the mine.
- Case study 2 illustrated an excellent correlation with ABA from core boreholes, *in situ* determinations, subsequent ABA and kinetic testing.
- Case study 3 used an example of a mine classified previously as an unlikely acid producer. *In situ* determinations in spoils of various ages showed that in the upper two to three metres the spoil was pH neutral to slightly alkaline. Long-term monitoring data from the borehole nearest the test pits, spanning more than a decade, showed that the water quality in the area was currently neutral to slightly alkaline.
- Other reported case studies from South African coal mines illustrated the use and value of ABA as a tool in the assessment of coal mine water chemistry.
- The most significant of these illustrates how ABA from an area where mining has long ceased, which is experiencing vast problems with AMD, consistently predicts that acidification is likely.

9. Further research

From the findings and experiences in this project the following suggested future research is needed:

1. Determination of threshold values for ABA parameters in South African coal mines.
2. Integration of all ABA and drainage (monitoring) in the coalfields to find regional trends and correlation to assist in the early identification and management of AMD in South Africa.
3. Extensive testing and validation of model codes used in AMD prediction.
4. Development of an affordable, user-friendly reactive transport model that can be used in South African coal mines.

10. AIMS AND ACCOMPLISHMENTS

The following is a discussion of the degree to which the aims of the project have been reached.

To investigate the applicability of existing global Acid-Base Accounting technologies to South African opencast coal mines.

An extensive review of available ABA procedures was done. Chapters 1-3 detail the theory of AMD, the use of international ABA methods, their methodologies and advantages/disadvantages of each method. Discussions with prominent practioners in the field of AMD in South Africa through personal meetings and workshops provided background to the currently used methods in South African opencast mines. The results from *in situ* test pits in the spoils at three different collieries were compared to static tests and showed an excellent correlation.

To refine Acid-Base Accounting methodologies for local conditions through experimentation.

Chapter 4 outlines the ABATE strategy for the integrated use of available tools in an approach that allows the tools to fit the objective and on-site situation. Chapter 5 details the results from testing of different static ABA methods and variations in methodologies. Chapter 6 describes the twenty-four kinetic tests done as part of this project. Repeatability and variation in methodology and apparatus were all tested to obtain a clear understanding of the impact of these aspects. From all these tests, recommendations have been made for methods to be used in South Africa.

To establish a creditable database, detailing results from this investigation for future reference.

All the results from this investigation are detailed in the report. The results are also in Excel spreadsheets for easy access and future reference. Where applicable the results are in a format compatible with the WISH software.

To select and recommend Acid-Base Accounting methodologies to be used in South African opencast coal mines.

From the extensive testing of the static methods a standardised method for initial pH, neutralisation potential and acid potential have been recommended. The reasons/advantages of the recommended methods have also been discussed. The recommended methodologies for static tests, kinetic tests, field methods and modelling have been outlined in a summary document of methods. An easy to use spreadsheet tool, ABACUS, has been developed to standardise the interpretation of static ABA data and, where the suggested sampling methodology has been followed, to provide a method for extrapolation to the field through volume-weighted techniques.

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PLEASE NOTE

THE COMPLETE MAIN REPORT

entitled

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by

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as well as its Appendices

the

Recommended Methods for Conducting and Interpreting Analytical Geochemical Assessments at Opencasrt Collieries in South Africa

as well as

ABACUS, a button-driven spreadsheet to assist users in interpretation of Acid-Base Accounting data.

ARE AVAILABLE ON THE ATTACHED CD ROM

1. INTRODUCTION

This document is a companion document to the full report title "On-site and Laboratory Methods of Spoil in Opencast Collieries and the Development of Acid-Base Accounting Procedures". The contents ***MUST NOT BE USED WITHOUT AN UNDERSTANDING OF THE PRINCIPLES IN THE MAIN DOCUMENT.***

The Institute for Groundwater Studies undertook research into acid-base accounting methodologies in South Africa. This study was particularly geared to do the following:

- Investigate the applicability of existing acid-base accounting methodologies to South African opencast coal mines.
- To refine acid-base accounting methodologies for local conditions.
- To establish a creditable database detailing results from this investigation for future reference.
- To select and recommend acid-base accounting methodologies to be used in South Africa.

This document is intended to serve as a quick guide for hydrogeologists and investigators into Acid -Mine Drainage at South African opencast coal mines, regulators evaluating these mines and laboratory personnel involved in ABA and other laboratory tests on this subject. The main report (available as a CD) provides a comprehensive discussion, with detailed results, of all the aspects dealt with in the section below.

2. Discussion on all the aspects ACID MINE DRAINAGE in BRIEF

Observed coal mine drainage in South Africa ranges widely in composition, from acidic to alkaline, typically with elevated concentrations of sulphate (SO_4), iron (Fe), manganese (Mn) and aluminium (Al), as well as common elements such as calcium, sodium, potassium and magnesium. The pH is most commonly either in the ranges of 3 to 4.5 or 6 to 7, with fewer intermediate or extreme values.

Acid mine drainage occurs when sulphide minerals in rock are oxidised, usually because of exposure to moisture and oxygen. This results in the generation of sulphates, metals and acidity that can have manifold environmental consequences. It is therefore of utmost importance to the mining industry to know the characteristics/capacity of waste rock, overburden, pit walls, pit floor and tailings to produce acid mine drainage.

Acidic mine drainage (AMD) is formed by the oxidation of pyrite to release dissolved Fe^{2+}, SO_4^{2-} and H^+, followed by the further oxidation of Fe^{2+} to Fe^{3+} and the precipitation of the iron as a hydroxide ("yellow boy") or similar substance, producing more H^+. Neutralisation of the acidic solution by limestone or similar materials can form neutral mine drainage with high SO_4, and possibly elevated Fe

and Mn. If appreciable Fe or Mn is present, these neutral solutions can become acid upon oxidation and precipitation of the Fe and Mn. (Rose and Cravotta, 1999)

Many factors control the rate and extent of AMD formation in opencast collieries. More abundant pyrite in the overburden tends to increase the acidity of drainage, as does decreasing the grain size of the pyrite. Iron-oxidising bacteria and low pH-values speed up the acid-forming reaction. Rates of acid formation tend to be slower if neutralisers such as naturally occurring carbonate minerals are present. Access of oxygen needed for pyrite oxidation is commonly the limiting factor in the rate of acid generation. Both access of air and exposure of pyrite surfaces are promoted by breaking the pyrite-bearing rock. The oxygen can gain access either by molecular diffusion through the air-filled pore space in the spoil, or by flow of air that is driven through the pore space by temperature or pressure gradients.

The most important reactions for an understanding of AMD are the following:

(1) $FeS_2 + 7/2\ O_2 + H_2O \Rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$

(2) $Fe^{2+} + 1/4O_2 + H+ \Rightarrow Fe^{3+} + 1/2\ H_2O$ (rate limiting step)

(3) $Fe^{3+} + 3H_2O \Rightarrow Fe(OH)_3$ (yellow boy) $+ 3H^+$

(4) $FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$

From this it should be evident that the overall reaction liberates four moles of protons for each mole of pyrite, as can be seen by the overall reaction:

$FeS_{2(s)} + 15/4O_2 + 7/2\ H_2O \Rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+$

This reaction also shows the vital components; air, water and pyrite, needed for the process to occur (with the mediation of bacterial catalysis).

In South African coal mines, the neutralisation of AMD is usually due to the naturally occurring carbonate minerals, calcite and dolomite, which are present in the sediments. The reaction with calcite is shown below:

$FeS_2 + 2CaCO_3 + 3{,}75O_2 + 1{,}5H_2O \Leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2CO_2$ (carbon dioxide exsolves into the atmosphere in open-system conditions)

Acidity produced from 1 mole of FeS_2 (64 g sulphur) is neutralised by 2 moles of $CaCO_3$ (200 g) or 1 g sulphur: 3.125 g $CaCO_3$ (Brady *et al.,* 1994).

Alternatively, where there is no free exchange of CO_2 with the atmosphere, the reaction is as follows:

$FeS_2 + 2CaCO_3 + 3{,}75O_2 + 3{,}5H_2O \Leftrightarrow Fe(OH)_3 + 2SO_4^{2-} + 2Ca^{2+} + 2H_2CO_3$ (carbon dioxide dissolves to form carbonic acid under closed-system conditions)

In the latter reaction the carbonic acid, H_2CO_3, dissociates to liberate further protons, thus 1 mole of FeS_2 is neutralised by 4 moles of $CaCO_3$, which results in a mass ratio of 1 g pyrite: 6.25 g calcite. To neutralise the pyrite-derived acidity to neutral levels (pH 7), twice as much calcite is needed to neutralise to slightly acidic levels

(pH 4)(Morin and Hutt, 1994) under closed conditions as opposed to open conditions. Realistic conditions for the opencast coal mines lie somewhere between the open and closed system, with a tendency towards the closed system (Krantz, 1993).

3. ABA and the ABATE STRATEGY

Acid-base accounting is a valuable and widely used tool in the evaluation of opencast coal mine spoil characteristics. ABA is, however, like all the other methods, used to evaluate the characteristics and behaviour of the spoil material; only one of the tools that should be used. Thus, although the project was focussed on ABA methods, an overall methodology, showing the strategic place of ABA, had to be developed. Much of the rationale behind the strategy was derived from the experiences of researchers/practitioners with vast experience world-wide.

The key questions to be asked in most prediction programs are:

- Is there a potential for AMD generation?
- Will the potential for acid generation be realised?
- When will the AMD be generated?
- How much AMD will be generated?
- For how long will AMD be generated?
- What will the water quality be?
- Will control measures work?
- Will the mine remain in compliance?

The Acid-Base: Accounting, Techniques and Evaluation (ABATE) strategy is thus proposed. Figure 1 illustrates the most important components of the integrated, multi-component ABATE strategy. The ABATE strategy is seen as an all-inclusive approach of methodologies, where the tools are determined by the objective of the investigation and the nature of the problem/on-site conditions. The individual components of the approach should be done according to standardised methods as discussed in this document, but the overall strategy should be as flexible as possible to accommodate the on-site conditions and objectives.

This figure is referred to as the so-called “prediction wheel” in drainage chemistry determination (after Morin and Hutt, 1999).

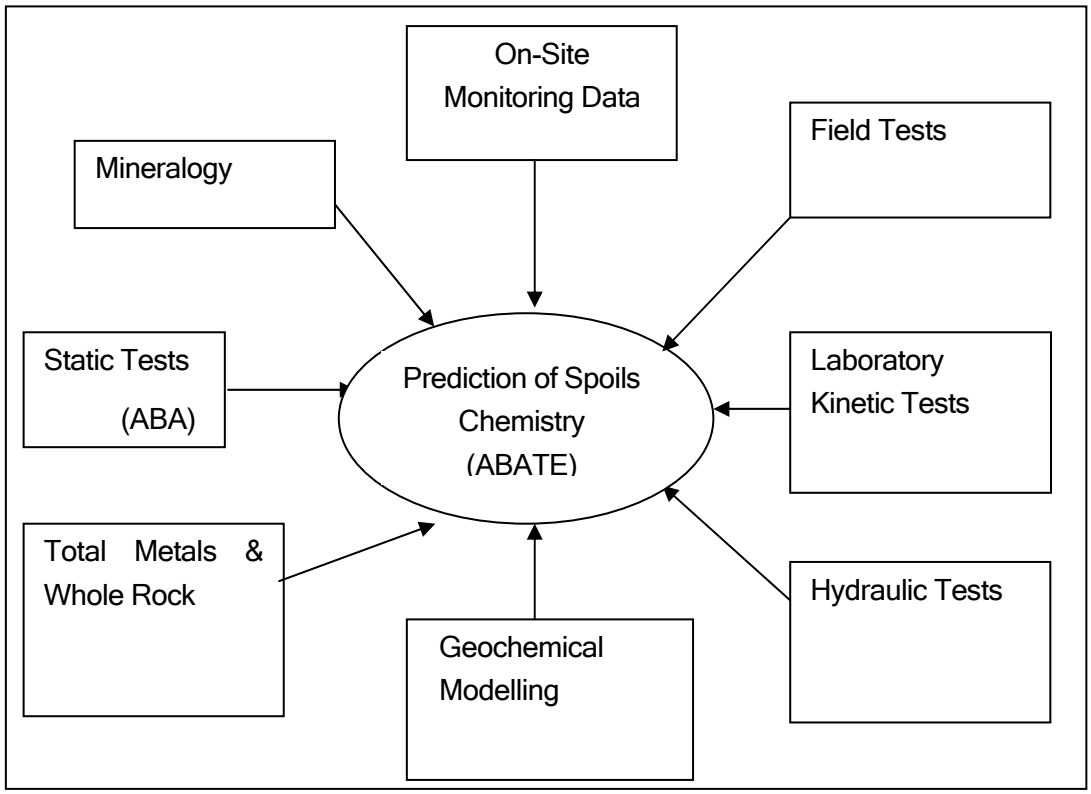

Figure 1. The Prediction Wheel for Mine Drainage Chemistry and ABA's part thereof (after Morin and Hutt, 1999).

This prediction wheel shows that many different aspects are required to arrive at the eventual answer. Depending on the type of information required (which of the key questions need answering and to what level of accuracy) and the on-site conditions (complexity, disposal methods, available information, etc.), different portions of the methods need to be applied. Predictive capability is best achieved by using a combination of data sets and methods, rather than by reliance on any single procedure (Cravotta, 1997).

The figure on the following page (Figure 2) shows the suggested steps to follow when trying to predict the occurrence and magnitude of AMD at opencast collieries in South Africa.

4. SUGGESTED SEQUENCE of ACTIVITIES

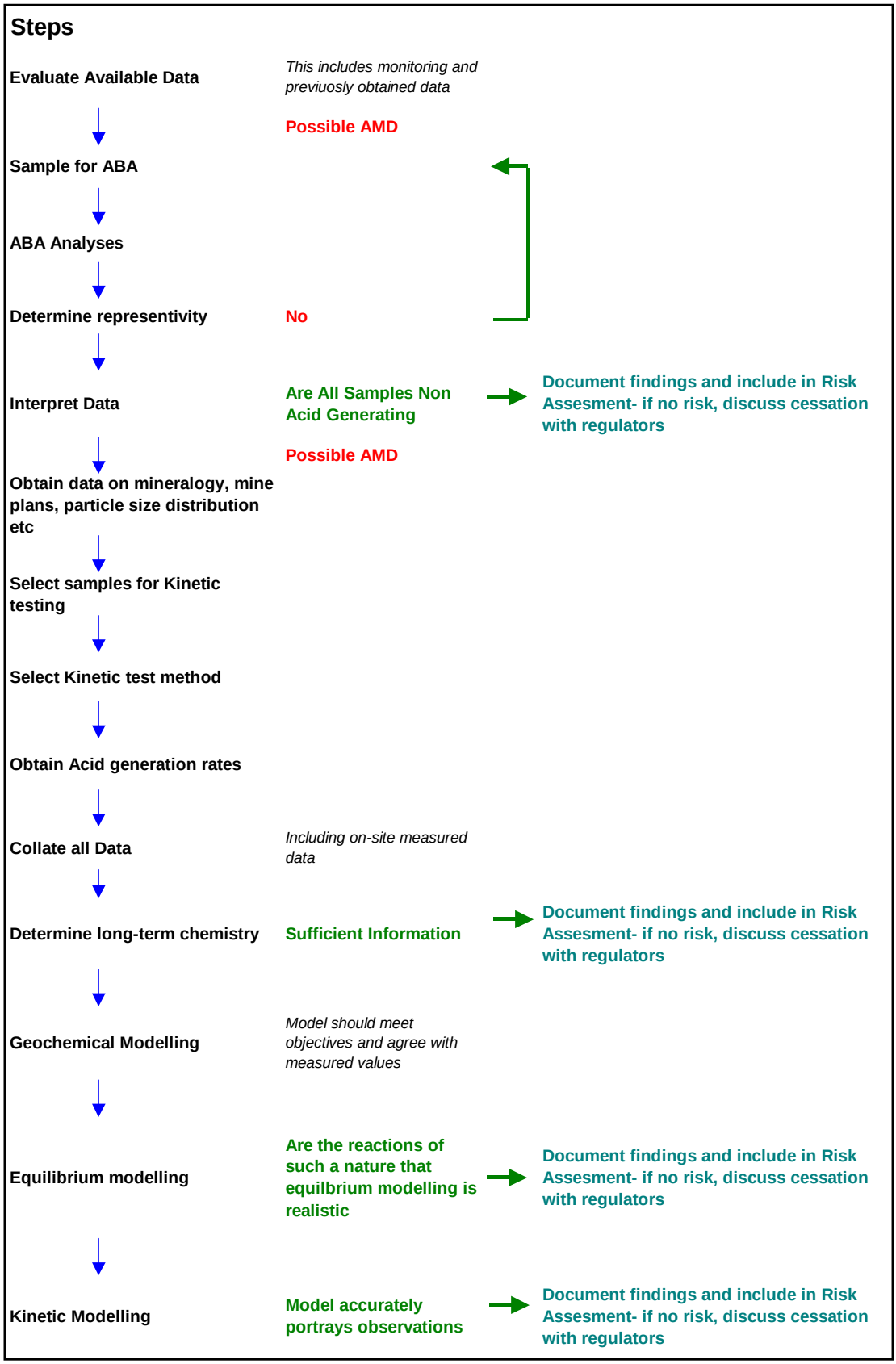

Figure 2. Suggested flow path.

5. STATIC METHODS

Acid-Base Accounting (ABA) is a first-order classification procedure whereby the acid-neutralising potential and acid-generating potential of rock samples are determined and the difference (net neutralising potential) is calculated. The net neutralising potential and/or the ratio of neutralising potential to acid-generation potential, is compared with a predetermined value, or set of values, to divide samples into categories that either require, or do not require, further determinative acid potential generation test work. ABA indicates the overall balance of acidification potential (AP) and neutralisation potential (NP) (Schafer Laboratory, 1997). In its most basic form, ABA is simply a screening process. It provides no information on the speed (or kinetic rate) with which acid generation or neutralisation will proceed and because of this limitation, the test work procedures used in ABA are referred to as Static Procedures (Mills, 1998c; Ziemkiewicz and Meek, 1994).

The primary advantages of the Acid-base accounting method are:

1. Short turn-around time for sample processing.
2. Low cost.
3. Relatively simple analytical procedures.
4. Relatively simple interpretation of results (Hunter, 1997b; Evangelou and Zhang, 1995).
5. Interpretation is based on decades of international research/experience.
6. Correlation to field has been shown by case studies (local and abroad).

The widespread use of static tests in AMD prediction has been justified on the basis of historical and generally successful applications to North American coalfields (Jambor, Dutrizac and Chen, 2000). Overall the static test can be regarded as a first screening level for mine drainage prediction, which provides a very good indication of acid-generating potential.

The limitations of ABA are thus the following (most of these limitations also apply to several other methods):

- It only provides a possibility of occurrence.
- Reaction rates are ignored (ABA generally tests the fast reacting species; slow reacting neutralising species will usually not prevent acidification. See comments by Jambor *et al.* (2000) discussed in the main document).
- Assume instant availability of reactive species. However, nearly all rock samples lacking carbonates (which are fast reacting thus instantly available) or not of dunite composition (predominantly olivine + serpentine) have insufficient NP to be classifiable as “not potentially acid-generating” if the minimum limit for

this category were to be set at, for example, 20 kg CaCO3 equivalent/tons of material (Errington, 1991).

- Simple reaction stoichiometry is assumed.
- Size effects are ignored (Limestone particles of greater than 6.4 mm are coated with precipitates and are only 20% utilised when acid conditions are in evidence (Scharer *et al.*, 2000). However, from this paper it is clear that if a 4:1 NPR is used then only 10% fines is required for the system to react as expected. From the trenches dug in the spoils a > 10% fines ratio is a valid assumption in South African conditions, therefore this limitation is a minor consideration in spoils).
- Extrapolation to the field is uncertain when volumetric calculations cannot be made.

Despite all these limitations ABA is a very important component of the ABATE strategy. It has been used widely across the world, and the interpretations and test methods are well-established. Acid-base accounting and other static tests only provide an initial assessment of the potential of mining wastes to produce AMD, but the methods are and will be widely used to get an overall view of the potential for a specific site. Static tests for coal mine overburden can be used for more than "screening". Currently researchers such as Cravotta (1997) have far more faith in ABA than in leaching tests for prediction of mine drainage quality in the northern Appalachians.

The following procedures are the most commonly used static test methods :

- Paste pH.
- Peroxide methods.
- Static Net Acid Generation (NAG) Procedure.
- BC Research Initial Test.
- Sulphur content.
- BC Research Confirmation Test.
- COASTECH modified biological oxidation test.
- Sobek Neutralisation Potential Method.
- Carbonate NP determination.
- Modified Acid-Base Accounting procedures for Neutralising Potential.
- Lapakko Neutralisation Potential Test Procedure.
- Calculated NP.
- Net Carbonate Value (NCV) for Acid-Base Accounting.

A detailed discussion of all these methods is given in the main report for this project. Several of the methods were evaluated and based on the findings from this research. The following methods are recommended for static testing (see main report for results of the assessments):

- Paste/Initial pH and solution products
- Acid Potential Using Hydrogen Peroxide or Leco Furnace
- Oxidation Products Analysed
- Neutralising Potential Using Sulphuric Acid

These methodologies will be outlined below.

5.1 ABA Terminology

- AP (Acid Potential) = S% x 31.25
- NP (Neutralisation Potential) - the capacity of a sample to consume acid (also referred to as base potential)
- NNP (Net Neutralising Potential) = NP - AP
- NPR = NP:AP

Units: Usually kg of $CaCO_3$ equivalent of net neutralisation potential per ton of rock

5.2 Samples Required

Representative samples should be selected for testing. Guidelines based on area and volumes have been suggested in certain regions overseas (SRK, 1989). Thus for example in Pennsylvania, an average of 1 cored borehole would be required for every 6 - 8 ha to give representative samples and results acceptable to the authorities (Tarantino and Schaffer, 1998). In the 1989 draft guidelines for British Columbia (SRK, 1989) the following graph was given to determine the minimum number of samples to be taken, based on the mass of geologic unit to be sampled (based on data collected by NORECOL Consultants):

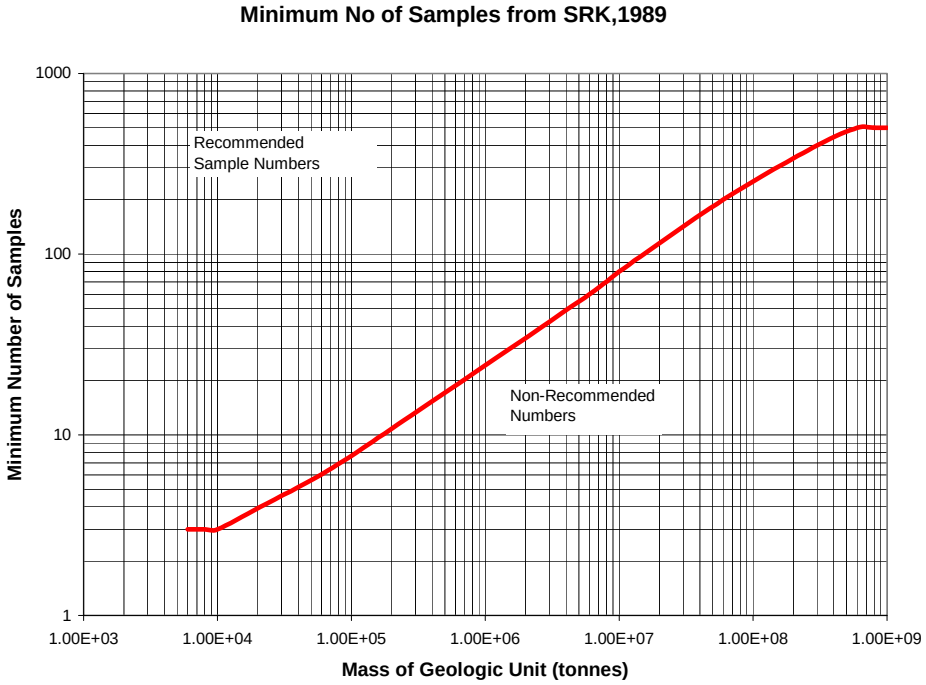

Figure 3. Minimum No. of samples based on mass of Geologic Unit.(from SRK, 1989)

These empirical methods are useful for a preliminary guide; they are, however, based on data from different environments to those encountered locally. It is therefore suggested that sampling programs are conducted in a stepwise fashion and that the representativity of the sample set be determined. Once a more complete database is available for South African opencast coal mines, analysis of the data should provide a more generic areal guideline for sample numbers.

There are several statistical methods to determine the adequacy of sampling. Several of these methods are very intricate and cumbersome in application and the use would be impractical to enforce.

Several parameters pertaining to ABA have normal or lognormal distribution in the field. Examples of these are initial pH (normal in undisturbed strata) and acid potential (log normal). If a population exhibits a normal distribution, the following equation can be used to evaluate the number of samples (n) required (Walpole, 1982):

$$n = (Z_{\alpha/2}\sigma / e)^2$$

where Z = the two tailed value of the standardised normal deviate associated with the desired level of confidence.

σ= the preliminary estimate of the standard deviation.

e = the acceptable error (half the acceptable confidence interval).

An example would be for 80% confidence levels (considered at this stage to be the minimum acceptable level), Z=1.26 and the error value (e) would be 10% of the determined mean for the sample set.

The error estimate associated with the (preliminary) sample set for each confidence level is largely determined by the number of samples in the set and the observed standard deviation (Walpole, 1982).

$$Z_{\alpha/2}\left(\sigma / \sqrt{n}\right)$$

It is important to reiterate that these equations are only valid for normal distributions. However, if data can be transformed, the equations are still valid, provided the transformation is taken into account for the error estimate (van Zyl, Personal Communication, 2000).

The representativity of a data set should therefore be based on an adequate three-dimensional distribution of the areas and the statistical requirements of the investigation.

5.2.1 Sample preparation

Representative samples must be obtained. These should then be quartered, recombined and resampled. From this, the portion submitted for crushing must be selected.

Samples are individually crushed in a jaw crusher; a disc mill or similar should be used to pulverise the crushed fragments to <325 mesh size.

The quartering and sub-sampling of the pulverised material must then again be done to select the portions to be used in ABA testing.

5.2.2 Paste/Initial pH

It is suggested that a distinction be drawn between the field determination of pH on rock samples and those in the laboratory. Thus, it is recommended that the term ”paste pH” be used for field determinations and “initial pH” for those in the laboratory.

It is recommended that a 1:10 ratio of sample to water, measured after 24 hours, be used. This allows a more realistic determination of the current pH and also allows solubility reactions to be more complete than an instantaneous or 10-minute measurement. The 1:10 ratio also allows analysis of the supernatant to provide an indication of the currently available leachable elements.

5.2.2.1 Methodology:

1. Use 1 g of crushed sample submitted for ABA
2. Add 10 ml of deionised water

3. Allow solution to stand for a 24-hour period
4. Measure and record pH as "Initial pH"

5.2.3 Acid Potential using Hydrogen Peroxide

5.2.3.1 Sample Preparation

Drill core and bulk rock samples should be crushed to a nominal 4 mm and a sub-sample pulverised to approximately 200 mesh (<75 µm). Tailing and process residue samples can be tested 'as received'.

5.2.3.2 Reagents

Reagent 1: H_20_2 - BDH 'Analar' Analytical Reagent 30% w/v (100 V).

5.2.3.3 Method

1. Add 120 or 80 ml, incrementally, of Reagent 1 to 4 g of pulverised sample in a 500 ml wide mouth conical flask or equivalent. Cover with a watch glass and place in a fume-hood or well-ventilated area. The H_2O_2 should be at room temperature before commencing test. In cases where there is very violent reaction and incomplete oxidation is possible, repeat the process with 2 g sample to ensure complete oxidation.
2. Allow sample to react until 'boiling' or effervescing ceases.
3. Allow solution to cool to room temperature, then record final pH as "Oxidised pH" (NAG pH).
4. Rinse the sample that has adhered to the sides of the flask down into the solution with deionised water.
5. Analyse the supernatant for sulphate (and all other ions) and back-calculate acid potential in kg/t (AP = S% x 31.25 kg $CaCO_3$ equivalent per ton). (See main document for open/closed system arguments).
6. Alternatively the % S can be determined by a Leco analyser.

5.3 Neutralising Potential Method

H_2SO_4 (0.06N) is added to pulverised rock samples. The pH of this slurry must be below 2.5 after 24 h, before back titration to a pH of 7 is done with NaOH (0.06N). If the pH is >2.5, more H_2SO_4 is added and the sample is left another 24 h for reactions to complete.

- 5 g sample weighed into a beaker and approximately 15 ml of 0.06N standardised sulphuric is added.

- The beaker is covered with parafilm (to prevent excess CO_2 exchange) and allowed to stand for 24 h.
- The pH is recorded.
- If the sample is still at a pH of more than 3, additional increments of acid are added and the process repeated.
- The procedure is repeated until the pH-level remains below 2.5 after 24 h.
- After an additional 24 h, the sample is titrated to a pH of 7 with standardised sodium hydroxide.

Calculations are given below.

5.4 Calculations

AP: $\frac{SO_4 \text{ (mg/L)}/\text{weight(g)}}{1000}$ x ml H_2O or H_2O_2 = kg SO_4/t of sample

Acid Open (AP $CaCO_3$kg/t) = $\frac{SO_4 \text{kg/t}}{48}$ x 50

Acid Closed = Acid Open x 2

Base Potential (NP)= $CaCO_3$ kg/t = (N H_2SO_4 x ml acid) - (N NaOH x ml alkali)/weight(g) x 50

NNP Open = Base (NP) – Acid Open (AP)

NNP Closed = Base (NP) – Acid Closed (AP x 2)

5.5 Total Acid-Base Potential for a Mine

The calculation of the total acid-base potential for the total mine is the next stage. The following is a step-by-step procedure list:

If the recommended procedure of core boreholes has been used for sampling, overall mine ABA can be determined by volumetric or depth normalisation techniques.

- Hodgson and Krantz provide the following methodology for depth normalisation: Relate the laboratory acid-base values to the field situation by calculating the acid-base distribution for the mine, based on lithostratigraphic information available from prospect boreholes. This value is calculated as follows. The normalised strata NNP is obtained by multiplying the sample NNP with the normalised strata thickness. Strata thickness is only available where core samples could be obtained. The mine NNP is obtained by summing all the normalised strata NNP's.
- A better method would be to relate the sample ABA values to the samples overall volume of influence. The recommended strategy is as follows:

1. Determine the area of influence of each core borehole using a technique such as Theissen polygons.
2. Calculate the equivalent tons of each ABA parameter by using these areas together with the sample density.

3. Sum these over the length of the borehole to determine the overall ABA parameters for each borehole.
4. Add these values for each area to obtain the overall assessment for each spoils area.

- Hodgson and Krantz (1995) provide the following guidance:
- Quantify each source of water to the pit, and calculate dilution factors to various portions of the pit.
- Identify areas and calculate the volumes of spoil which will be flooded when the pit has filled to its maximum capacity, after pit closure. This spoil will not contribute to the total acid potential of the pit provided that the flooded material does not come into contact with acidic ferric-rich waters.
- Subdivide the pit into areas of uniform spoil characteristics. Delineate areas where coal discards, coal slurry or other material with a high acid-generating potential have been dumped. The latter will be so-called 'hot spots' where significant acid generation will be initiated.
- Identify mixing cells and flow paths within the spoil, along which spoil waters of different compositions will flow and mix. Apply chemical models to each cell to predict the salinity and elemental compositions for the spoil water, as it evolves as a result of mixing on its way to the decanting point of the pit.

5.6 Screening Criteria

Until there is a large enough, comparable acid-base accounting database in South Africa, it is recommended that the international criteria be used.

The criteria to be used are the following:

- Net Acid Generating Test (NAG) pH
- Net Neutralising Potential (NNP)
- Neutralising Potential Ratio (NPR)
- % S & NPR

A brief description of each set will be given in the sections below.

5.6.1 Net Acid Generating Test (NAG) pH

This value will be obtained from the acid potential test described previously.

These can serve as a rough guideline but not as stand-alone criteria in categorising the samples.

Final pH in NAG Test	Acid Generating Potential
> 5.5	Non-acid generating
3.5 to 5.5	Low risk acid generating
<3.5	High risk acid generating

The 5.5 pH-value stems from the fact that pure deionised water in equilibrium with CO_2 will have a pH-value of around 5.69. Therefore anything above this should be non-acid generating.

5.6.2 Net Neutralising Potential

Research and experience across the world have shown than there is a range from –20 to 20 kg/t CaCO3 where the system or sample can either become acidic or remain neutral. However, when used in conjunction with the other criteria, this uncertainty can often be resolved.

Where Net Neutralising Potential (NNP) = Neutralising Potential (kg/t CaCO3)-Acid Generating Potential (kg/t CaCO3)

The criteria are as follows:

If NNP =NP-AP <0 The sample has the potential to generate acid

If NNP =NP-AP >0 The sample has the potential to neutralise acid

More specifically any sample with NNP<20 is potentially acid generating and any sample with NNP > -20 might not generate acid

The graph below shows how the NNP can the NAG pH using the methodologies described can be combined to visually portray the results. The graph also serves as a first-order QA/QC procedure since a negative NNP should have a low final pH and a high positive NPP should remain neutral under oxidising conditions.

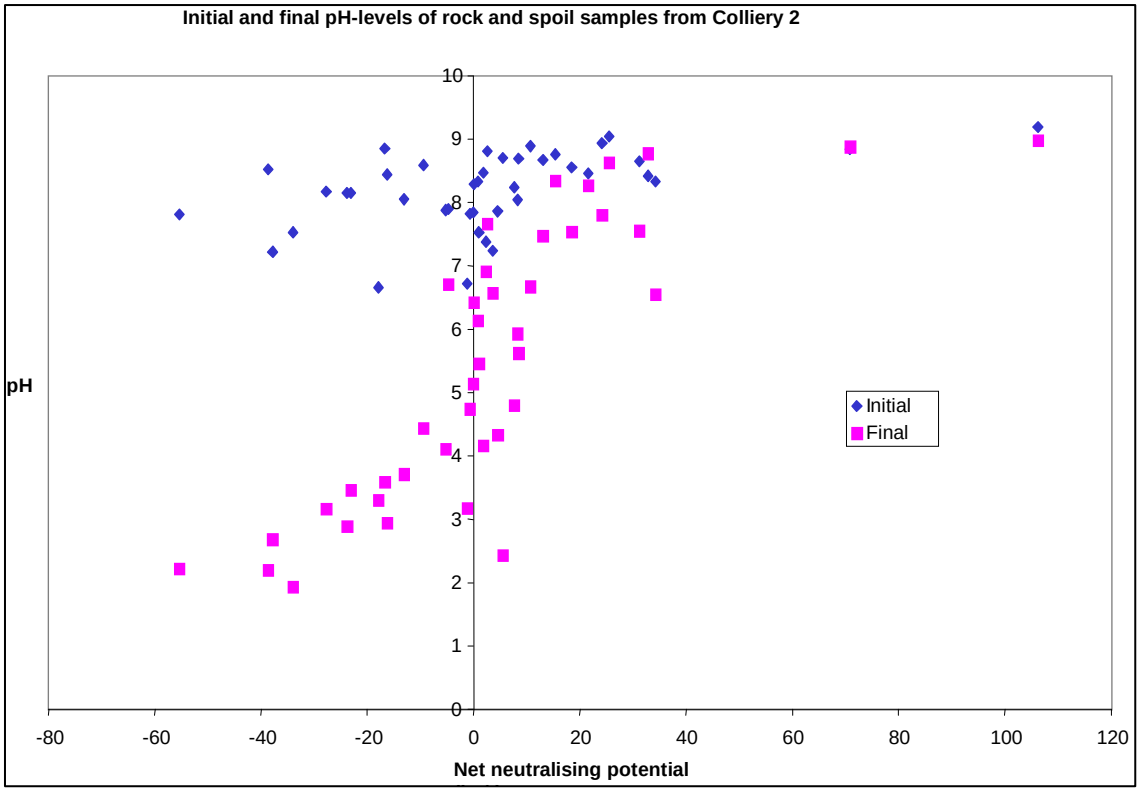

Figure 4: Initial and Oxidised (NAG) pH vs NNP

5.6.2.1 Neutralising Potential Ratio (NPR)

Guidelines for screening criteria based on ABA (from Price *et al.,* 1997b).

POTENTIAL FOR ARD	INITIAL NPR SCREENING CRITERIA	COMMENTS
Likely	<1:1	Likely AMD generating
Possibly	1:1 - 2:1	Possibly AMD generating if NP is insufficiently reactive or is depleted at a faster rate than sulphides
Low	2:1 - 4:1	Not potentially AMD generating unless significant preferential exposure of sulphides along fracture planes, or extremely reactive sulphides in combination with insufficiently reactive NP
None	>4:1	No further AMD testing required unless materials are to be used as a source of alkalinity

The criteria above can also be plotted to give a visual indication of the likelihood of acid generation as shown in Figure 5.

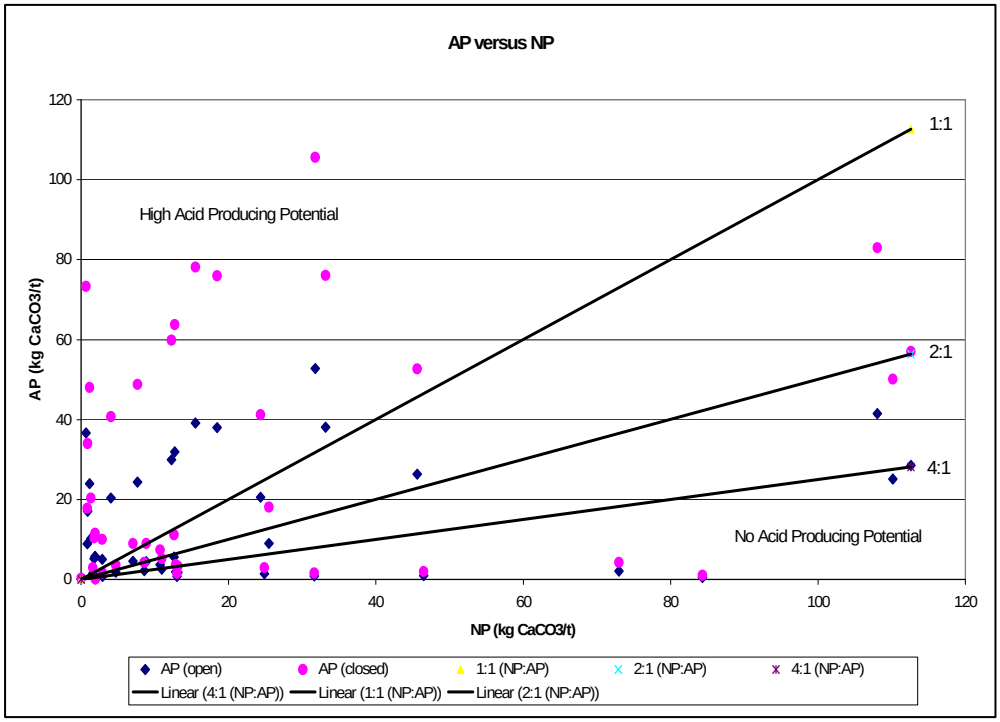

Figure 5. Plot showing different categories of acid-generation potential based on NPR.

5.6.2.2 % S and NPR

A set of rules, based on several of the factors calculated in ABA, was reported by Soregaroli and Lawrence (1998). It has been shown that for sustainable long-term acid generation, at least 0.3% Sulphide-S is needed. Values below this can yield acidity, but this is likely to be only of short-term significance. Using this fact and the NPR values, another set of rules can be derived as follows:

- Samples with less than 0.3% Sulphide-S are regarded as having insufficient oxidisable Sulphide-S to sustain acid generation.
- NPR ratios of >4:1 are considered to have enough neutralising capability.
- NPR ratios of 3:1 to 1:1 are considered inconclusive
- NPR ratios below 1:1 with sulphide-S above 0.3% are potentially acid generating

This can again be graphically evaluated, with the red block showing high likelihood of acid generation, the green low, and the grey region uncertain. Samples would only plot in the white region if a high sulphide value occurs in a rock with very high neutralising capabilities.

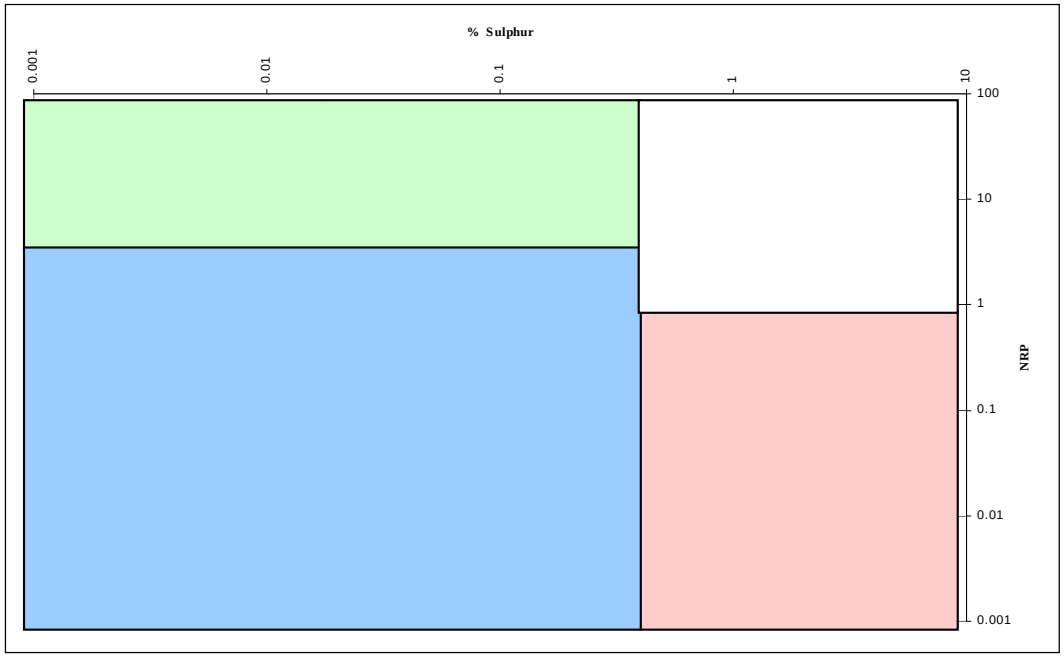

Figure 6. Evaluation plot using %S and NPR to differentiate samples

The overall criteria for an opencast spoil can be evaluated in a similar way, once the volumetric calculations have been made.

5.6.2.3 Extrapolation to the entire mined area using Theissen Polygons

One of the biggest criticisms of ABA is that the results are often difficult to extrapolate to a field scale. This section will explain an extrapolation technique that can be used, if lithological samples have been tested across the extent of the mine.

The Theissen polygon technique is used by the Pennsylvanian State authorities to assist in the evaluation of opencast coal mines (Perry, 1998). The Theissen polygon method is used conventionally in determining the average rainfall in a catchment based on the value and locality of each measuring station. It provides an excellent method for weighting the influence of each borehole on which ABA is done. When the entire extent of the borehole has been tested, as is recommended in this document, it provides a relatively easy, yet powerful, volumetric calculation to predict what would happen at an opencast mine.

The areas that each borehole "represents" can therefore be calculated. Using the methodology set out by Perry (1998) and the spreadsheets included in the ABACUS tool (see 5.6.3), it is possible to calculate the approximate tonnage of overburden that will be spoiled and the associated tonnage of acid production and

neutralisation potential, based on the areal determination, fraction-spoiled and average density of each layer.

5.6.3 Integrating the criteria

In order to be consistent with the application of criteria, a simple Excel-based tool called " Acid-Base Accounting Cumulative Screening tool", or ABACUS, has been developed. This tool applies all the rules outlined above and incorporates several of the graphical presentations. It is felt that this will assist both the practitioners and regulators in consistent application and interpretation of the rules associated with ABA.

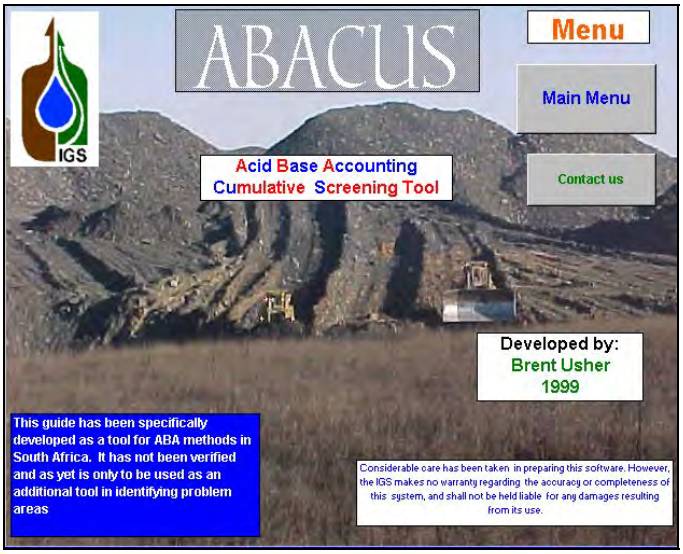

Figure 7. ABACUS entry screen.

The tool is very simple and is menu/button driven, with macros programmed to guide the user to the correct interpretation.

The inputs required are the following:

- Sample number.
- Neutralising potential.
- Acid Potential or % S.

Based on these the following will be given:

- Open system NNP.
- Closed system NNP.
- Net Neutralising Ratios (NPR).
- Interpretations based on the screening criteria discussed in the preceding section.
- Interpretive graphs will be automatically generated.

- Additionally, another concept has been incorporated, namely that of an ABA index. This index uses all the values obtained from different tests and ratios calculated to provide a universal value to interpret the data. This ABA index will need to be evaluated over time and the factors assigned to each type of test reassigned. Currently the values used are arbitrarily assigned, but it has been tested for sensitivity and output generated with various real and hypothetical values.
- Conversion to a WISH compatible data sheet.

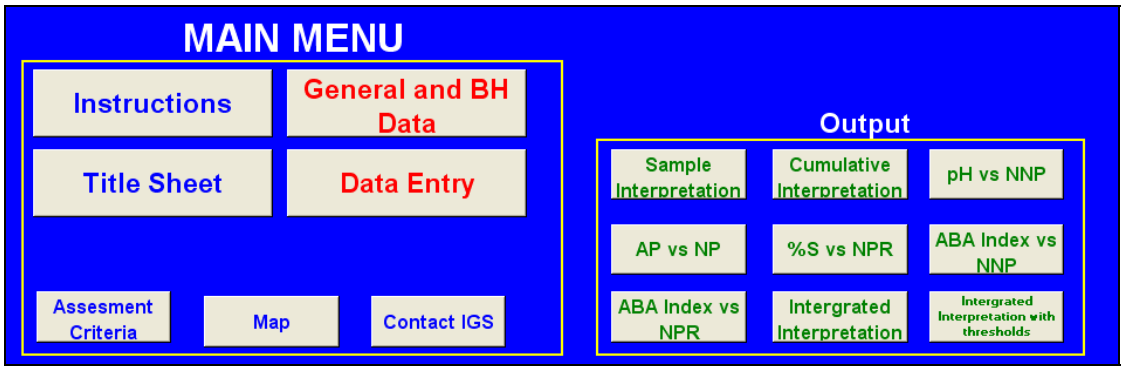

Figure 8. Menu for ABACUS.

A step-by-step guide to input and interpretation is given with ABACUS.

The system can accommodate the volumetric calculations, as discussed in the preceding section, in cases where depth specific information is available for the area under investigation. Application of such volumetric calculations is given in Section 5.6.2.3 of the main report.

6. KINETIC TESTS

The term kinetic is used to describe a group of test work procedures wherein the acid-generation (and metal volatilisation and transport) characteristics of a sample are measured with respect to time (Mills, 1998g and Chemex Labs, 1997). Many types of kinetic tests have been documented and these can vary in complexity, duration, cost and the kinds of data that can be obtained. In the course of the project, 24 kinetic tests were run, with some of the humidity cells running for around eighty weeks.

6.1 Types

The following list shows different categories of tests:

1. Humidity cells
2. Column tests
3. Accelerated biological oxidation tests
4. Field tests

5. Specialised test apparatus

6.2 Reasons for doing kinetic tests

6.2.1 The reasons for doing kinetic tests include:

For a proposed new mine, specific objectives for both the short- and long term can include:

- Validation of static test results and classification
- Determination of the rate of sulphide oxidation/acid generation
- Determination of the rate of neutralisation depletion
- Determination of the availability of NP
- Time to the onset of AMD
- Evaluation and selection of AMD control methods
- Prediction of water quality
- Comparison of different mitigation methods

For an existing coal mine where AMD might already be a problem, some or all of the above objectives also apply.

In addition, the following could be obtained:

- Evaluation of the extent of oxidation
- Evaluation of the extent of neutralisation
- Evaluation of stored reaction products within wastes

6.3 Suggested methodology

6.3.1 Humidity cells

The recommended laboratory test is a humidity cell, and the given procedure should be followed unless a deviation is justified. Kinetic tests are not optional, but are critical in predicting drainage chemistry even in the absence of acid generation (Morin and Hutt, 1997). In Designation: D5744-96 Standard Test Method for Accelerated Weathering of Solid Materials using a Modified Humidity Cell (ASTM, 1996), a ”standardised methodology” is provided for the running of humidity cells. Much of the methodology discussed below originates from this and similar methods.

Humidity cells have been in use for almost 30 years. A humidity cell is typically a cylinder fitted with a base plate equipped with a drain hole and tubing nipple. Approximately 2 - 3 cm from the bottom of the base plate is a removable perforated plate or screen which supports the sample. Materials such as inert geofabrics or

landscape fabric may be used to prevent particularly fine samples from passing through the perforated plate. The size and shape of the humidity cell will vary whether the sample is waste rock or tailings. For waste rock forming the spoils, the humidity cell is usually tall and slender, with dimensions approximately as shown in the diagram (Figure V). The precise dimensions of the cell are less important than adhering to the basic conditions, which are described below.

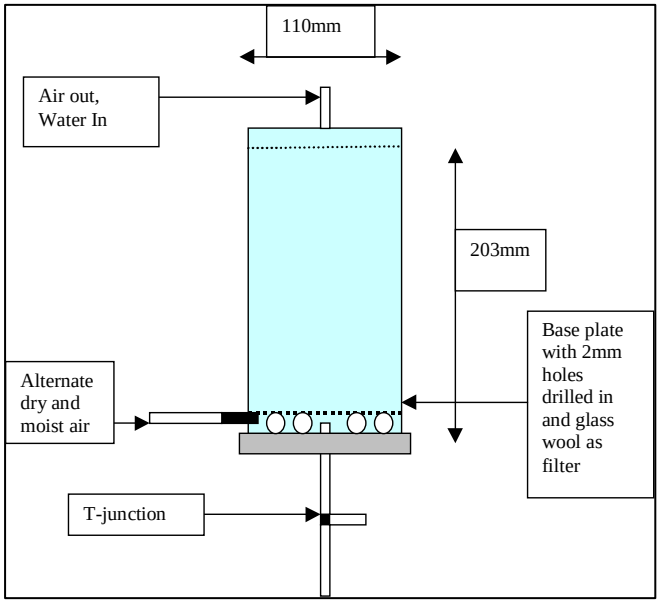

Figure 9. Humidity cell configuration used at the IGS.

Approximately 1 kg (dry weight) of sample is placed in a humidity cell, forming a relatively flat surface. Air is continuously pumped into the cell according to a cyclic pattern. Air is introduced below the sample in a waste rock cell so that it can circulate more freely through it. One testing "cycle" takes place over 7 days. The first 3 days of the cycle is the "dry" portion during which background laboratory air is passed through a waste-rock sample. The next 3-day period is the "wet" portion of the testing cycle, when laboratory air is first pumped through a humidifier unit and then into a cell. On the final day of the testing cycle, a sample "rinse/leach" is done. A known amount of distilled/deionised water is added to the top of the cell, allowing the sample to soak for a specified period, and then drained for analysis. The purpose of the weekly rinse/leaching is to wash out any weathering reaction products that have accumulated in the cell during the week.

6.3.2 Methodology

6.3.2.1 Initial procedure

1. Collect a minimum of 2 kg of sample for humidity cell testing. Record sample information on a humidity cell pre-test sample information sheet (Figure C-3).
2. The beginning of the humidity cell test program will be Week 0. Humidity cells are operated on a weekly cycle.

3. If the sample is rock (i.e. waste rock, ore, etc.), crush the sample to 80% minus 2 cm.

4. Split out sufficient representative portions of the sample and send for all static tests, discussed above

5. Record information on a pre-test sample information sheet. Label these results "pre-test data".

6. Accurately weigh 1 kg of the sample and carefully place in the cell. If the sample is moist, determine water content so a dry weight can be calculated or preferably allow to air-dry before testing. Ensure that the sample has a relatively level surface in the cell.

7. Clamp the outlet. Add approximately 750 ml deionised water to the top of the cell. Enough water should be added to the sample to completely saturate the sample and allow for collection of at least 300 - 500 ml of leachate.

8. Record the amount of water added on a weekly data sheet.

9. Put a collection flask under the cell with the hose draining into it.

10. Allow rock samples to soak for1 -2 hours, letting all suspended particles to settle. Disconnect the hose clamp and drain off the leachate into the collection flask. If the cell will not drain in a reasonable time (i.e. about an hour), check to see if the drainage hose is blocked.

11. Record the volume of leachate collected

NOTE: If excess solids flow from the humidity cell with the leachate, it may be necessary to filter the leachate through coarse filter paper into a clean weighed filter flask. Transfer as much of the solids as possible from the collection flask to the filter apparatus by swirling before transferring. Weigh the filtrate plus the filter flask and record the weight. Record the volume of the filtrate. Keep a record of all weights and calculations. Immediately filter the leachate through a 45 micrometer filter into a 500 mL polyethylene bottle. Label the bottles with the project name, sample ID, cycle number and date. Record all data for this initial rinse as Week or Cycle 0. Analyse as soon as possible or use appropriate sample preservation techniques (e.g. as discussed in Weaver, 1992).

12. Place -25 mL of the "raw" leachate in a 30 mL beaker and perform pH and conductivity measurements on the sample using calibrated instruments. Record all results.

13. Submit the remaining "raw" leachate immediately for complete analysis for the parameters listed below.

Carefully scrape any residue in the filter apparatus back into the humidity cell. Place the filter paper on top of the humidity cell to dry, ensuring it will not be disturbed. When the filter paper and residue have dried, return any solids to the humidity cell.

6.3.2.2 Parameters measured

For each cycle, the following parameters should be measured to facilitate calculations and interpretation:

- Volume of leachate added and collected
- pH
- Specific conductivity
- Alkalinity and/or acidity
- Sulphate
- Dissolved metals of interest (must include Ca and Mg)

Other parameters that can be measured include:

- Redox potential
- Weight of cell and contents after each stage of each cycle to determine moisture content of the test sample (Lawrence and Day, 1997)

Shown below is an example from the research done in this project to show the repeatability of the technique:

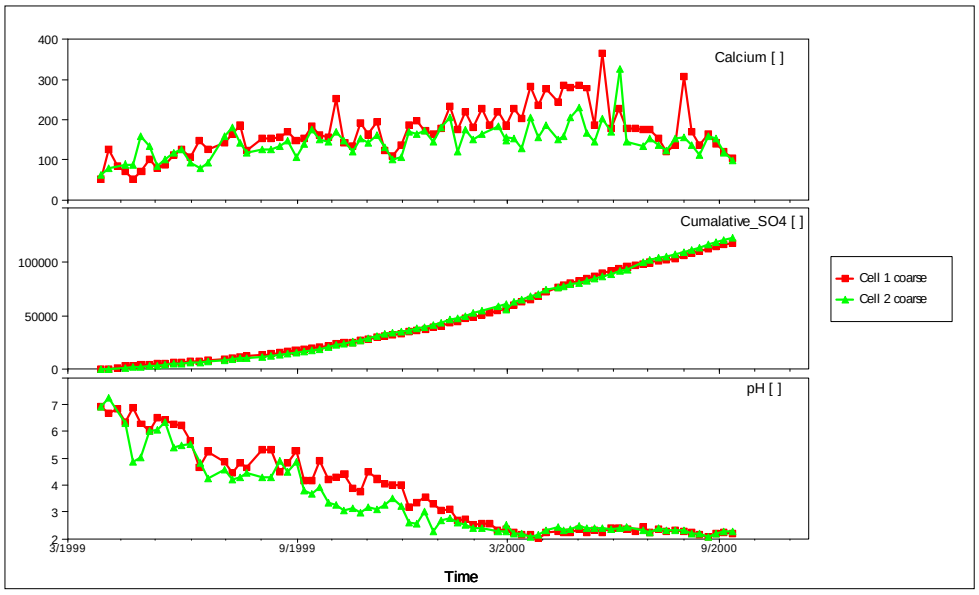

Figure 10. Repeatability of humidity cells .

6.3.2.3 Weekly procedure

1. For the first three days after each rinse episode, dry air is passed through the humidity cell. Recommended flow rates are from 1 to 10 L/s. Connect the humidity cell to a dry air source (see practical pointers below for some ideas from the experiences in this project) to allow a gentle flow rate through the sample. If several cells are running, splits can be taken from a main air line

leading to each humidity cell. Use hose clamps or in-line airflow control taps to ensure that each cell receives roughly the same air flow rate.

2. On the morning of the fourth day, a 3-day wet air cycle begins. Switch the air supply from a dry source to a humid one. Disconnect each humidity cell from the main dry air supply line. The humidifier should be roughly half full of water and contain an immersion heater which is set to 30º C. The air from the main dry air supply is switched to pass through the humidifier unit. This air passes through the humidifier and exits from an aquarium type diffuser. The air pressure is adjusted to provide an adequate air flow without causing rolling waves in the humidifier. Again, if more than one humidity cell is running, use hose clamps associated with each humidity cell to ensure that each cell receives roughly the same air flow rate.

3. On the seventh day, sampling procedures begin. Shut off the main air supply. Disconnect the air supply hose from each of the waste rock humidity cells and clamp shut (waste rock cells have the air inlet at the bottom and will allow leach water to drain back into the humidifier if not clamped).

4. Ensure that the drain hose at the bottom of the cell is clamped. Place a clean 500 mL beaker under each cell with the hose draining into it. Carefully add 500 ml of deionised water. Record the amount of water added. All samples must have good contact with the water.

5. Allow rock samples to soak for approximately 1 - 2 hours again, allowing suspended particles to settle. Disconnect the hose clamp and drain off the leachate into the collection flask. If the cell does not begin to drain in a reasonable time (i.e. about 1-2 h), check the drainage hose for blockage. Allow draining to continue overnight to remove as much rinsing water as possible.

6. Record the volume of leachate collected.

7. Repeat preservation/sampling and analyses as for the initial leaching.

8. Repeat procedure until cell rates have stabilised geochemically.

6.3.3 Duration

The standard ASTM methodology suggests a minimum period of 20 weeks for testing. The duration of the humidity cell test is usually at least 40 weeks, or until the rates of sulphate generation and metal leaching have stabilised at relatively constant rates for at least 5 weeks. Experience, internationally and from this project, has shown that stabilisation can take more than 60 weeks, and significant changes may take place even after several years. Therefore, the criteria on which to close down a cell depend on the site-specific objectives and uncertainty of predictions. Particularly, because of uncertainty and associated risks, some mines have continued kinetic tests for up to 5 years (and some are still continuing).

6.3.4 Calculations

The key objectives of laboratory kinetic tests are (a) long-term stable reaction rates under kinetic conditions and (b) depletion times for acid-generating, acid-neutralising, and metal-leaching minerals. Therefore, interpretations of the tests focus on calculating these values. Recommended equations are listed in Table I.

Table I. Calculations for Humidity Cells (from Morin and Hutt, 1997).

Acid generation

Acid Production Rate(mg $CaCO_3$/kg/wk) = Acidity (mg $CaCO_3$/L)* Volume Leachate Collected /Sample Weight

Sulphate Production Rate(mg/kg/wk) = Sulphate (mg/L)* Volume Leachate Collected/ Sample Weight

Remaining S_{total} (% of original) = {Initial %S-[(Cumulative Sulphate Production Rate(mg/kg)*32.06/96.06/1000))]/Initial S total as %S}*100%

Remaining $S_{sulphide}$ (% of orginal) = {Initial $\%S_{sulphide}$-[(Cumulative Sulphate Production Rate(mg/kg)*32.06/96.06/1000))]/Initial $S_{sulphide}$ as %S}*100%

Sulphate Production Rate by Surface Area (mg/m2/wk) = Sulphate Production Rate (mg/kg/wk) /Surface Area (m2/kg)

Molar Ratios

Carbonate Molar Ratio = [(Ca mg/L)/40.08) + (Mg(mg/L)/24.31) +(Sr(mg/L)/87.62)] /(SO_4(mg/L)/96.06)

Feldspar Molar Ratio = [(Ca (mg/L)/40.08)+ (K(mg/L)/2*39.1)+ (Na(mg/L)/22.99)] /(SO_4(mg/L)/96.06)

Acid Neutralisation and NP Consumption

Alkalinity Production Rate(mg $CaCO_3$/kg/wk) = Alkalinity (mg $CaCO_3$/L)* Volume Leachate Collected/ Sample Weight

Carbonate Ratio NP Consumption (mg $CaCO_3$/kg/wk) = Carbonate Molar Ratio *Theoretical NP Consumption (mg/kg/wk)

based on :

$2\ H^+ + SO_4^{2-} + (Cax,Mg1-x)CO_3(s) = x\ Ca^{2+} + (1-x)Mg^{2+} + SO_4^{2-} + H_2CO_3$

or $2\ H^+ + SO_4^{2-} + 2(Cax,Mg1-x)CO3(s) = 2x\ Ca^{2+} + (2-2x)\ Mg_{2+} + SO_4^{2-} + 2\ HCO_3^-$

Feldspar Molar Ratio Total NP Consumption (mg $CaCO_3$/kg/wk) = Feldspar Molar Ratio *Theoretical NP Consumption (mg/kg/wk)

based on :

$2\ H^+ + SO_4^{2+} + H_2O + CaAl_2Si_2O_8 = Ca^{2+} + SO_4^{2+} + 2\ Al(OH)3 + 2H4SIO4$

$2\ H^+ + SO_4^{2+} + H_2O + 2KAlSi_2O_8 = 2K^+ + SO_4^{2+} + 2\ Al(OH)3 + 4H4SIO4$

$2\ H^+ + SO_4^{2+} + H_2O + 2NaAlSi_2O_8 = 2Na^+ + SO_4^{2+} + 2\ Al(OH)3 + 2H4SIO4$

Theoretical NP Consumption at pH 6 (mg CaCO3/kg/wk) = Sulphate Production Rate (mg/kg/wk)* 100.09/96.06

based on:

$2\ H^+ + SO_4^{2+} + CaCO3(s) = Ca^{2+} + SO_4^{2+} + H_2CO_3$

Empirical Open-System NP consumption around neutral pH(mg/CaCO3/kg/wk) = Theoretical NP Consumption (mg/kg/wk)+Alkalinity Production Rate (mg/kg/wk)- Acidity Production Rate(mg/kg/wk)

based on :

$2\ H^+ + SO_4^{2-} + CaCO3(s) = Ca^{2+} + SO_4^{2+} + H_2CO_3$

plus $H_2CO_3 + CaCO_3(s) = Ca^{2+} + 2\ HCO_3^-$

minus un-neutralized acidity

Theoretical Closed System NP consumption pH 6.5 (mg/CaCO3/kg/wk) = [Theoretical NP Consumption (mg/kg/wk)*2]- Acidity Production Rate (mg/kg/wk)

based on :

$2\ H^+ + CaCO_3(s) = Ca^{2+} + 2\ HCO_3^-$

minus un-neutralized acidity

Remaining NP(% of original) + {[Initial NP (t CaCO4/1000 t)- Cumulative NP Depletion Rate (mg/kg)/1000)]/Initial NP (t CaCO4/1000 t)}*100%

Table 2 Calculations for Metal Leaching from Humidity Cells (from Morin and Hutt, 1997).

Metal Leaching
Metal Leach Rates (mg/kg/wk) = Metal Concentration (mg/L)* Volume of Leachate Collected (L)/ Sample weight (kg)
Remaining Metal (% of orginal) = {Initial Metal content(mg/kg)-[(Cumulative Metal Leach Rate(mg/kg)/Initial Metal Content(mg/kg) }*100%
Notes: At later stages of some testing programs, analyses for sulphate, alkalinity and metals are not done on a weekly basis but may be decreased to monthly. In this case weekly values for rates can be calculated through interpolation of the proceeding and subsequent measured values.

6.3.5 Practical pointers

6.3.5.1 Air supply

Any source of constant dry air supply is applicable. From cost determinations, the use of pressurised air cylinders is probably excessive where several cells are being operated. Normal air compressors can be used but the demands on the mechanical parts is too great to be sustained, and failure often occurs. This results in loss of supply for certain periods while standby systems are connected. This is naturally undesirable. For most of this project, an electric air pump usually used for aquarium applications was used. This type of pump can supply a constant air supply and operates by a diaphragm, which responds to changes in the electromagnetic fields in an alternating current. It has very few mechanical parts and has been very effective in supplying a constant source of air.

6.3.5.2 Regulation of air supply to each cell

Ensuring that each cell receives sufficient air is a constant challenge, since the relative air permeability of different cells varies according to the type of material and grain size within the cell. Furthermore, as the moisture content changes in the dry cycle and also occasionally preferred air pathways are formed, the flow requirements are changed. Hose clamps from a central source can be effective. However, it was found that using standard tubing and cheap accessories available from most pet shops, in-line taps were most effective in controlling air-flow. It is also necessary to form a loop of the air supply system, so that a more equilibrated air supply is obtained than a system merely draining from a central source. Fitting the cells with tight-fitting lids and bubblers also helps in the regulation of the air-flow and also provides a visual check that each cell is receiving an appropriate flow rate.

6.3.5.3 Humidifier

The design of a humidifier can be made as simple as possible. For this project a 25 Litre plastic drum was used. The necessary in- and outlet holes were drilled and solid piping used to hold the aerator and outlet tubing in place. Sealing all these

points with silicon proved to be effective in sealing the system without losing a significant amount of air pressure through leakage. The drum has held up under the constant pressure as it appears to be an effective humidifier system.

Effective humidification can only be achieved if the aeration is effective. The best way to ensure this is to use an aeration stone similar to those used in fish tank systems. The greater the surface area the air can pass through, the more effective the bubbling is; thus these aerators should be as large as possible. They do need replacing approximately every 4 months since the air holes become clogged, reducing their effectiveness. Humidifier water should preferably be deionised to ensure that the system's reaction is only as a result of the minerals in the system and natural water. This water needs replacing approximately every 2 months, due to turbidity.

6.3.5.4 Temperature control

Temperature control is extremely important for the determination of rates in the field. The optimal temperature range for the *Thiobacillus bacteria* is from around 30º C. The tests should be run at as constant a temperature as possible, to ensure that the observed rates are due to changes in the system rather than temperature changes. Hendry (Personal Communication, 2000) has found that changes in the *in-situ* rates in humidity cells are found with deviations of less than 0.2º C.

6.4 Other laboratory kinetic methods

Several other methods can be used to obtain equivalent information from kinetic tests. In this project, use was made of aerated trays with a large enough area to ensure a constant air supply, and very regular irrigation to ensure sufficient moisture for the oxidation reactions to occur. The cycles and amount of elutant were kept the same. Results from these duplicate tests appear to be very promising in terms of duplication and repeatability. Alternate methodologies can also be applied when a kinetic test is used to illustrate/determine the effect of different management options (covers, water submersion, etc.). In all these cases, it is recommended that standard humidity cells are also done on the same test material. Thus where multiple samples are being tested according to any modified method, at least 20 - 25% of these should be duplicated by standard humidity cell methodologies to prove that they provide equivalent information on acidification, leaching and reaction rates. Where the impact of a particular aspect is to be determined/shown, each of these tests should be compared to the standardised test method through duplicate standard tests, so that the impact of the changed methodology is evident.

6.5 Conclusions from the Research in this Project

Humidity cells are excellent kinetic tests to supplement static ABA. Their advantages are that they can supply rates of reaction and can provide a better assessment of on-site rates. Research by several authors has shown the sulphate production rate to be an accurate assessment of the sulphide oxidation rate where

high enough flushing rates are maintained to prevent secondary mineral precipitation.

Hornberger and Brady (1998) give the following as general principles of kinetic test design and performance, and as guidelines to the major factors to be considered:

1. The size, shape and structure of the kinetic test apparatus should be as simple as is practicable, given that multiple arrays of these devices may be needed to concurrently test multiple rock samples from a proposed mine site. The apparatus may need some complexity to allow fluids and gases (i.e. oxygen and carbon dioxide) to enter, circulate through and exit the apparatus.

2. The dimensions of the kinetic test apparatus should be in proportion to the particle size distribution and volume of the rock sample to be tested, so that there are no adverse interactions (e.g. airlocks or other testing artifacts) between the sample and its container. For example, with a columnar-shaped apparatus, the inside diameter of the column should be at least several times greater than the largest particle diameter within the volume of rock samples.

3. The goals of sampling for kinetic testing should be to obtain rock samples that are representative of the physical (i.e. particle size distribution) and chemical (i.e. mineralogic composition) characteristics of the consolidated overburden strata, backfilled mine spoil or waste dump to be simulated in the test.

4. Multiple lithologic units should not be combined in the same kinetic test apparatus, in composite samples, or especially not in layers, unless the potential acidity or alkalinity of the individual lithologies has already been accurately and unequivocally determined from similar kinetic tests, static tests or equivalent geochemical information.

5. The volume of influent water minus the volume of water consumed during the kinetic test determines the volume of effluent water or leachate. These volumes of water should be properly proportioned to the volume of rock sample and should generally not exceed 1:1 and preferably 0.5 L water to 1 kg sample.

6. Rock samples in kinetic tests should usually not be in a completely saturated condition for the duration of the test, because pyrite oxidation rates will be greatly diminished.

7. Samples should not be agitated excessively once the test is underway. Test protocols that disrupt the oxidising environment, such as shaking the cells, high addition of acidic water and extreme wetting and drying cycles, create an oxidising environment that more closely represents field conditions and are therefore recommended (Frostad and Lawrence, 2000).

8. The pore gas composition within the kinetic test apparatus should be similar to that within reclaimed surface mine spoil, particularly to have a partial pressure of carbon dioxide sufficient to facilitate the dissolution of carbonate minerals.

9. Iron-oxidising bacteria must be present and relatively abundant within the kinetic test apparatus, if the test conditions and results are expected to be representative of pyrite oxidation potential in the mine environment. There is no need for inoculation as several authors have shown that the bacteria are generally present or that the bacteria only have a transient, unnatural effect (Cravotta, 1997, Morin and Hutt, 1997).

10. Maintain temperature conditions between 20°C and 40°C during the test to provide optimum conditions for a healthy bacteria population.

Based on these principles and the findings in this project, the following is recommended:

- Humidity cells should be used as the method of choice for laboratory kinetic tests.

- The standard methodology should be as follows:

    1. Set an apparatus with dimensions similar to those given in the section above or scaled up proportionally when greater mass/particle size is to be used.

    2. Use appropriate methods to maintain the temperature of these tests at 30°C.

    3. Leach with deionised water, collect and analyse for pH, sulphate, alkalinity and the parameters of choice (with Fe, Mg and Ca as minimum).

    4. Pass air through on a cyclic dry/humidified cycle for three days each.

    5. Leach with deionised water on the seventh day, using flushing volumes of half that of the test sample, collect leachate and analyse.

    6. Determine rates of production for all the parameters of choice, together with rates of NP and AP depletion. Report in terms of mass product/mass sample/time period.

This project, and others elsewhere, have shown that very simple methods can supply equivalent information. However, where deviation of the above guidelines is applied, it is recommended that duplicate humidity cells be used as reference to demonstrate that the modified method yields the same results. This is also proposed where a variation on the standard test is done to establish the influence of

a particular management option. In summary thus, the standard humidity cell method should be used as far as possible and where deviating from it, duplicate standard methods should be used for the purpose of evaluation.

The ideal kinetic test for the prediction of mine drainage quality will be:

(a) practical to construct and operate.

(b) of reasonable time and cost requirements to encourage widespread acceptance and use.

(c) representative of the physical, chemical and biological conditions of the mine environment (i.e. in conformance with the preceding eight principles).

(d) readily interpretable due to the capability of producing the range of acidity, alkalinity, sulphate and metal concentrations found in acidic and alkaline mine drainage.

As a final point, the views of Hornberger and Brady (1998) concerning standardisation of the methodology, are briefly discussed. These authors feel that two major advantages of developing standard kinetic procedures are that almost everyone, especially for mine permitting purposes, would be using the same test procedures (which facilitates data comparison and database building) and that scientific and legal controversies between government and industry users of prediction techniques over interpretations of the test results and accuracy of the predictions would be substantially reduced.

In summary the following points are pertinent to kinetic testing:

Factors to be borne in mind include:

- The upscale of kinetic test results to field scale and long periods is often problematic.
- Type of test and equipment should be driven by the environment and answers that are required.
- The length of the testing period is difficult to determine prior to testing.
- From this study humidity cells are suggested as the kinetic test of choice.

Humidity cell tests are vitally important within the ABATE strategy since:

- They provide rates of production under test conditions.
- They provide expected reaction sequence.
- They can be used to test different influences on reaction rate.
- They are short-term tests to determine long-term effects.
- Results can be used in geochemical modelling.

Kinetic tests are the only method of verifying/obtaining much of this data in the predictive program.

From the 24 kinetic tests in this project the following comments are pertinent:

- The humidity cell procedure used in this project was repeatable. Cells run with duplicate samples yielded results that were very similar.
- Good correlation was found between standard humidity test methodologies and more simplified methods. Three sets of duplicate tests illustrated that cheaper and less labour-intensive test protocols could yield similar results.
- The humidity cell results correlated very well with the static ABA done prior to testing.
- Humidity cells can provide reaction rates for different species. Reaction rates for all the cells tested could be obtained.
- Increasing the humidity causes an increase in the reaction rate, in agreement with international research.
- The rates of flushing were sufficiently high to prevent secondary mineral precipitation.
- Humidity cells may not provide an indication of acidity for samples that are uncertain, according to the static test results.
- Standardised tests should be used wherever possible, to build up a database of rates for South African coalfields.
- Where the influence of any particular aspect, e.g. the effect of a cover, is to be proved using a kinetic test, a standard test should be done as a base case for comparison.
- The degree and rate of NP depletion can be determined from these cells.
- The theoretical depletion of NP correlated very well with the pH-development in the cells that acidified.
- The $Ca+Mg/SO_4$ ratio appears to be an excellent early indicator of imminent acidification.
- Humidity cells should be able to provide “threshold” values for acid and neutralising potentials. This will greatly enhance the usefulness and likely success of the prediction of acidity.
- The usefulness of these cells for direct translation to field rates is, as yet, unclear from this research and from research worldwide.
- The variability observed in most spoils as far as mineral, rock/fine size and distribution and depth of soil cover makes the determination of sufficient kinetic tests for spoils an unfeasible task.

- The suggested ASTM test period of 20 weeks is shown to be insufficient by the research in this project. This makes standardisation of the procedure extremely difficult.

7. FIELD METHODS

Field methods are a very important and useful component of the ABATE process. Field measurements provide real data and can add valuable understanding to the overall interpretation and prediction of the mine drainage chemistry.

The most important field methods suggested are the following:

- Rock sampling
- Water sampling
- *In-situ* down-the-borehole logging
- Trenching in spoils

7.1 Rock sampling

There are two main methods of obtaining samples for further testing, namely, cored boreholes and random. Both of these methods could provide sufficiently representative samples. However, it is suggested that for opencast mines, core boreholes be used as the method of choice. The reason is that this provides a complete assessment of all the material likely to be in the spoil, and with sufficient boreholes will provide the most representative assessment of the overall characteristics. A previous section discusses how the results from such cored boreholes can be used to evaluate an entire mine.

7.1.1 Representative samples

The representativity of the samples tested is a vital component of the ABATE process. Without a high degree of confidence in the representativity of the samples, the uncertainty inherent in all the subsequent interpretation and modelling is compounded. By applying appropriate statistical techniques, the minimum number of samples required by the mine can be determined (See section 5.2).

As can be expected, an increase in the number of samples will generally lead to an increase in the confidence (statistically and perceived) of the interpretation.

A further caveat is that the degree of confidence has to be higher for mines deemed non-acid producing by field and static testing alone.

7.2 Water sampling and monitoring

The results of on-site and surrounding water monitoring are important components in ABATE.

Sampling localities include boreholes, pits, discharge points and surface water. This water sampling is useful since it can be used to:

- Give an indication of current acidification
- Provide early warning systems
- Allows comparison to ABA results

Where possible, as much data from the mine as from surrounding mines with similar characteristics must be collected, since this is often the best prediction tool there can be (Brady,1998).

Detailed methodologies for sampling and monitoring are laid out in documents such as Weaver (1992), DWAF (1998) and WDEP (1996). Detailed on-site monitoring and regional evaluation should include water-level data, and not only chemical data, as this will provide insight into likely flow directions and rates.

7.2.1 Down-the-hole profiling

Profiling of the water within and surrounding the spoils is also recommended. This allows *in-situ* assessments that are critical to understanding the system. Suggested parameters include:

- pH
- EC
- temperature
- dissolved oxygen
- redox potential

Using all the parameters, the hydrochemical description of the system can be improved and correlation with features such as coal seams, the influence of refilling pits, etc. can be evaluated. The dissolved oxygen, redox and temperature values can also provide useful information regarding the pyrite oxidation reactions occurring in the immediate environment of the profile. Crucial evidence of stratification of water can also be gathered to improve the conceptual model of the contaminant transport. All these parameters, at a specific depth, are vital for input into, and calibration of, detailed geochemical models used to predict the hydrochemical evolution.

7.3 Test pits in spoils

It is suggested that at existing mines, where evaluation of the characteristics is needed, some test pits are dug in the spoil. Generally, this can be done with the equipment used on site by the mine. Digging several test pits in areas of different spoil orgin and age will enhance the understanding of the site and provide a cross-check and validation of predictions for that site. Test pits in established spoils help to determine areal and age variation.

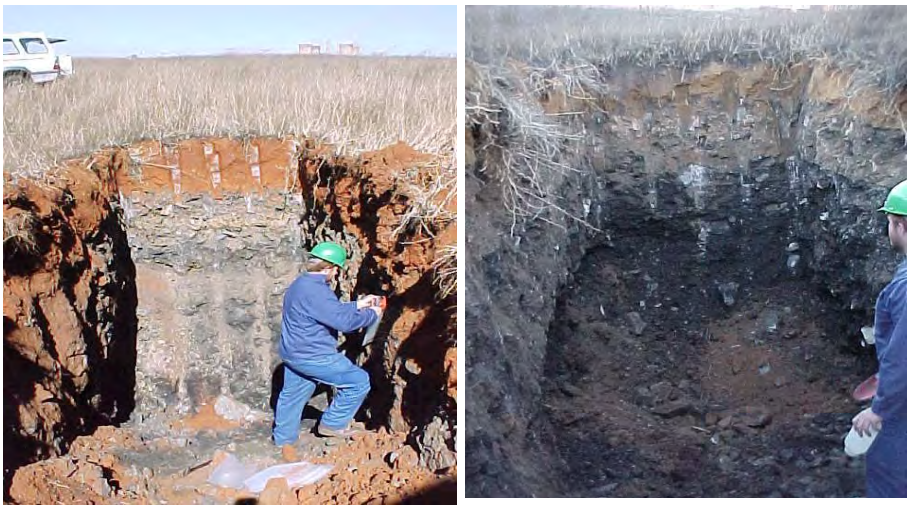

Figure 11. Two profiles - a non-acidic pit on the left and an acidic pit on the right.

7.4 Other methods

Where it is required to make a full assessment of on-site acid production and other reaction rates, the following parameters are also required to be determined in the field:

- Oxygen (and CO_2) pore gas profiles
- Temperature profile across the site
- Moisture content profile

7.5 Conclusions from this project

Detailed fieldwork, that should include the following, is suggested:

- Water sampling and ongoing monitoring.
- Representative sampling of spoil material, preferably through boreholes so that volumetric and depth determinations can be made.
- *In-situ* profiling of water.
- Test pits in established spoils to determine areal and age variation.

The usefulness of field methods is that they:

- are the most reliable measurements.
- represent the best Kinetic reactor there is (As Morin and Hutt (1997) state, " Undoubtedly the most valuable and representative kinetic test that can be operated at a mine site is the full-scale operation of mine site components").
- determine current situation.
- provide understanding of controls on chemistry.
- allow comparison to ABA.
- serve as an early warning system.
- provide information to make decisions on appropriate control measures.

8. MODELLING

Modelling can play a critical role in the ABATE process. Care must, however, be taken so that the output from these models is evaluated according to the applicability and confidence of the input within the model. The most important consideration is that the quality of the input parameters, together with the correct conceptualisation and use of the appropriate model, determines the quality and usefulness of the output.

Input parameters required by these models include:

Climatic Data.
Physical Data (e.g. dimensions, porosity, moisture content, particle sizes, preliminary physical modelling).
Hydrological Data (infiltration rates, etc.).
Mineralogical Data (field descriptions, interpretation of ABA and preparation of mineralogical inputs).
Water Quality Data (monitoring data).
Transport-Related Parameters
Field Data: Water Chemistry, Mineralogy, Surface Area, Temperature, Oxygen, Water Balance, Pile Structure,
Laboratory Data: Column Test, Humidity Cells,
Database: Kinetic, Equilibrium Thermodynamic.
Shown below in is a suggested outline or approach to using such models for opencast collieries in South Africa.

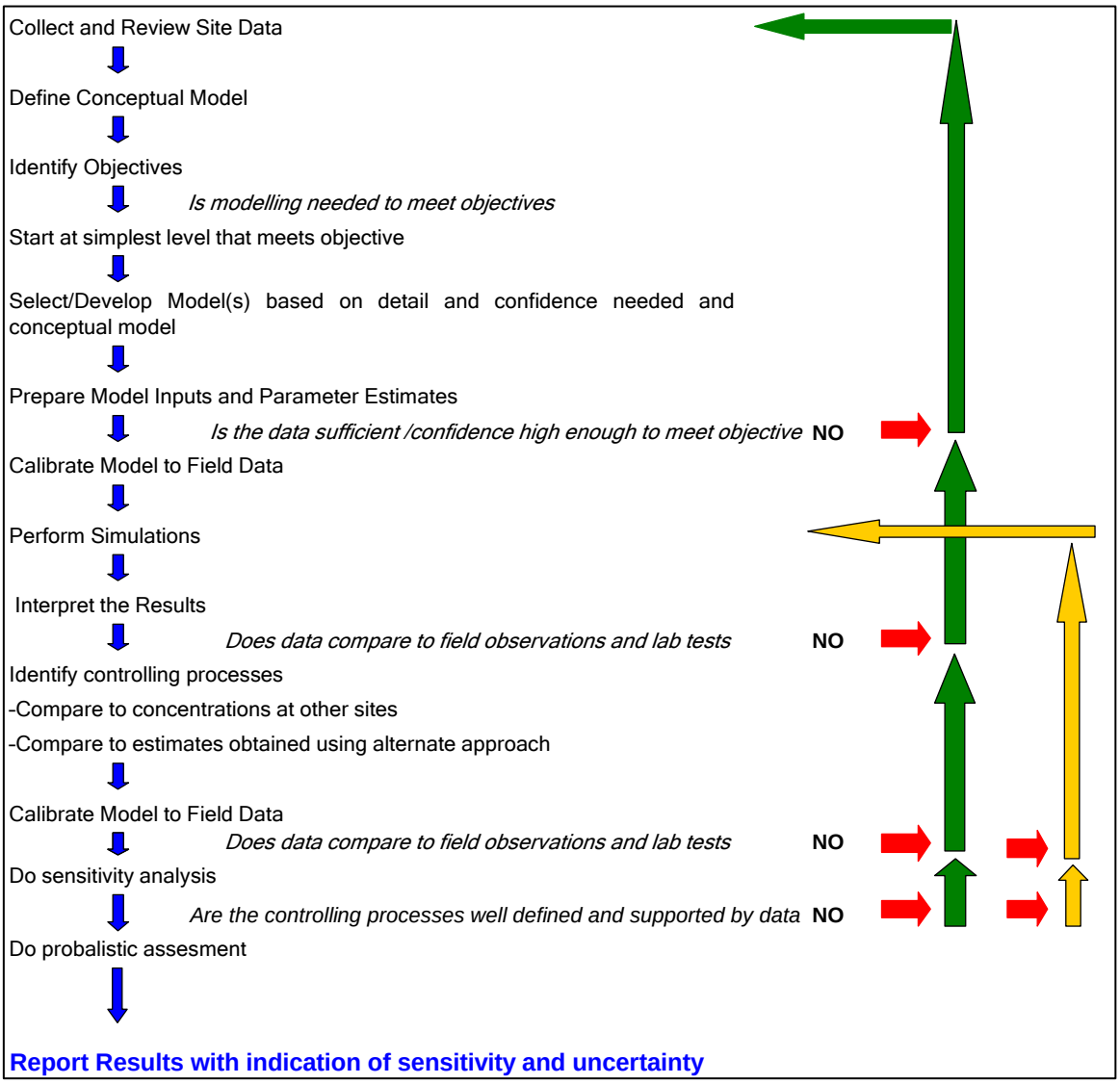

Figure 12. Suggested flow path for hydrogeochemical modelling for prediction of AMD.

In the main report a detailed discussion on the data requirements, modelling approach and applicability of several codes is provided. A matrix of common codes and their applicability is provided in the main report.

A very important aspect relating to the uncertainty associated with geochemical models is also dealt with. To evaluate the sources of uncertainty several aspects need to be considered. The following facts of uncertainty are discussed in the main report (from Bethke (1996) and other authors):

1. Is the chemical analysis used accurate (and representative) enough to support the modelling?
2. Does the thermodynamic dataset contain all the species and minerals likely to be important in the study?

3. Are the equilibrium constants for the important reactions in the thermodynamic database sufficiently accurate?
4. Do the kinetic rate constants and laws apply well to the system being studied?
5. Is the assumed nature of equilibrium appropriate?
6. Most importantly, is the conceptual model correct?
7. Are the flow- and transport parameters of the system well-defined?
8. Is the mineralogical data representative?
9. Have specific on-site conditions (temperature, Redox conditions, dissolved oxygen etc.) been accurately measured?
10. Is the geochemical modelling code appropriate to the system modelled?:

In addition to dealing with these questions, the effect of varying common factors such as particle size (and by implication reactive surface area), water flow, partial gas pressures, different published reaction rates etc are illustrated in section 8.2 of the main report.

8.1 Conclusions Regarding Modelling

- Several input parameters which have been accurately determined are needed.
- Selection of appropriate model tool is vital.
- Provides long-term (+100 years) estimates of changes/trends in AMD quality.
- Enables a comparison between different options.
- Provides the basis for comparing the risk and costs associated with each option.
- It is often associated with large uncertainties.
- Field and laboratory validation can decrease uncertainty.
- Regarded as an advanced step in the ABATE process.
- Illustrations using simplified simulations showed how relatively minor variations (relative to the uncertainty of most of the data used in the models) can yield significantly different results.

Despite limitations, modelling is considered to be a very useful tool in prediction.

9. CASE STUDIES

Three case studies showed the application of ABA to a field scale.

- All of these studies showed a good correlation to static ABA and observations in the field.

- Spoils are extremely heterogeneous. Great variation in particle size, moisture content and the type of material was observed in test pits in the spoil.
- The depth of soil cover has no apparent impact on the spoil water chemistry. Oxygen and moisture penetrate into the system, regardless of the thickness of soil cover.
- Temperatures in the pits can be very low at surface. A rapid increase in the spoil temperature with depth is present in most pits, and at 3m temperatures above 20°C have been recorded. In several of the pits, elevated temperatures ranging from 25-50°C have been recorded.
- There are localised areas of acidification, which are due to specific optimal microclimates; it seems that mineralogical composition plays a more important role than the age of spoils.
- The Optimum case study showed how several of the components in the ABATE process could be used to determine the likely quality emanating from the mine.
- The ATC comparisons illustrated an excellent correlation with ABA from core boreholes, *in-situ* determinations, subsequent ABA and kinetic testing.
- Case study 3 used an example of a mine (Kriel) classified previously as an unlikely acid producer. *In-situ* determinations in spoils of various ages showed that in the upper two to three metres the spoil was pH-neutral to slightly alkaline. Long-term monitoring data from the borehole nearest the test pits, spanning more than a decade, showed that the water quality in the area was currently neutral to slightly alkaline.
- An additional three reported case studies from South African coal mines illustrated the use and value of ABA as a tool in the assessment of coal mine water chemistry.
- The most significant of these illustrates how ABA from an area where mining has long ceased and which experiences considerable problems with AMD, consistently predicts that acidification is likely.

10. FINAL REMARK

As a final remark, Price (1998) should be kept in mind:

- *"Although our understanding of Acid Rock Drainage is far from complete, the available prediction and mitigation tools combined with a well informed, cautious approach should allow mines with a potential for AMD to meet receiving environment objectives and minimise the liability and risk."*

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APPENDIX 1

Detailed methodologies for several ABA methods

STATIC METHODOLOGIES

1 STATIC NET ACID GENERATION (NAG) PROCEDURE

1.1 Sample Preparation

Drill core and bulk rock samples should be crushed to nominal 4 mm and a sub sample pulverised to approximately 200 Mesh (<75 µm). Tailing and process residue samples can be tested 'as received'.

1.2 Reagents

Reagent 1: H_20_2 - BDH 'Analar' Analytical Reagent 30% w/v (100 V), or equivalent, diluted 1:1 with deionised H_20 to 15% (Refer to Note 1).
Reagent 2: NaOH -0.50 M Standardised Solution.

Reagent 3: NaOH - 0.10 M Standardised Solution.

1.3 Method

1.Add 250 ml of Reagent 1(15 % H_2O_2) to 2.5 g of pulverised sample in a 500 ml wide mouth conical flask, or equivalent. Cover with a watch glass, and place in a fume-hood or well ventilated area (refer to note 2). The H_2O_2 should be at room temperature before commencing test.

2.Allow sample to react until 'boiling' or effervescing ceases. Heat sample on hot plate and gently boil until effervescence stops or for a minimum of 2 hours. Do not allow sample to boil dry - add deionised water if necessary.

3.Allow solution to cool to room temperature then record final pH (NAG pH).

4.Rinse the sample that has adhered to the sides of the flask down into the solution with deionised water. Add deionised water to give a final volume of 250 ml.

5.Titrate solution to pH 4.5 while stirring with the appropriate NaOH concentration based on final NAG solution pH as follows:

NAG solution pH	Reagent	NaOH Concentration
>2	2	0.10 M
<2	3	0.50 M

1.4 Calculation

Net Acid Generation (NAG) = 49 x V x M/W, where:

NAG = net acid generation (kg H_2SO_4/tonne), V = volume of base NaOH titrated (ml), M = molarity of base NaOH (moles/l), W = weight of sample reacted (g)

NOTE: If NAG value exceeds 25 kg H_2SO_4 per tonne, repeat using a 1.00 g samples.

1.5 Notes and Precautions

1.1. The pH of the H_2O_2 used in the NAG test should be checked to ensure it is between pH 4 and 7. If the pH is less than 4 then add dilute NaOH (use a solution made up by adding 1 g NaOH to 100 ml deionised H_2O) until the pH is greater than 4 (aim for a pH between 4 and 6). The pH is adjusted to greater than pH 4 to ensure that the phosphoric acid, used to stabilise H_2O_2 in some brands, is neutralised. The pH of the 15 % H_2O_2 should always be checked to ensure that any stabilising acid is neutralised, otherwise, false positive results may be obtained.

1.2. The NAG reaction can be vigorous and sample solutions can 'boil' at temperatures of up to 120^{o}C. Great care must be taken to place samples in a well ventilated area or fume cupboard.

1.3. Caution should be taken in the interpretation of NAG test results for coal reject samples and other materials which may contain a high content of organic material (such as potential acid sulphate soils, dredge sediments and other lake or marine sediments). All organic material must be completely oxidised otherwise acid NAG results can occur which are unrelated to sulphides. Several aliquots of H_2O_2 reagent may be added to the sample to breakdown any organic acidity.

1.4. Samples with positive NAPP value, high sulphur content and high ANC must be carefully evaluated (Miller *et al.*, 1997)

2 BC RESEARCH CONFIRMATION TEST

2.1 Equipment

1.250 ml Erlenmeyer flasks, preferably with a baffled base to facilitate oxygen mass transfer during agitation. 2.Temperature controlled gyratory or reciprocating shaker/incubator equipped with clamps for Erlenmeyer flasks (provision for CO_2 enrichment of the air is desirable). 3.pH meter equipped with a combination pH electrode. 4.Pipette, 5 ml

2.2 Reagents

1.Sulphuric acid, 6N or 12N.

2.Distilled or deionised water.

3.Reagent grade nutrient salts, typically $(NH_4)_2SO_4$, KCl, K_2HPO_4, $MgSO_4.7H_2O$, and $Ca(NO_3)_2$.

4.Bacterial culture containing *T. ferrooxidans* [Cultures should be selected based on their known ability to be able to oxidise ores, waste rock or tailings of similar mineralogy to the test sample.].

2.3 Procedure

1.Crush and pulverise the sample to pass a 400 mesh (Tyler) screen.
2.Prepare bacterial cultures for use as inoculate using standard laboratory techniques. The cultures should have been previously grown on and adapted to ore or waste rock containing pyrite with a sulphur content at least as high as the test sample. Whole pulp inoculate are preferred to cells recovered from solution only. If solids free inoculate, containing very low soluble metal concentrations are required, these should be prepared by differential centrifugation techniques.
3.In duplicate, weigh out 15-30 g (low weight for high sulphur contents) of sample into an Erlenmeyer flask with 70 ml of a nutrient medium containing (typically) 3 g/l $(NH_4)_2SO_4$, 0.1 g/l KCl, 0.5 g/l K_2HPO_4, 0.5 g/l $MgSO_4.7H_2O$, and 0.01 g/l $Ca(NO_3)_2$.
4.Place flask on shaker and periodically add sulphuric acid (6 or 12 N) as required to bring pH to a stable value between pH 2.5 and 2.8. Do not proceed until pH is stable.
5.Inoculate flasks with 5 ml of an active *T. ferrooxidans* culture. Record weight of flask, cap flask with a cotton or foam plug, and place on shaker at 35^{o}C.
6.Monitor flask regularly for pH. Before each measurement, add distilled water to bring flask to original weight to allow for evaporation. In some cases, the sampling of flasks for a soluble species (e.g. Fe, Cu. Zn) might assist in determining progress of the oxidation process.
7.When oxidative activity has ceased, as evidenced by a stable pH (or metal concentration), add half the weight of sample originally used and continue shaking for 24 hours.
8.Record the pH and if above 3.5, terminate the test. If not, again add half the weight of sample and agitate for up to an additional 72 hours and record the final pH.

Typically, about 3 to 4 weeks following inoculation, are required to complete this test.

3 THE MODIFIED ACID BASE ACCOUNTING PROCEDURE FOR NP

3.1 Procedure

1.Add a few drops of 25% HCl to 1 to 2g of pulverised sample (80% minus 200 mesh) on a watch glass or piece of aluminium foil. Observe the degree of reaction and assign a fizz rating as "none, slight, moderate, or strong fizz".

2.Weigh approximately 2.00g of pulverised sample into a 250ml conical flask and add approximately 90ml of distilled water.

3.At the beginning of the test (time = 0), add a volume of certified or standardised 1.0N HCl according to the fizz rating as follows:

Fizz Rating	Volume of 1.0 N HCl (ml)	
	At time = 0 hour	At time = 2 hour
None	1.0	1.0
Slight	2.0	1.0
Moderate	2.0	2.0

4.Place the flask on a shaking apparatus such a reciprocating shaker, maintained at room temperature. After approximately 2 hours, add the second acid quantity as indicated in the above table.

5.After approximately 22 hours, check the pH of the pulp. If it is greater than 2.5, add a measured volume of 1.0N HCl to bring the pH into the range 2.0 to 2.5. If the pH is less than 2.0, too much acid was added in steps 2 and 3. In this case, repeat the test adding a reduced volume of HCl.

6.After 24 hours, terminate the test and add distilled water to the flask to bring volume to approximately 125ml. Measure and record the pH, making sure it is in the required range of 2.0 to 2.5.

7.Titrate the contents of the flask to a pH of 8.3 (this being the usual endpoint for acidity titrations, corresponding to the stoichiometric equivalence point for carbonate/bicarbonate in natural waters in which carbonic acid it the most dominant weak acid, using standardised 0.5N or 0.1N NaOH.

8.Calculate the NP of the sample as follows:

$$\text{Modified NP (kg } CaCO_3\text{/t)} = \frac{[(\text{N x vol(ml) of HCl}) - (\text{N x vol(ml) NaOH}) \times 50]}{[\text{weight of sample(g)}]}$$

4 BC RESEARCH INITIAL TEST

4.1 Assay

The neutralisation potential of a sample is determined by titrating a slurry of finely ground sample with 1.0 N sulphuric acid to a stable end-point of 3.5 using an automatic pH titrator. This choice of end pint is based on the assumption that it represents the limit above which iron and sulphide-oxidising bacteria are not active. Therefore, if the theoretical acid production is not sufficient to lower the pH to below pH 3.5, then bacterial oxidation of the material will not occur and AMD formation is unlikely. This acid consumption, in units of kg H_2SO_4 per tonne of material is calculated as follows:

$$\text{Acid Consumption} = \frac{\text{ml 1.0 N } H_2SO_4 \text{ x } 0.049 \text{ x } 1000}{\text{Sample mass (gram)}}$$

This value can be converted to units of kg $CaCO_3$/tonne for comparison with the results of acid-base accounting tests. Typically, the test takes at least 24 hours to complete. Although the test is more time consuming than acid base accounting, the test is considered to provide a good estimation of the practical NP since excess acid is not employed as in the acid-base accounting methods. In addition, the use of sulphuric acid provides a better simulation of field conditions than hydrochloric acid. AP values based on sulphide-sulphur analysis is advisable (Bruynesteyn, 1984, Cuncan and Bruynesteyn, 1979, and Lawrence and Day, 1997).

5 LAPAKKO

5.1 Sample Preparation

Grind or pulverise sample so that 70% passes a 325 mesh (<44 µm).

5.2 Titration Test

Prepare a stirred mixture of 10g sample in 100ml distilled water.

Using an automatic titrator titrate with 1.0 N sulphuric acid until a pH of 6.0 is reached. The test is complete when less than 0.1ml acid is added over a 4hour period. The amount of acid added can then be used to calculate the NP as follows:

$$\text{NP (kg } CaCO_3\text{/tonne)} = \frac{\text{Acid volume (ml) x Normality Acid x 50}}{\text{Sample weight (g)}}$$

The test can be very time consuming, due to the slow rate of acid addition necessary to prevent over-addition. The acid strength should also be low (<0.05N) for the same reason. (Lapakko, 1994)

pH 6 was selected since it is a commonly applied water quality standard. Therefore, the neutralisation potential available above this pH represents the amount of acid that a mine waste could neutralize while maintaining drainage pH in a range that meets water quality standards.

It should be noted that this method is intended to give the NP present, rather than the NP available for reaction in the field. Consequently, the value determined for waste rock will exceed that which is practically available in the field. This is the natural consequence of not running the test on field size particles, which would consider the mode of occurrence of neutralising minerals. It's just a bit difficult to squeeze some of that field-sized material into these beakers. Nonetheless, for future testing Lapakko (1994) would consider using a larger particle size for waste rock. In their lab they have made the additional modification of using 2g rather than 10g in the test.

For some solids, this procedure can be quite slow (Lawrence and Wang, 1996). This is particularly the case for elevated carbonate contents and cases where the carbonate occurs with magnesium or magnesium and iron mixtures. The method is time consuming and not recommended for routine assessments (MEND, 1996).

6 PEROXIDE SIDERITE CORRECTION FOR SOBEK METHOD

The method, as developed by a Pennsylvania-West Virginia Overburden Task Force (Leavitt *et al.,* 1995), is as follows (for triplicate samples and a blank):

1. Place 2g sample in each of three beakers with a fourth beaker having no sample.
2. Add an amount and strength of HCl to each beaker based on the sample fizz rating, and adjust volume to 100ml.
3. Add boiling chips to beakers and cover with watch glass.
4. Boil gently for 5 minutes and allow to cool.
5. Gravity filter beakers contents using Whatman No. 40 (0.45 µm) filter.
6. Add 5ml of 30% H_2O_2 to the filtrate.
7. Boil for a further 5min (boiling chips and watch glasses), then cool.
8. Hand titrate, as per Sobek Method, with standard NaOH to achieve and hold an endpoint pH of 7.0 for 30 sec (Skousen *et al.,* 1997)

APPENDIX 2

Specialist Workshop on ABATE Project Participants and Comments Arising

Workshop on acid-base accounting project procedures held at the Water Research Commission on 15 March 2000

Present on invitation:

NAME	ORGANISATION	E-MAIL ADDRESS
Blanchè Postma	DWA&F	TCF@dwaf.pwv.gov.za
Meiring du Plessis	WRC	Meiring@wrc.org.za
Louis de Wet	Waterlab	Waterlab@iafica.co,za
Jaco vd Berg	Jasper Muller Associates	Jaco@jma-cc.co.za
Andrew Johnstone	Groundwater Consulting Services	Gcs@icon.co.za
John Cowan	SRK	Jcowan@srk.co.za
Alistair James	Metago	Arjames@mweb.co.za
Adel Meyer	Metago	Adele@metago.co.za
Nico Bezuidenhout	Wates, Mering and Barnard	Nocibez@wmb.co.za

Comments received for consideration:

1. The acronym ABATE is agreed upon to describe the test procedures that will be used in South Africa.
2. To determine the sample size, we normalise the data set and apply test statistics valid for normal distributions. The suggestion was made that a beta distribution should be considered.
3. Confidence limits for predictions must by high, 90% for instance, for system that will remain alkaline. For system that will become acid, a low confidence limit such as 60% should be sufficient. Thereafter it becomes an engineering problem to design for and manage the problem.
4. In testing the validity of the sample size, units clearly different from the other should be removed from the statistical analysis; otherwise distorted statistical results may be obtained.
5. Where selective spoil handling is done by a mine, this spoil should be tested separately for its chemistry and sample size.
6. Geophysical borehole logging should be considered as an indirect method that could assist in recognizing different horizons and thus in the reconciliation of laboratory analyses with the field situation.

7. Reactive sulphur measurement procedure should be considered in the determination of the acid generating potential of a sample.

8. The term neutralisation potential is considered to be synonymous to that of base potential.

9. The workshop recommends that a ratio of 1:10 for the measurement of natural pH should be standardised upon for the reason that the fluid may be separated afterwards and analysed chemically. In the field, a 1:1 paste pH is recommended.

10. For base potential titration, a final pH of 7,0 is recommended.

11. It is recommended that 0,06 sulphuric acid should be used in base potential titrations because of the greater stability of sulphuric acid and its greater reactivity with dolomitic lime.

12. For acid potential determination, the H_2O_2 method with no stabilising agent is recommended because it provide a final pH and a leachate that may be analysed.

13. A Leco analyzer provides stable results in the range between 0,1 – 11%. Louis de Wet (Waterlab) will provide material of which the sulphur content has been determined on a Leco analyzer for H_2O_2 determination by the IGS.

14. Consideration should be given for modified limits to the NAG test. The weathered horizon that naturally has a pH of 5,0 but no sulphur should not be considered in the NAG test.

15. A comparison should be made between the EPA shake flask tests versus the stir tests suggested by the IGS.

16. Humidity cells cannot really be standardised because of the scale differences between lab and field situations.

17. Humidity cells cannot successfully simulate the differences between spoils and tailings because of the barometric lung effect.

18. Methodologies finally recommended should be as close as possible to existing overseas methodologies for the sake of comparing data and also since many international companies operate in South Africa and abroad.

19. All methodologies finally recommended should be considered as tools and not as standards.

20. Mines should not be committed to an extensive all-inclusive set of test procedures if sufficient results are forthcoming from a subset of the prescribed test procedures.

21. Special mention must be made of the relevant of mineralogy in ABATE.

22. William Pulles acts at a co-ordinator for the compilation of the best practice guideline for the DWA&F. The WRC document should be the scientific document that should serve as the basis for the compilation of the ABATE section in these guidelines.

23. A well-balanced approach should be striven towards, not losing sight of practicalities.

24. Guidelines should be provided as to the conditions under which ABATE should be used.

25. Standardised procedures for cross laboratory testing should be provided, if this is feasible.

A form(s) for laboratory analysis and data reporting should be provided. The WISH format could be considered for these purposes.

APPENDIX 3

Laboratory determination and PHREEQC comparison of Buffering levels for different minerals

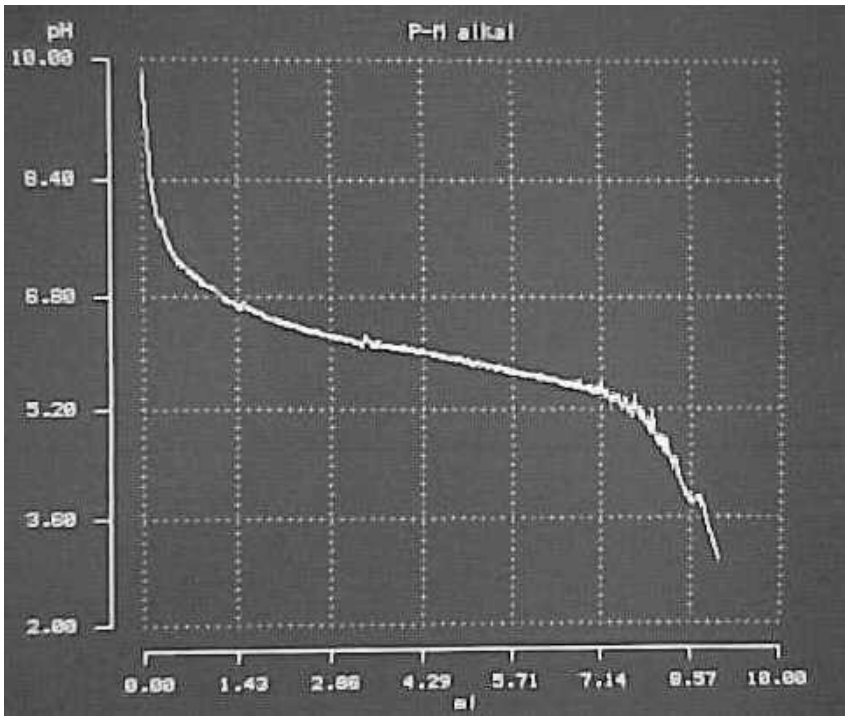


Figure 1. Calcite buffering of H_2SO_4 using an automatic titrator (screenshot)

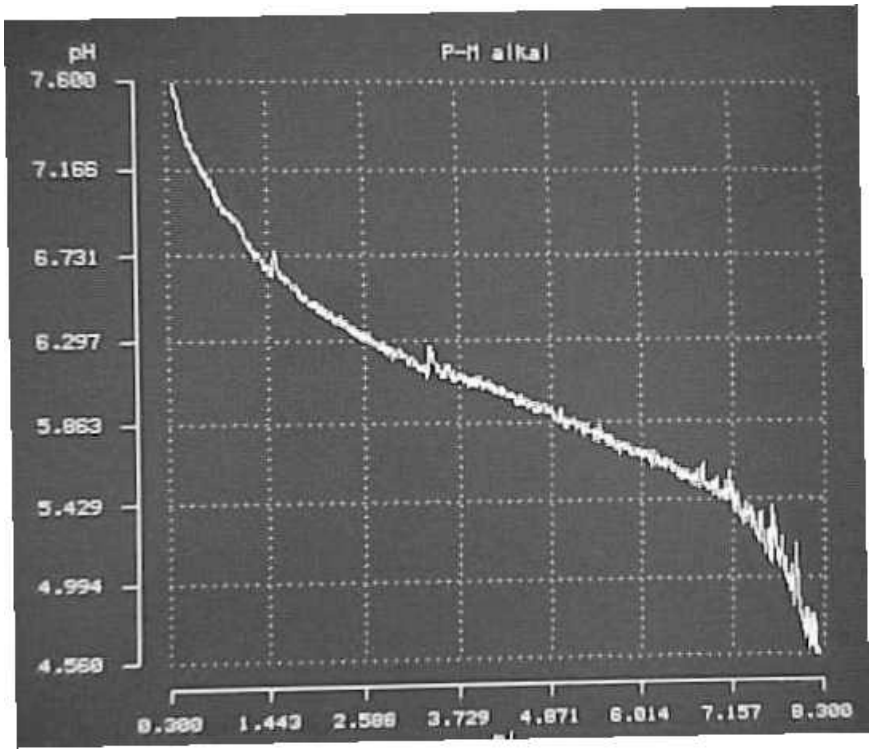


Figure 2. Calcite buffering of H_2SO_4 using an automatic titrator (screenshot). Close-up.

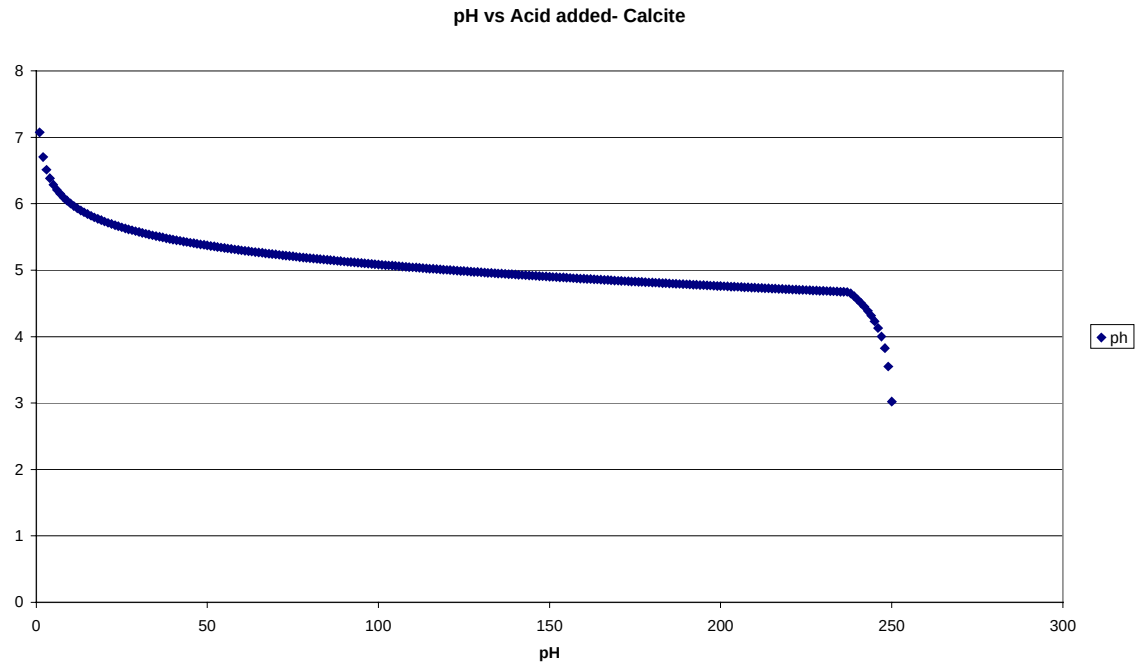


Figure 3. Calcite buffering of H_2SO_4 as determined by PHREEQC.

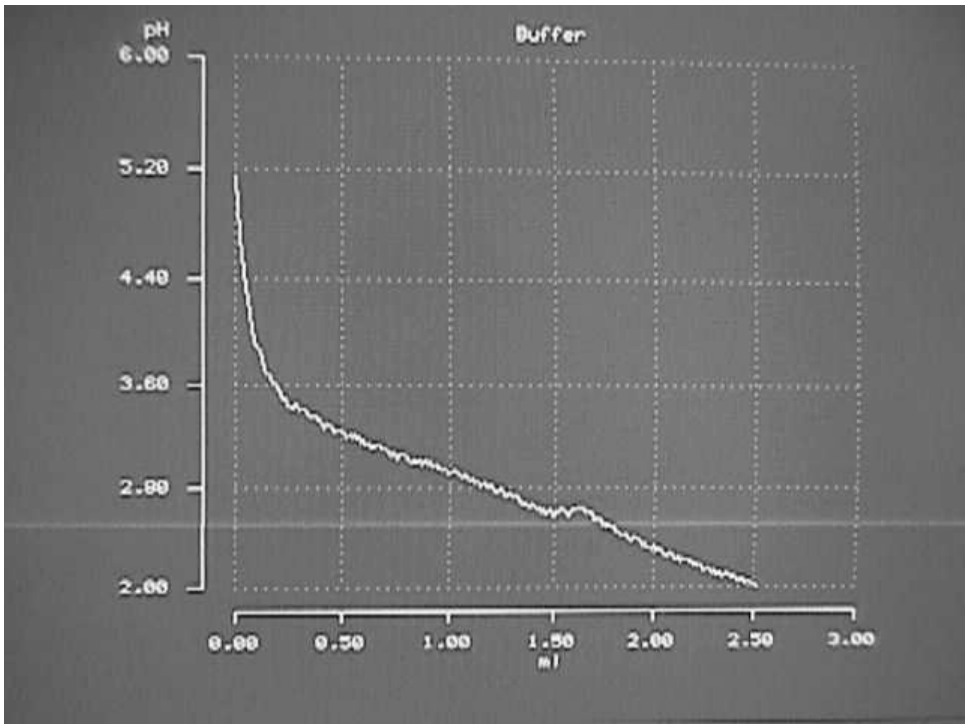


Figure 4. Kaolinite buffering of H_2SO_4 using an automatic titrator (screenshot).

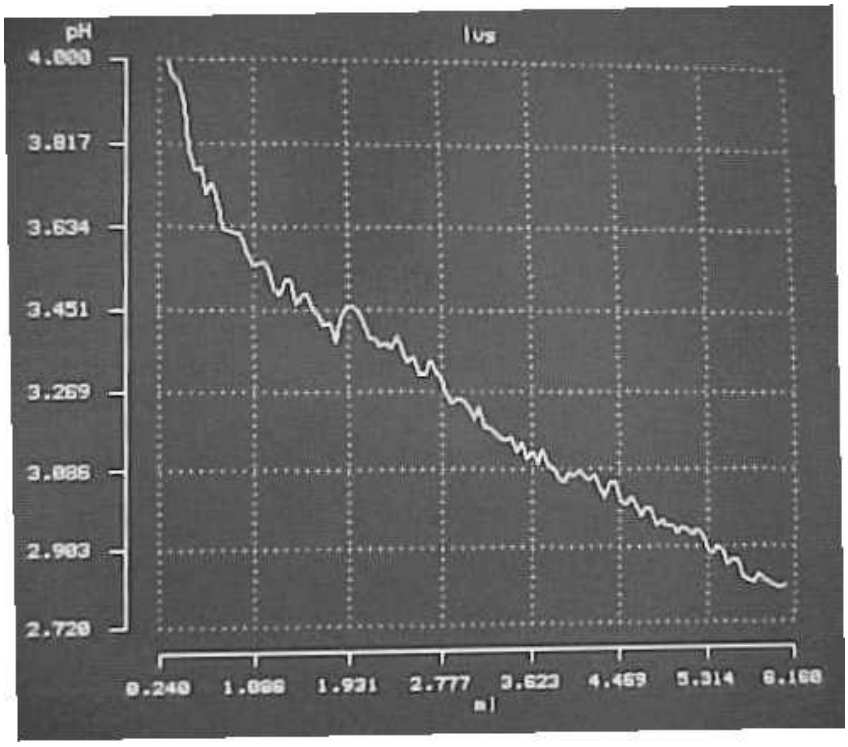


Figure 5. Kaolinite buffering of H_2SO_4 using an automatic titrator (screenshot). Close-up.

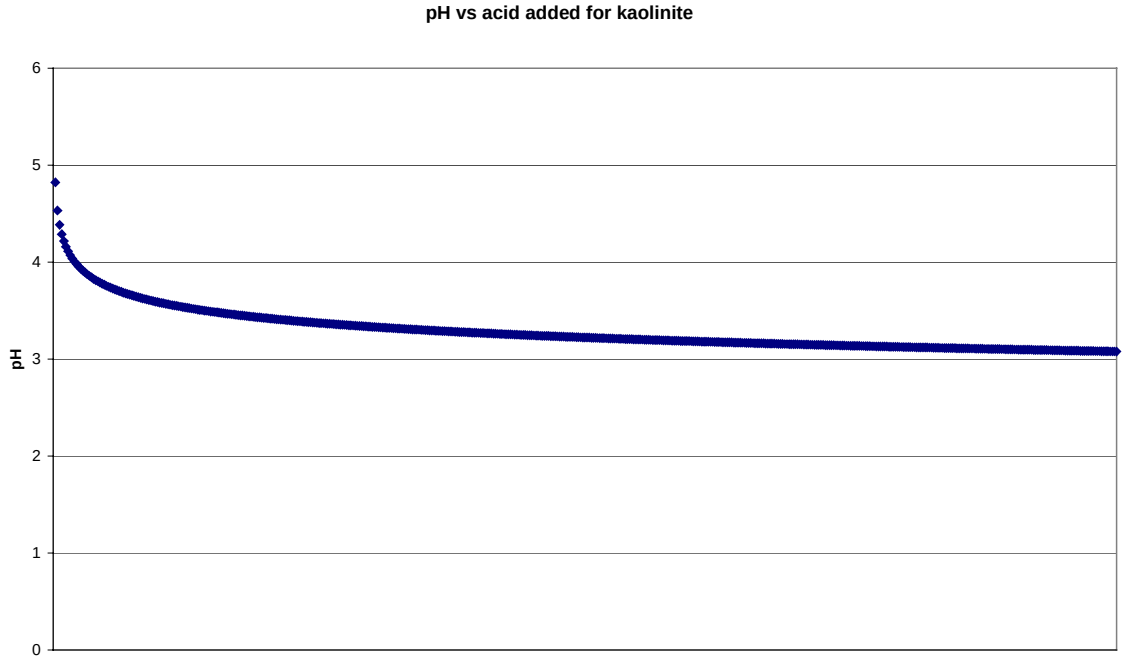


Figure 6. Kaolinite buffering of H_2SO_4 as determined by PHREEQC.

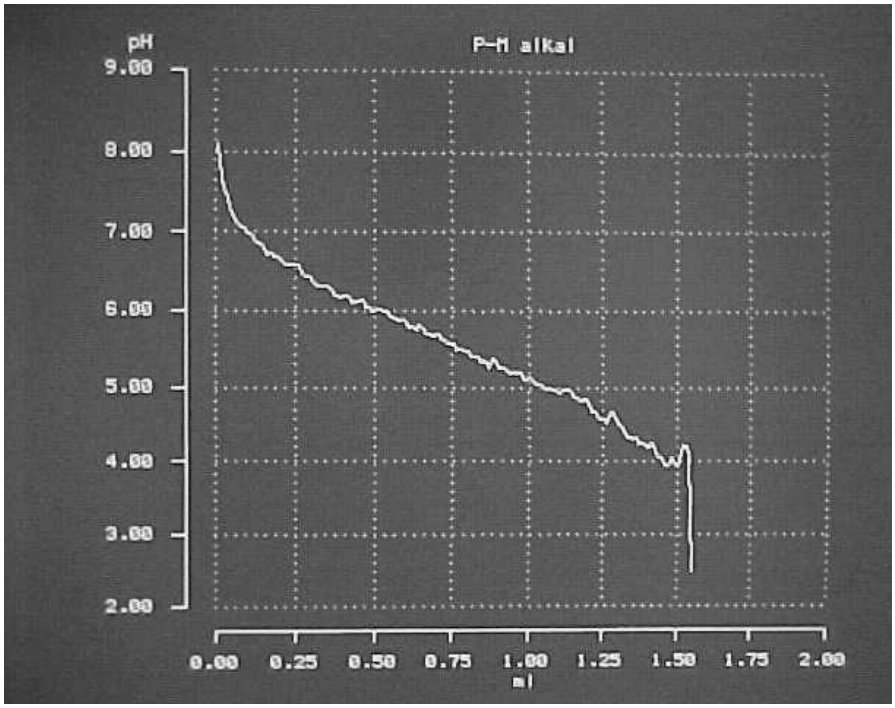


Figure 7. Siderite buffering of H_2SO_4 using an automatic titrator (screenshot).

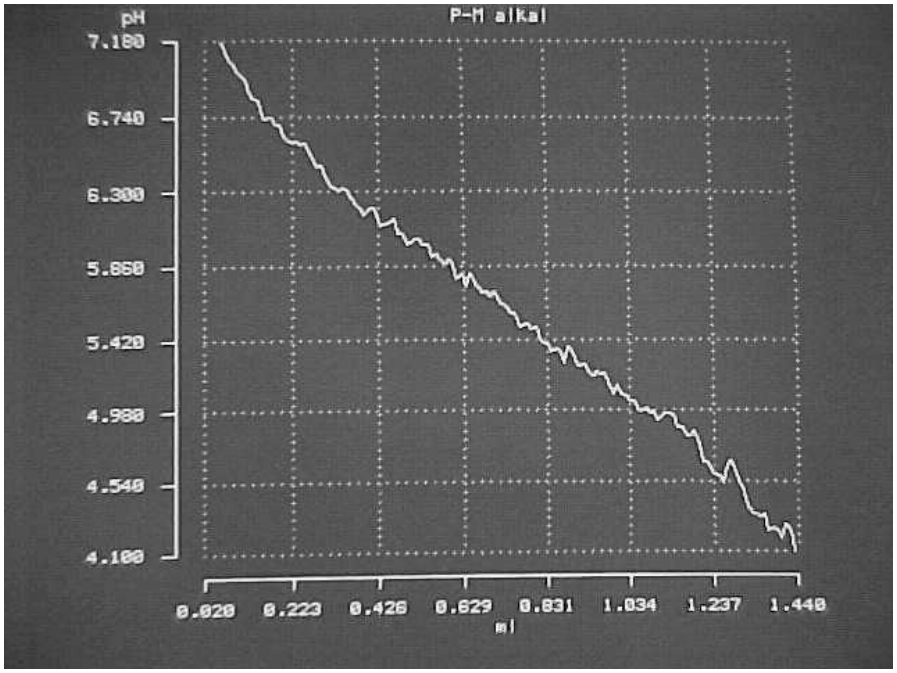


Figure 8. Siderite buffering of H_2SO_4 using an automatic titrator (screenshot). Close-up.

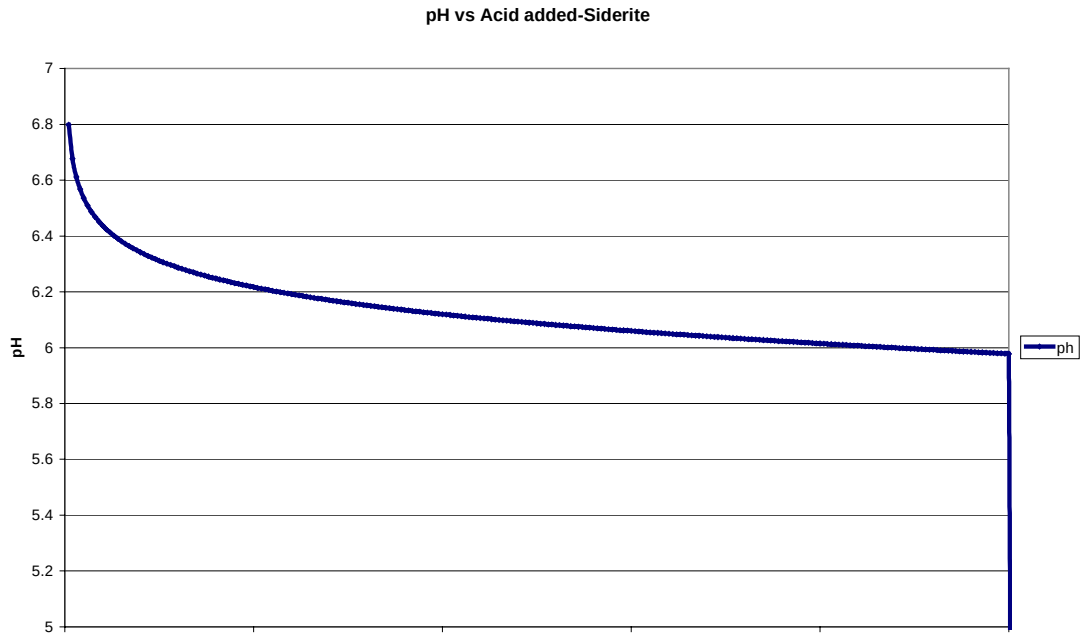


Figure 9. Siderite buffering of H_2SO_4 as determined by PHREEQC.

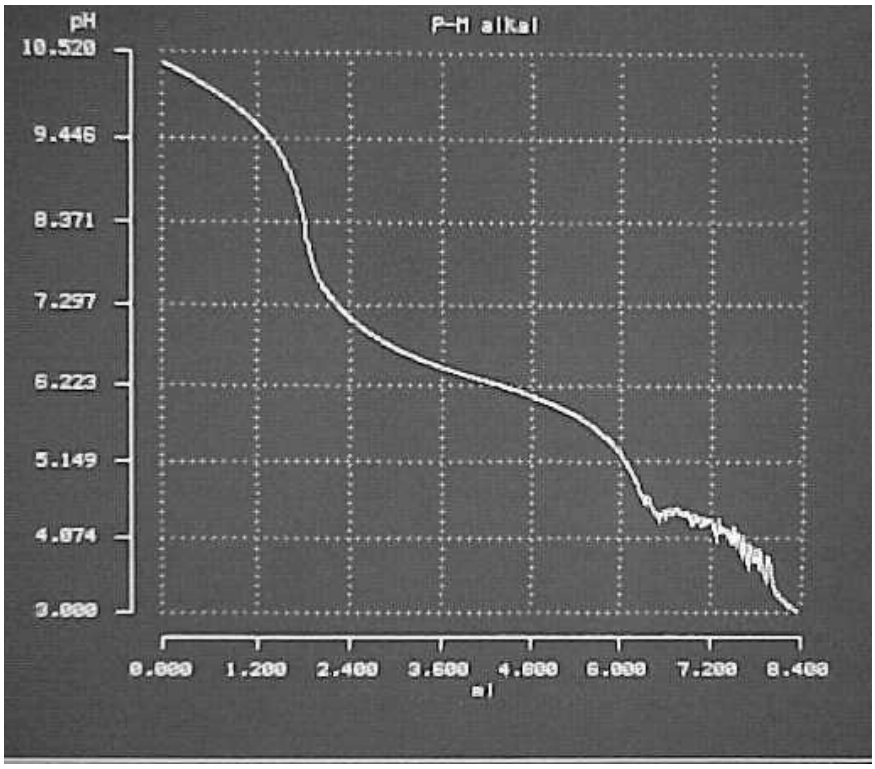


Figure 10. Calcite, $NaHCO_3$ and Kaolinite buffering of H_2SO_4 using an automatic titrator (screenshot). Close-up.

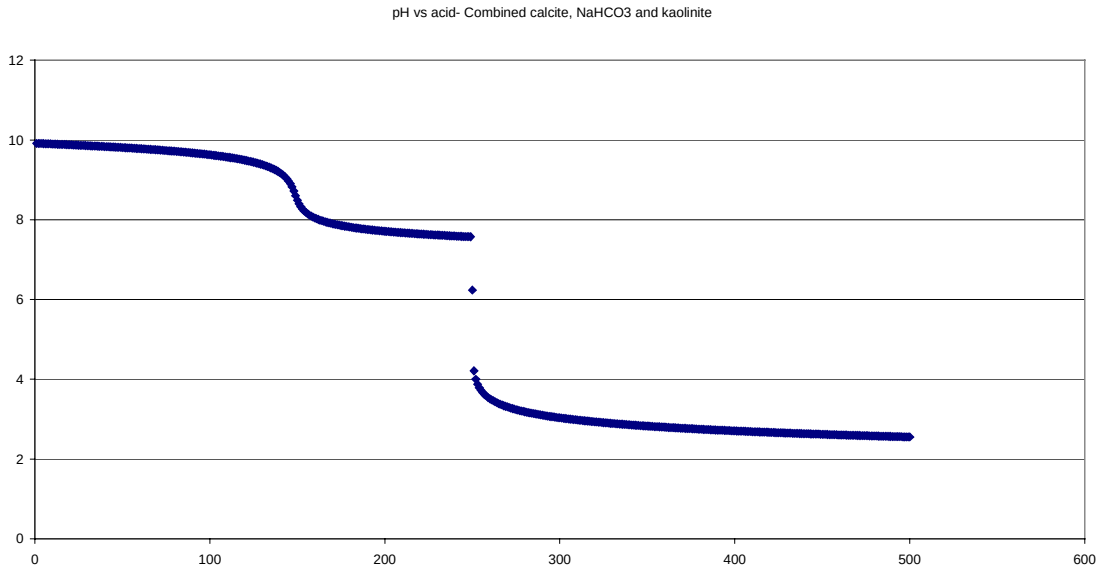


Figure 11. Calcite, $NaHCO_3$ and Kaolinite buffering of H_2SO_4 as determined by PHREEQC.

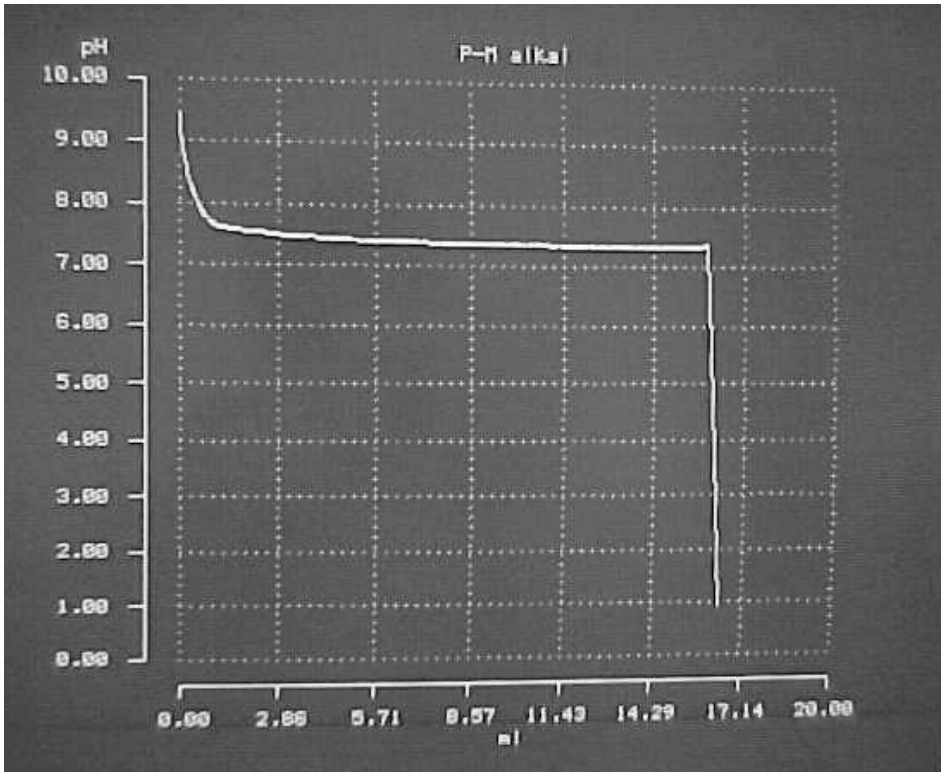


Figure 12. Dolomite buffering of H_2SO_4 using an automatic titrator (screenshot). Close-up.

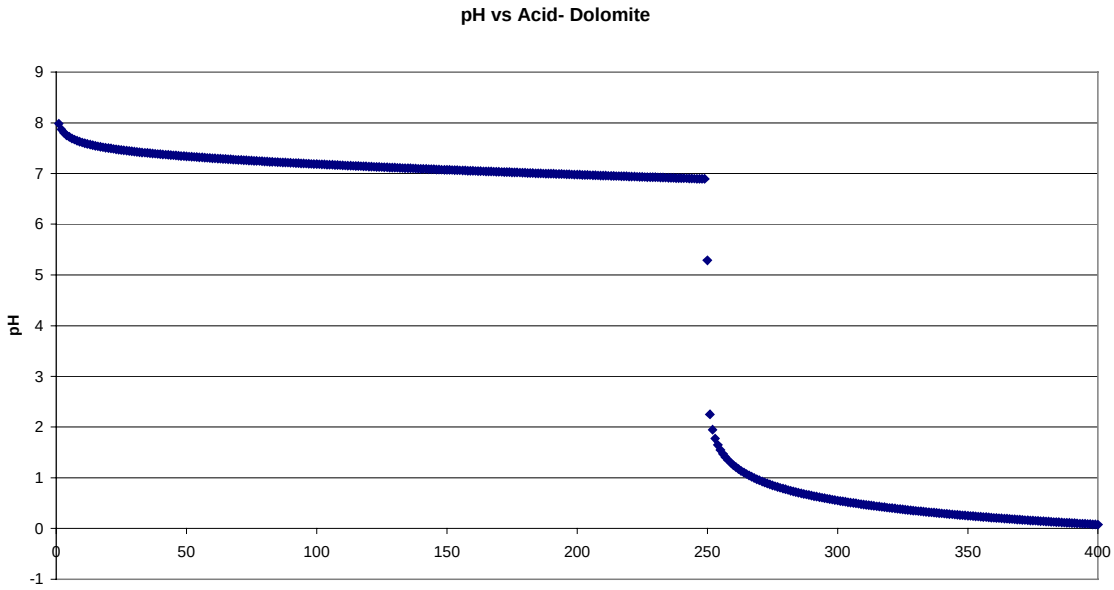
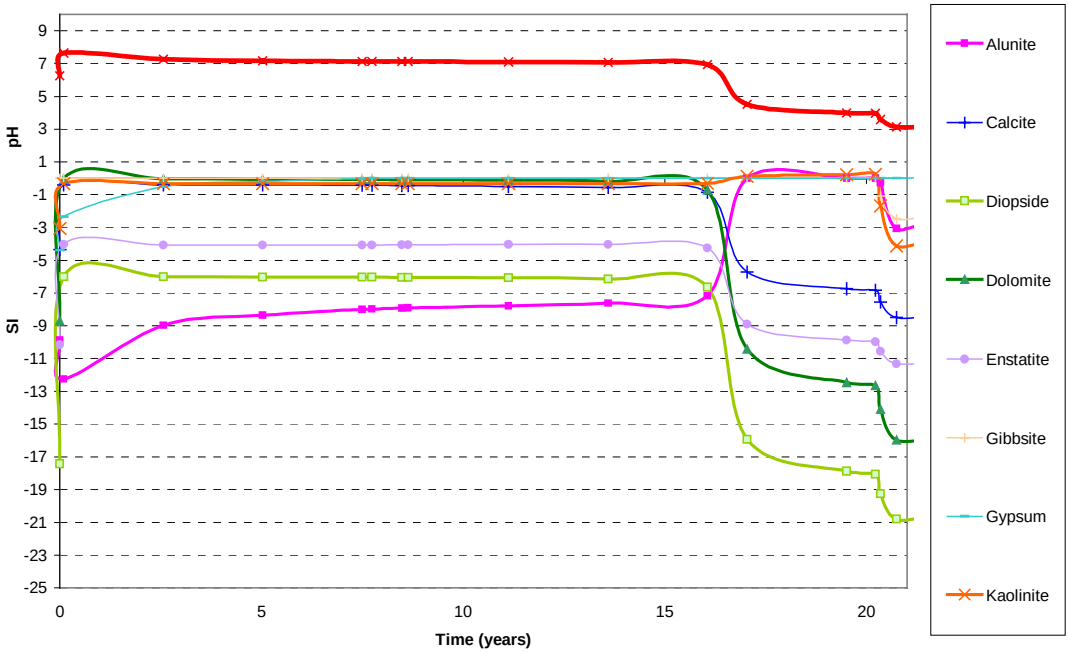


Figure 13 Dolomite buffering of H_2SO_4 as determined by PHREEQC.

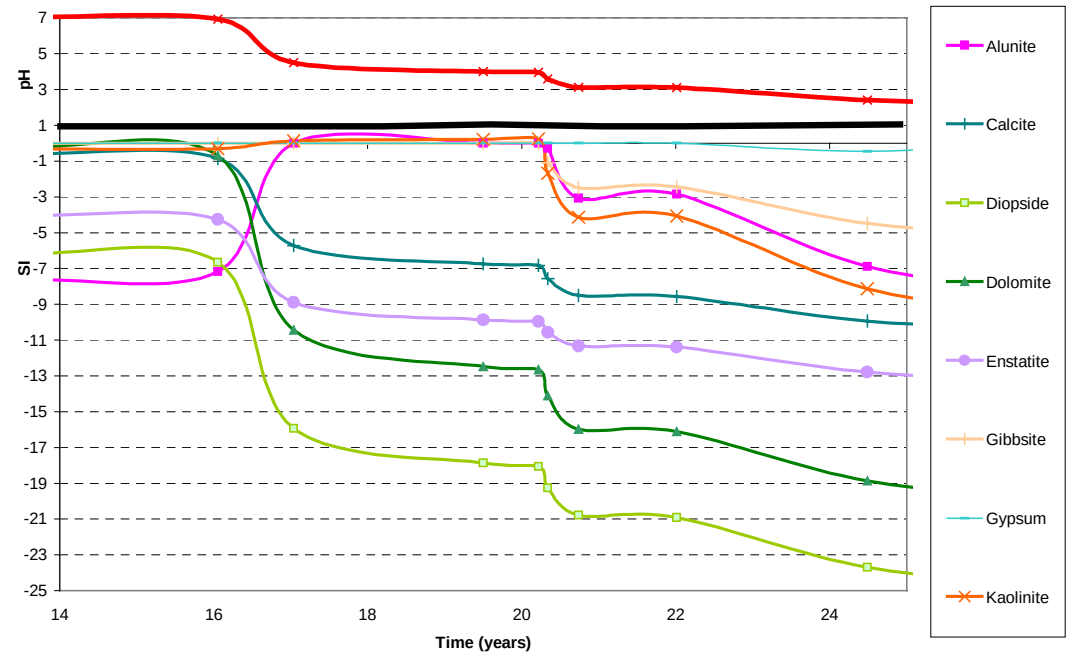
APPENDIX 4

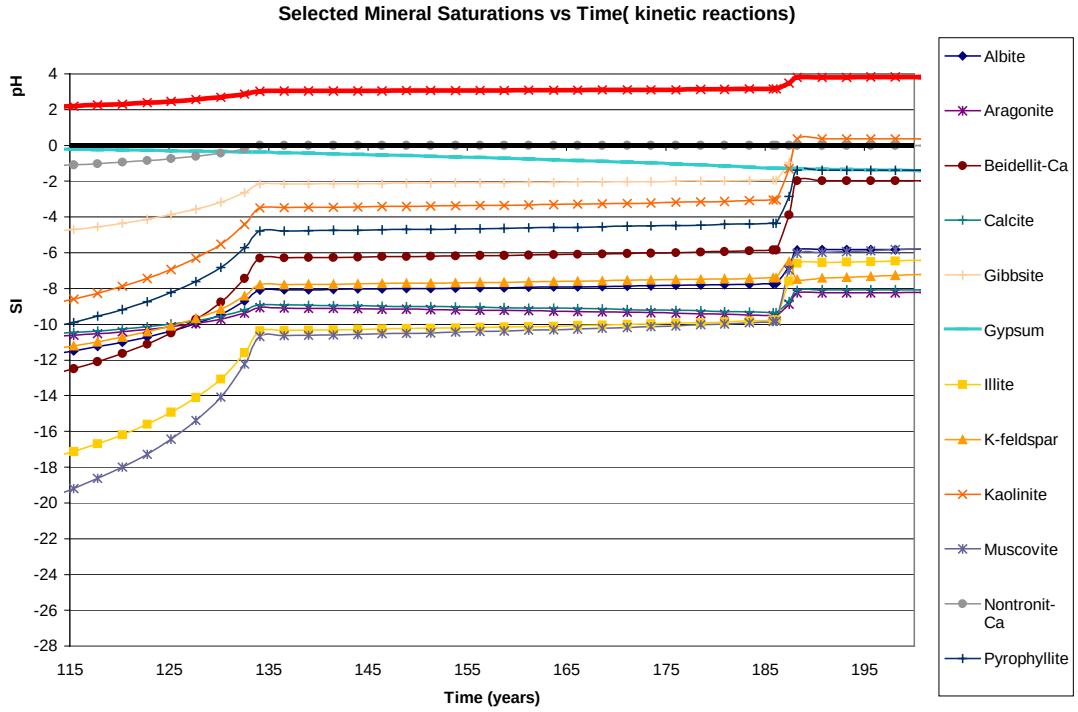
Detail of minerals due to change in pH over time, based on geochemical modelling

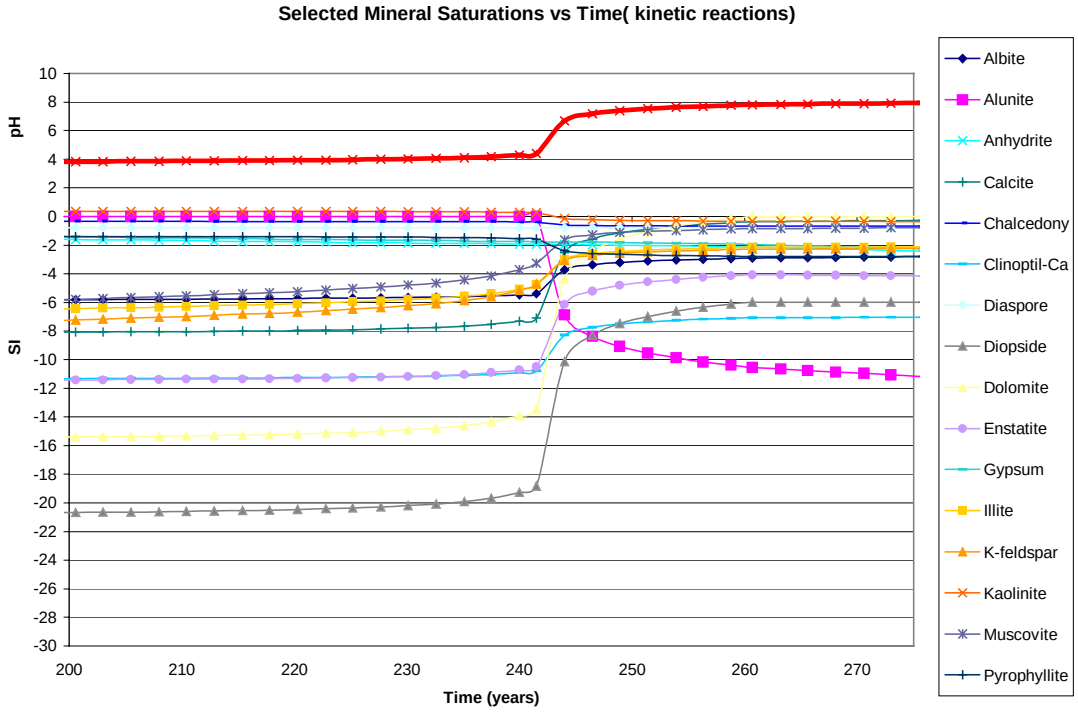
Selected Mineral Saturations vs Time(kinetic reactions)



Selected Mineral Saturations vs Time(kinetic reactions)

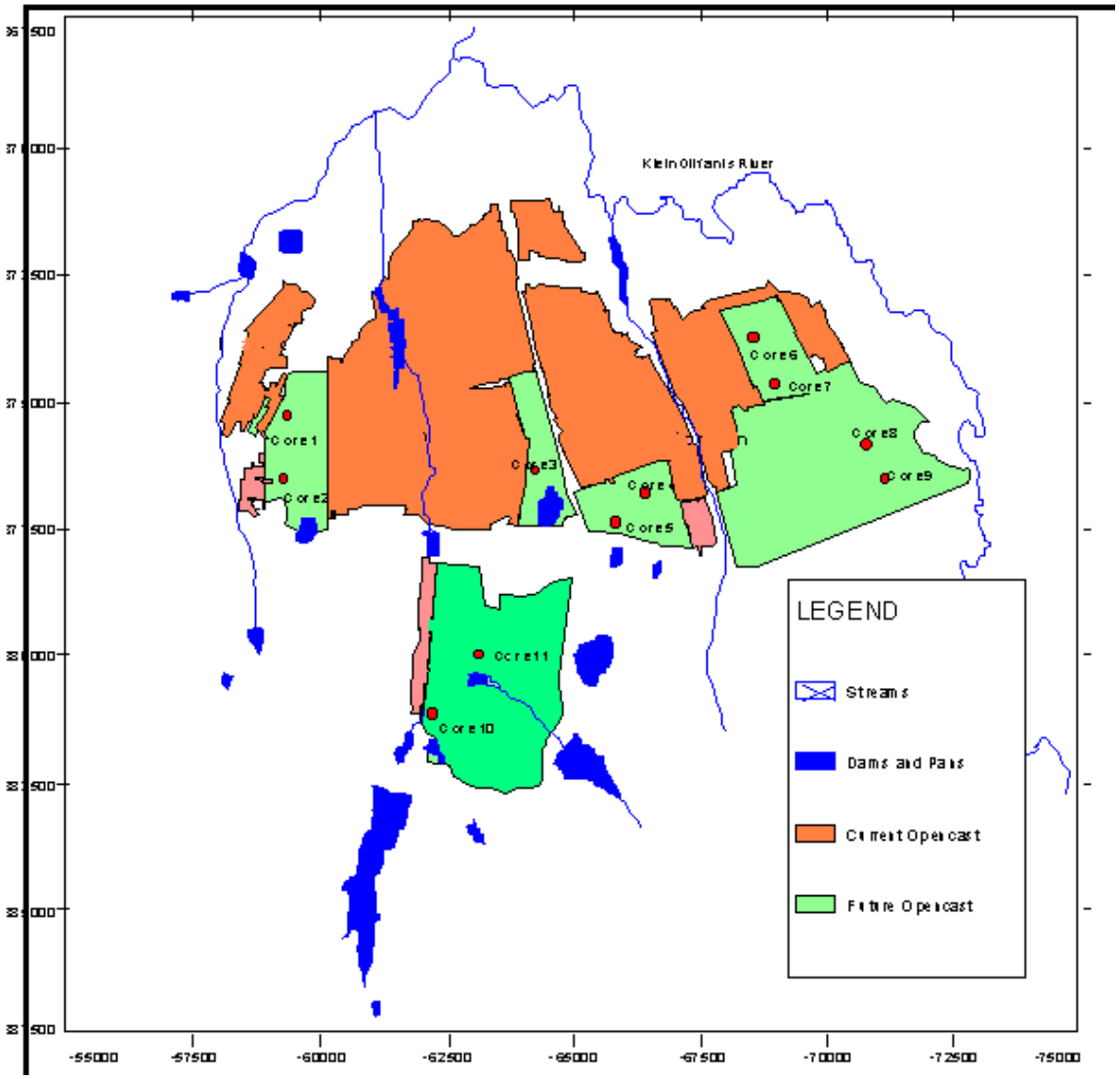



Selected Mineral Saturations vs Time(kinetic reactions)
pH
SI
Time (years)
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
115
125
135
145
155
165
175
185
195
Albite
Aragonite
Beidellit-Ca
Calcite
Gibbsite
Gypsum
Illite
K-feldspar
Kaolinite
Muscovite
Nontronit-Ca
Pyrophyllite

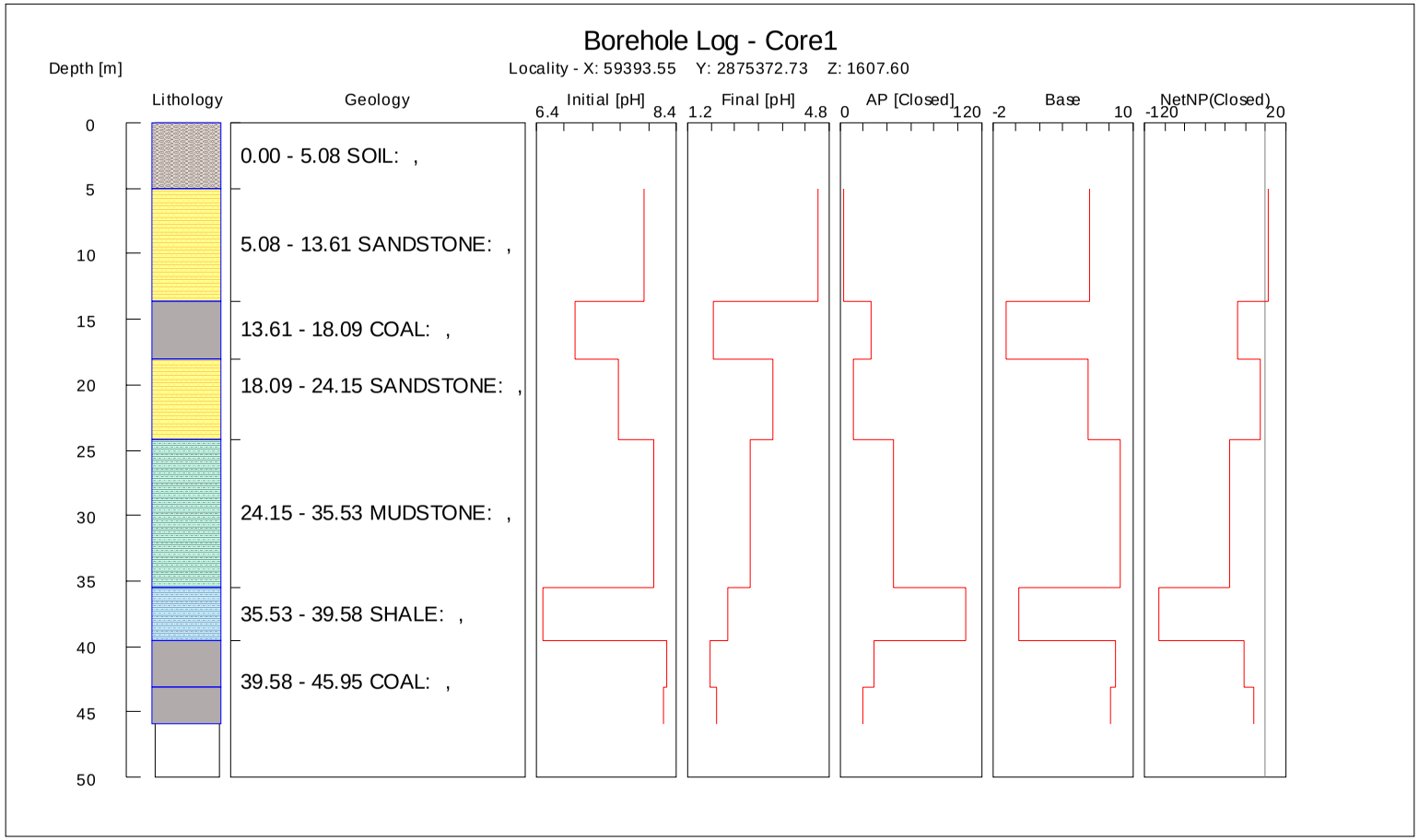

Selected Mineral Saturations vs Time(kinetic reactions)
pH
SI
Time (years)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
-22
-24
-26
-28
-30
200
210
220
230
240
250
260
270
Albite
Alunite
Anhydrite
Calcite
Chalcedony
Clinoptil-Ca
Diaspore
Diopside
Dolomite
Enstatite
Gypsum
Illite
K-feldspar
Kaolinite
Muscovite
Pyrophyllite

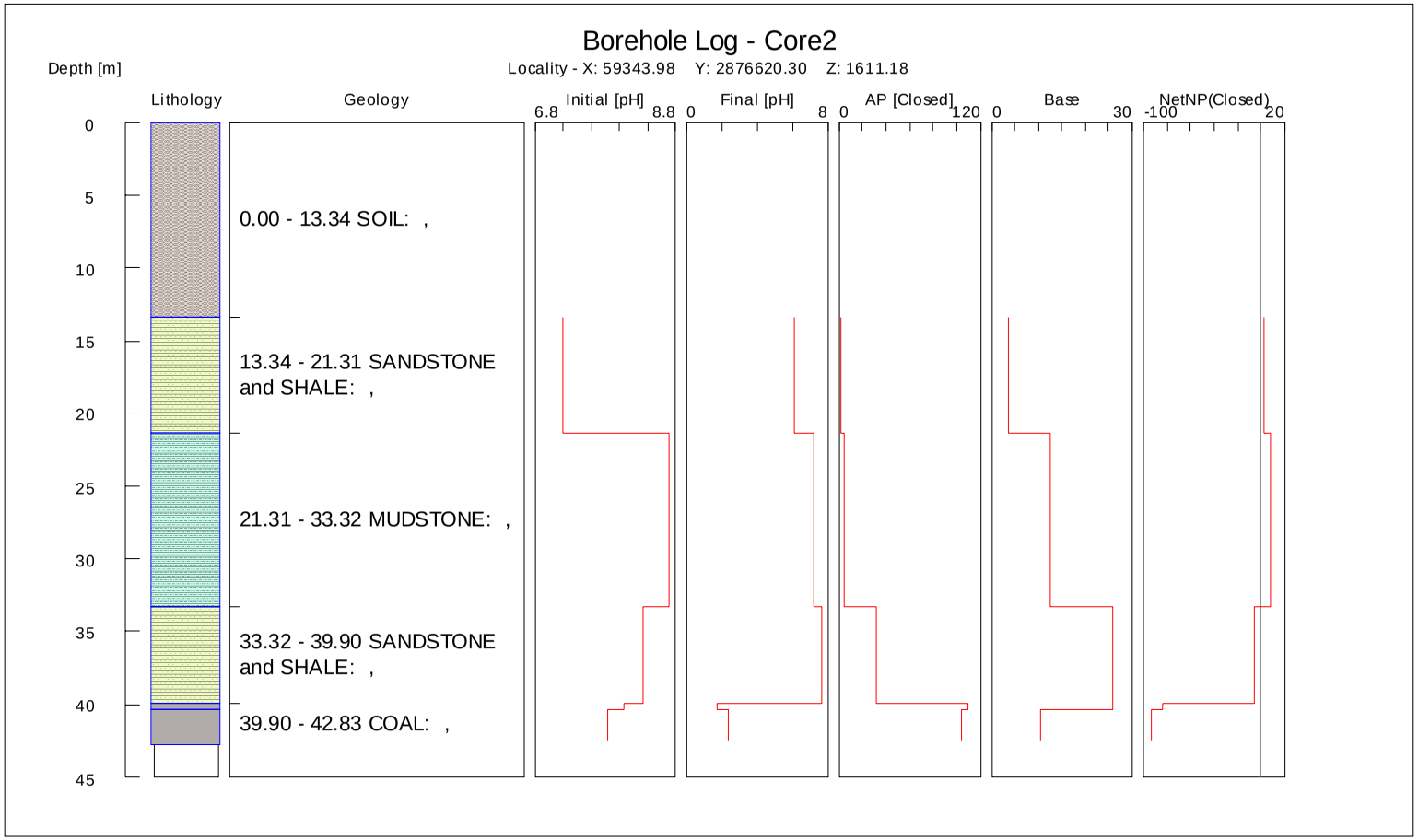
APPENDIX 5

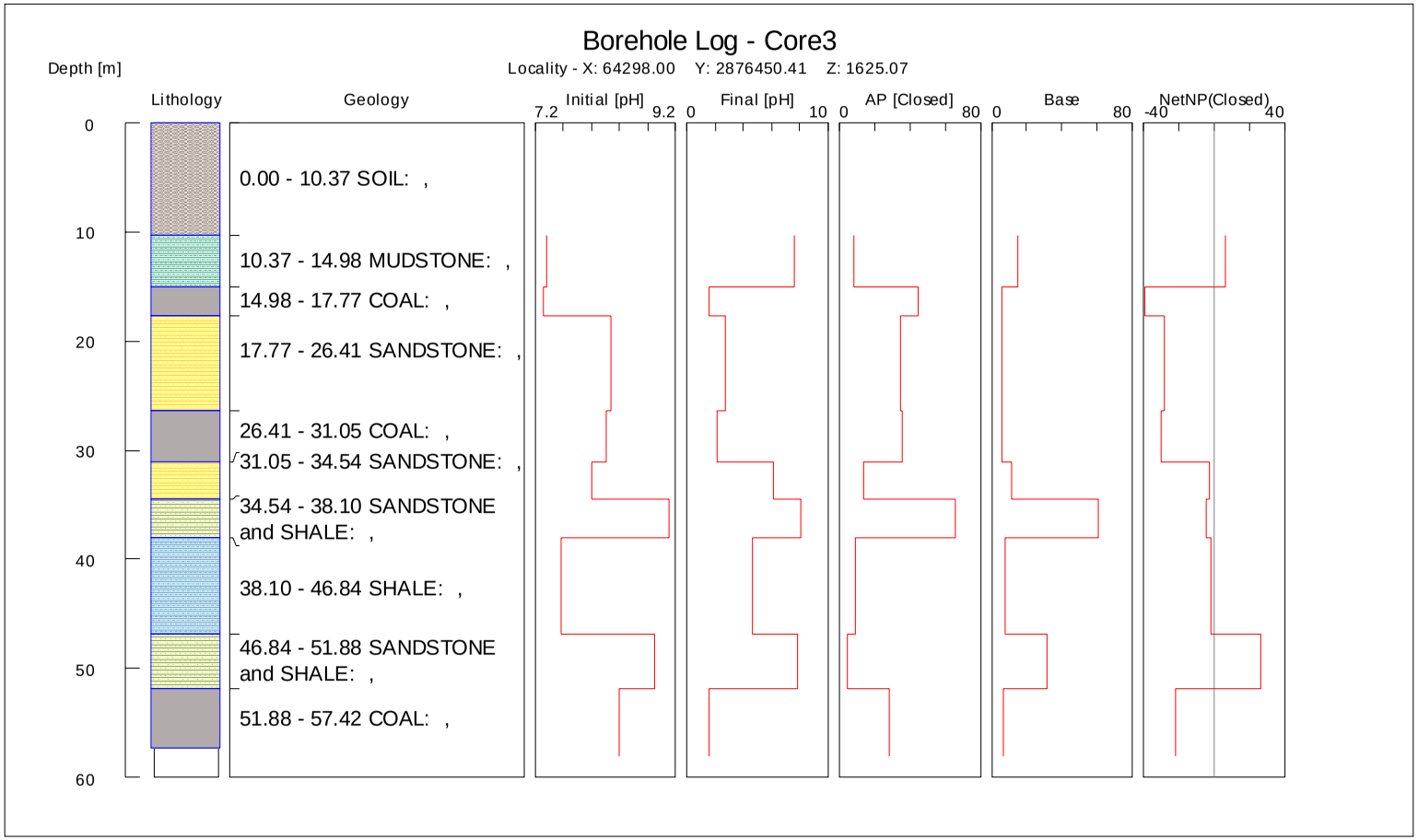
Borehole logs and graphs of acid-base accounting

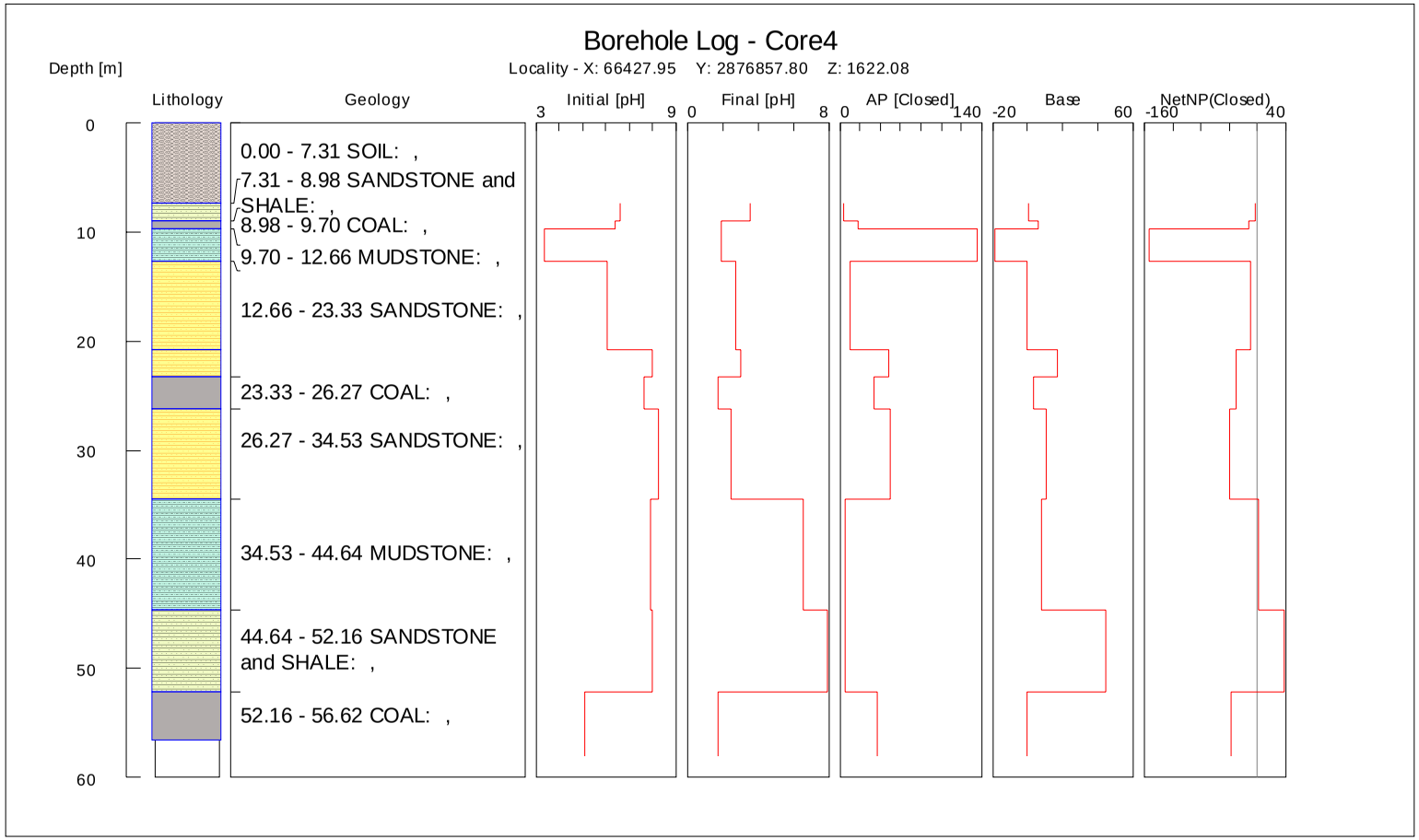


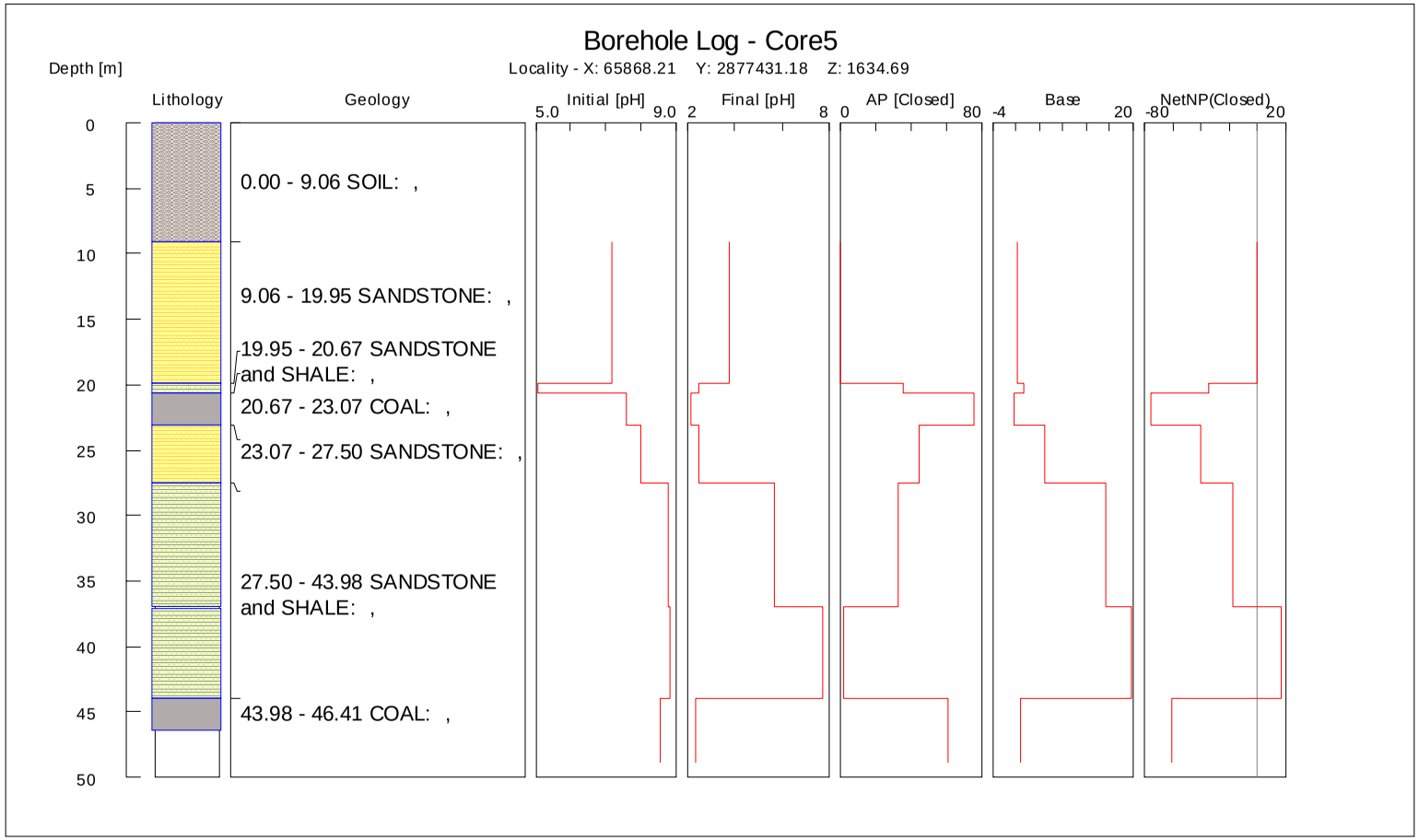
Localities of cored boreholes

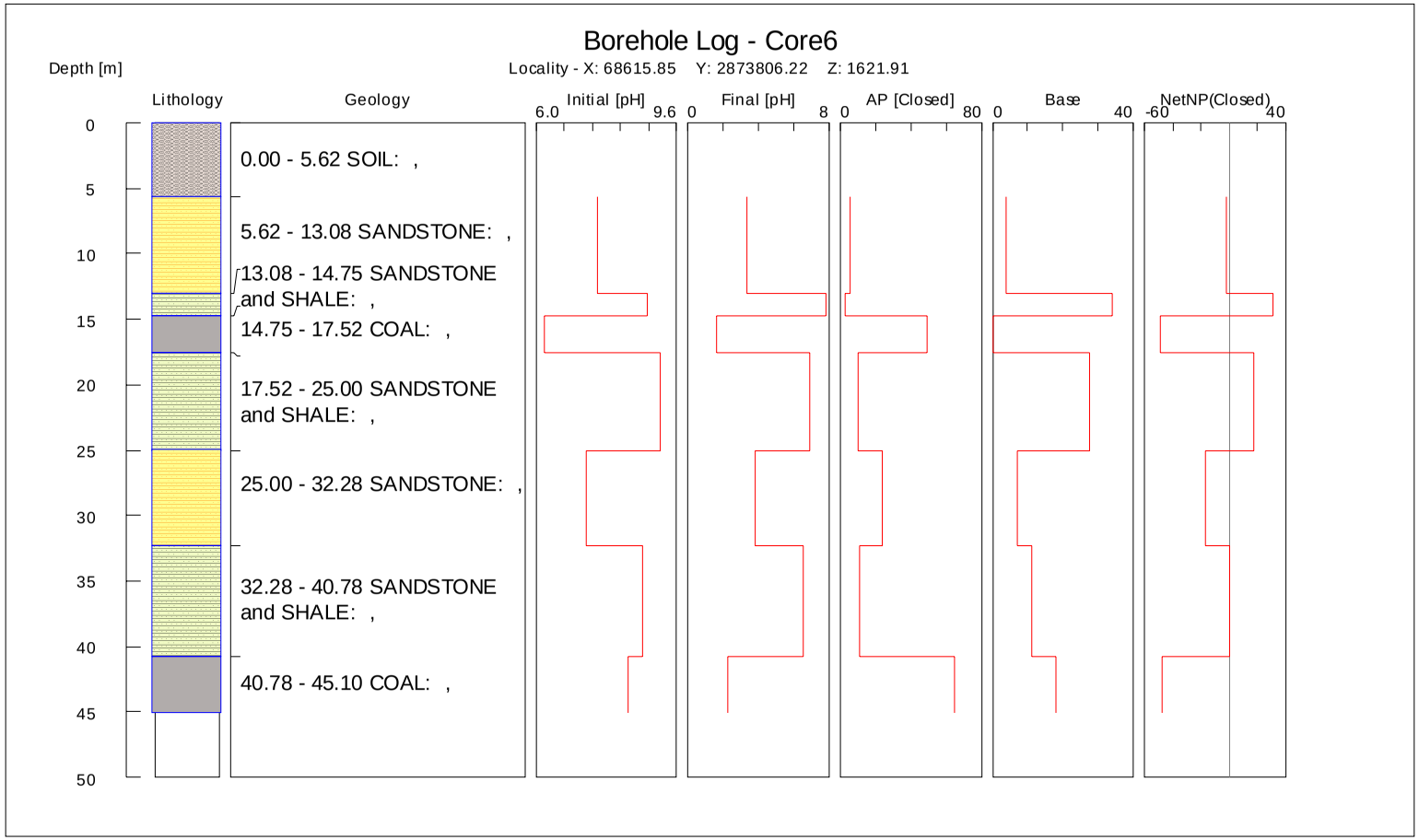

Borehole Log - Core1
Locality - X: 59393.55 Y: 2875372.73 Z: 1607.60
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0.00 - 5.08 SOIL: ,
5.08 - 13.61 SANDSTONE: ,
13.61 - 18.09 COAL: ,
18.09 - 24.15 SANDSTONE: ,
24.15 - 35.53 MUDSTONE: ,
35.53 - 39.58 SHALE: ,
39.58 - 45.95 COAL: ,

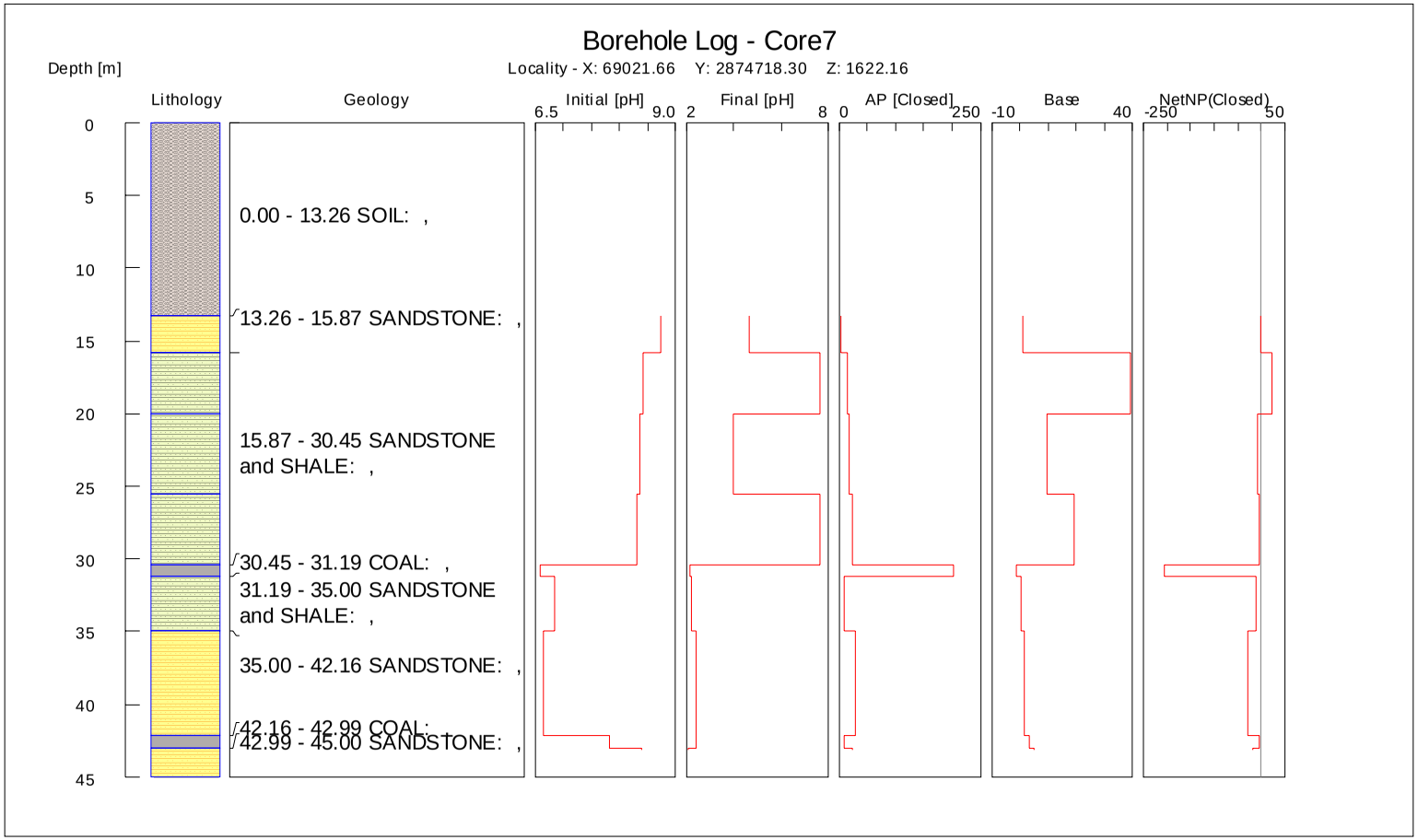

Borehole Log - Core2
Locality - X: 59343.98 Y: 2876620.30 Z: 1611.18
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0
5
10
15
20
25
30
35
40
45
6.8
8.8
0
8
0
120
0
30
-100
20
0.00 - 13.34 SOIL: ,
13.34 - 21.31 SANDSTONE and SHALE: ,
21.31 - 33.32 MUDSTONE: ,
33.32 - 39.90 SANDSTONE and SHALE: ,
39.90 - 42.83 COAL: ,

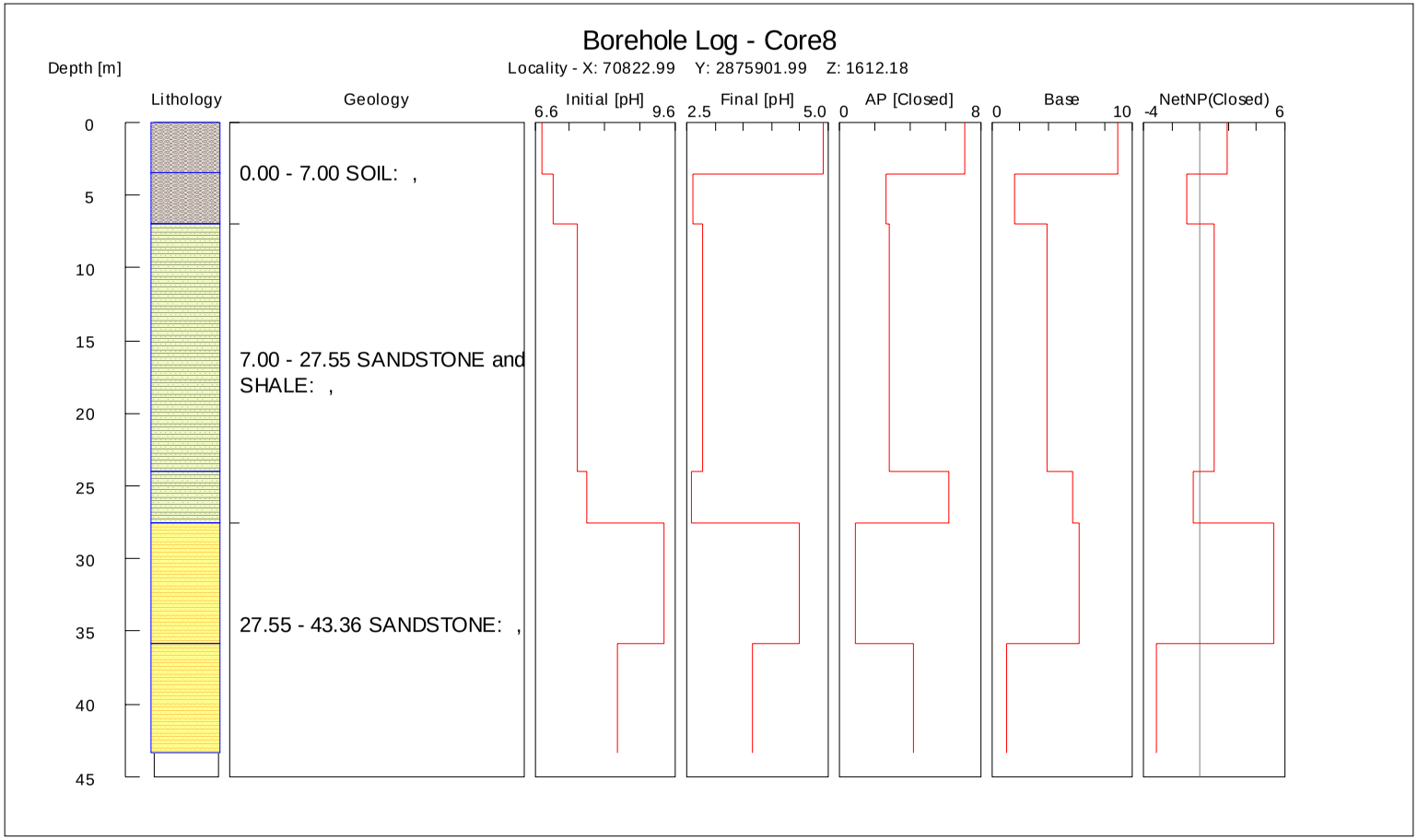

Borehole Log - Core3
Locality - X: 64298.00 Y: 2876450.41 Z: 1625.07
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
7.2
9.2
0
10
0
80
0
80
-40
40
0
10
20
30
40
50
60
0.00 - 10.37 SOIL: ,
10.37 - 14.98 MUDSTONE: ,
14.98 - 17.77 COAL: ,
17.77 - 26.41 SANDSTONE: ,
26.41 - 31.05 COAL: ,
31.05 - 34.54 SANDSTONE: ,
34.54 - 38.10 SANDSTONE and SHALE: ,
38.10 - 46.84 SHALE: ,
46.84 - 51.88 SANDSTONE and SHALE: ,
51.88 - 57.42 COAL: ,

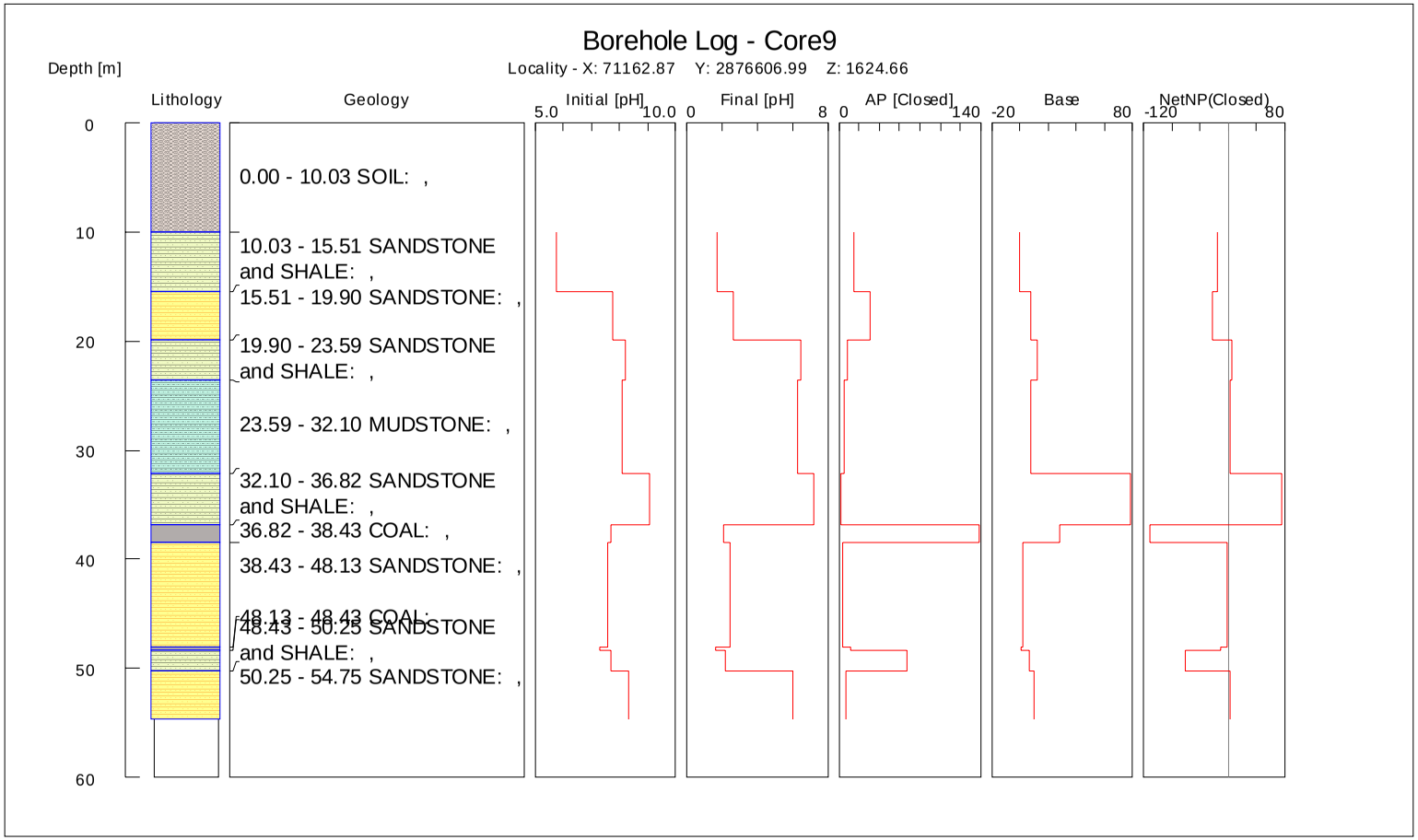

Borehole Log - Core4
Locality - X: 66427.95 Y: 2876857.80 Z: 1622.08
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0
10
20
30
40
50
60
3
9
0
8
0
140
-20
60
-160
40
0.00 - 7.31 SOIL: ,
7.31 - 8.98 SANDSTONE and SHALE: ,
8.98 - 9.70 COAL: ,
9.70 - 12.66 MUDSTONE: ,
12.66 - 23.33 SANDSTONE: ,
23.33 - 26.27 COAL: ,
26.27 - 34.53 SANDSTONE: ,
34.53 - 44.64 MUDSTONE: ,
44.64 - 52.16 SANDSTONE and SHALE: ,
52.16 - 56.62 COAL: ,

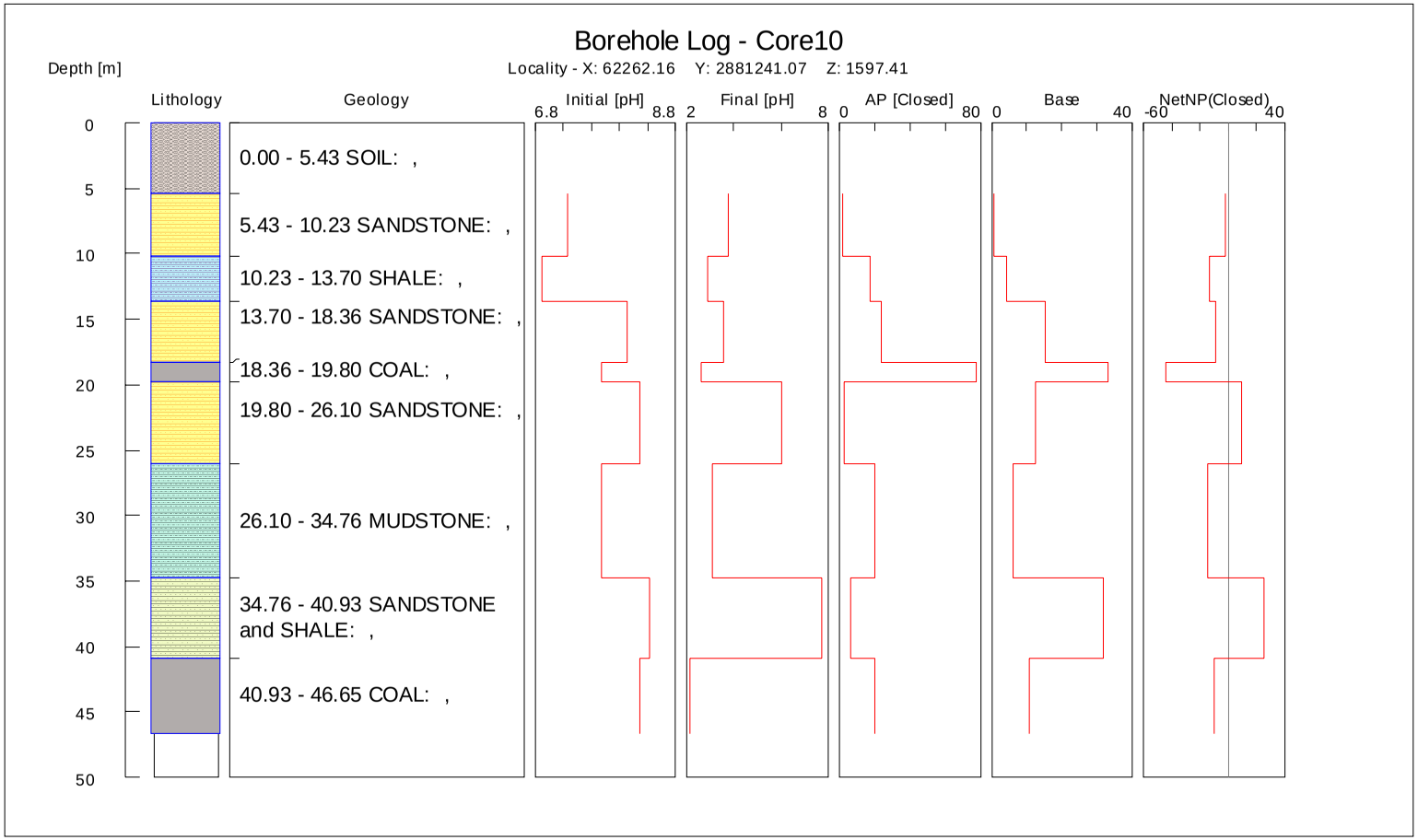

Borehole Log - Core5
Locality - X: 65868.21 Y: 2877431.18 Z: 1634.69
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0
5
10
15
20
25
30
35
40
45
50
5.0
9.0
2
8
0
80
-4
20
-80
20
0.00 - 9.06 SOIL: ,
9.06 - 19.95 SANDSTONE: ,
19.95 - 20.67 SANDSTONE and SHALE: ,
20.67 - 23.07 COAL: ,
23.07 - 27.50 SANDSTONE: ,
27.50 - 43.98 SANDSTONE and SHALE: ,
43.98 - 46.41 COAL: ,

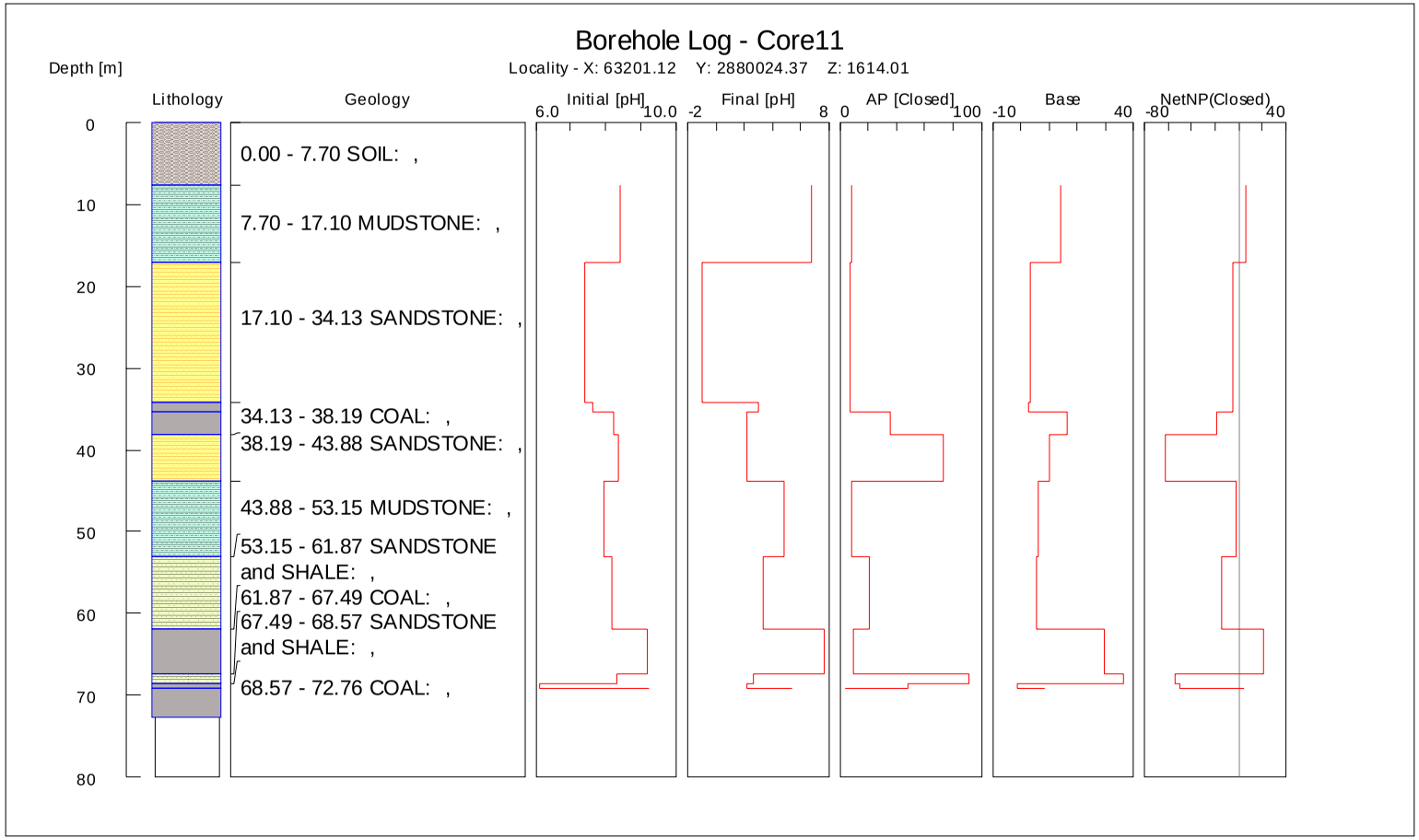

Borehole Log - Core6
Locality - X: 68615.85 Y: 2873806.22 Z: 1621.91
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0.00 - 5.62 SOIL: ,
5.62 - 13.08 SANDSTONE: ,
13.08 - 14.75 SANDSTONE and SHALE: ,
14.75 - 17.52 COAL: ,
17.52 - 25.00 SANDSTONE and SHALE: ,
25.00 - 32.28 SANDSTONE: ,
32.28 - 40.78 SANDSTONE and SHALE: ,
40.78 - 45.10 COAL: ,


Borehole Log - Core7
Locality - X: 69021.66 Y: 2874718.30 Z: 1622.16
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
6.5
9.0
2
8
0
250
-10
40
-250
50
0
5
10
15
20
25
30
35
40
45
0.00 - 13.26 SOIL: ,
13.26 - 15.87 SANDSTONE: ,
15.87 - 30.45 SANDSTONE and SHALE: ,
30.45 - 31.19 COAL: ,
31.19 - 35.00 SANDSTONE and SHALE: ,
35.00 - 42.16 SANDSTONE: ,
42.16 - 42.99 COAL: ,
42.99 - 45.00 SANDSTONE: ,


Borehole Log - Core8
Locality - X: 70822.99 Y: 2875901.99 Z: 1612.18
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0
5
10
15
20
25
30
35
40
45
6.6
9.6
2.5
5.0
0
8
0
10
-4
6
0.00 - 7.00 SOIL: ,
7.00 - 27.55 SANDSTONE and SHALE: ,
27.55 - 43.36 SANDSTONE: ,


Borehole Log - Core9
Locality - X: 71162.87 Y: 2876606.99 Z: 1624.66
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0
10
20
30
40
50
60
5.0
10.0
0
8
0
140
-20
80
-120
80
0.00 - 10.03 SOIL: ,
10.03 - 15.51 SANDSTONE and SHALE: ,
15.51 - 19.90 SANDSTONE: ,
19.90 - 23.59 SANDSTONE and SHALE: ,
23.59 - 32.10 MUDSTONE: ,
32.10 - 36.82 SANDSTONE and SHALE: ,
36.82 - 38.43 COAL: ,
38.43 - 48.13 SANDSTONE: ,
48.13 - 48.43 COAL: ,
48.43 - 50.25 SANDSTONE and SHALE: ,
50.25 - 54.75 SANDSTONE: ,


Borehole Log - Core10
Locality - X: 62262.16 Y: 2881241.07 Z: 1597.41
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
6.8
8.8
2
8
0
80
0
40
-60
40
0
5
10
15
20
25
30
35
40
45
50
0.00 - 5.43 SOIL: ,
5.43 - 10.23 SANDSTONE: ,
10.23 - 13.70 SHALE: ,
13.70 - 18.36 SANDSTONE: ,
18.36 - 19.80 COAL: ,
19.80 - 26.10 SANDSTONE: ,
26.10 - 34.76 MUDSTONE: ,
34.76 - 40.93 SANDSTONE and SHALE: ,
40.93 - 46.65 COAL: ,


Borehole Log - Core11
Locality - X: 63201.12 Y: 2880024.37 Z: 1614.01
Depth [m]
Lithology
Geology
Initial [pH]
Final [pH]
AP [Closed]
Base
NetNP(Closed)
0
10
20
30
40
50
60
70
80
6.0
10.0
-2
8
0
100
-10
40
-80
40
0.00 - 7.70 SOIL: ,
7.70 - 17.10 MUDSTONE: ,
17.10 - 34.13 SANDSTONE: ,
34.13 - 38.19 COAL: ,
38.19 - 43.88 SANDSTONE: ,
43.88 - 53.15 MUDSTONE: ,
53.15 - 61.87 SANDSTONE and SHALE: ,
61.87 - 67.49 COAL: ,
67.49 - 68.57 SANDSTONE and SHALE: ,
68.57 - 72.76 COAL: ,

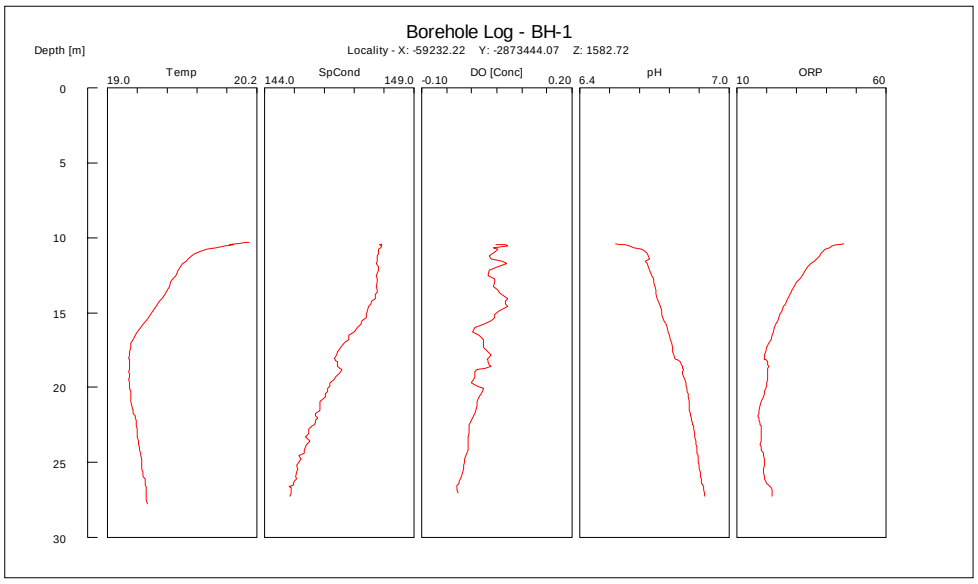


Figure a Hydrochemical logs of spoil water.

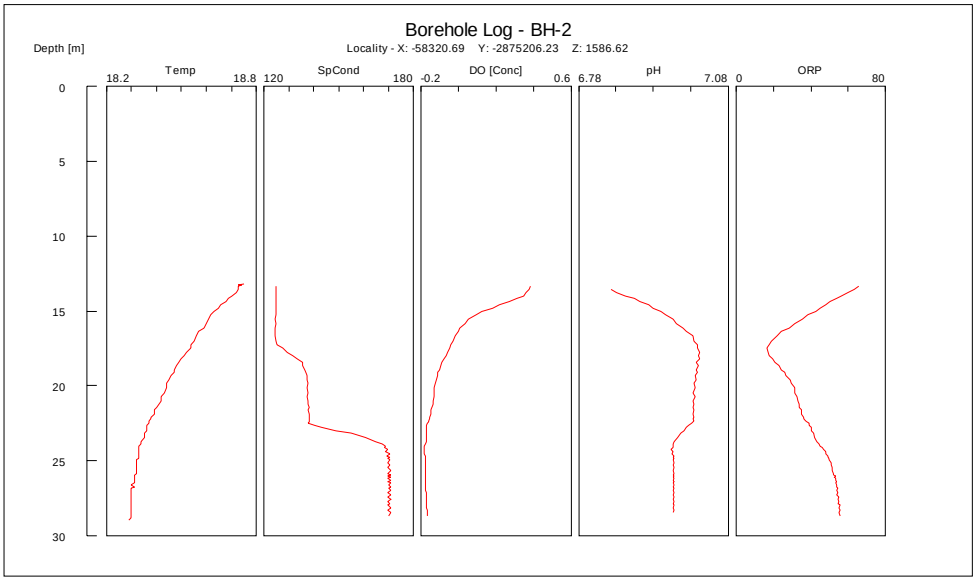


Figure b. Hydrochemical logs of spoil water.

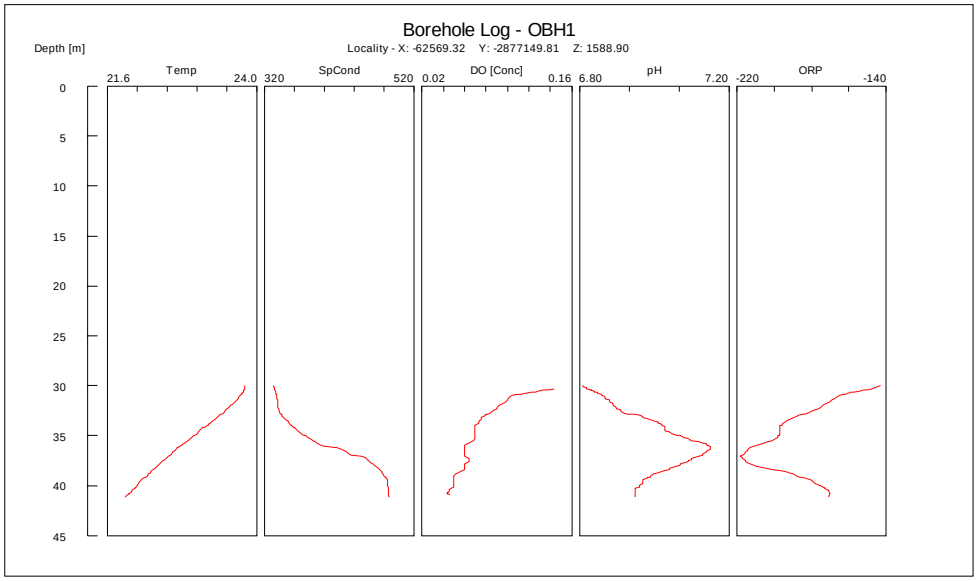


Figure c. Hydrochemical logs of spoil water.

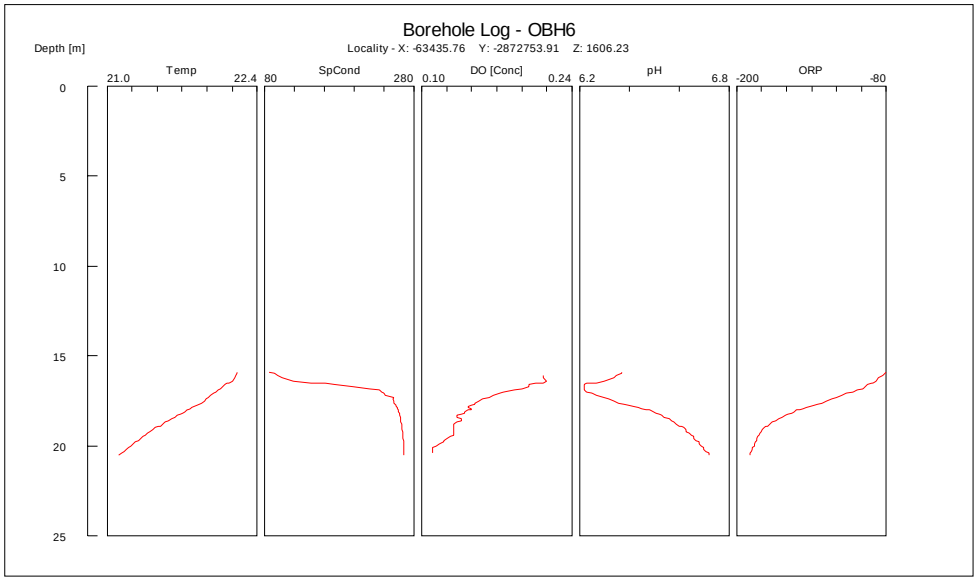


Figure d.Hydrochemical logs of spoil water.

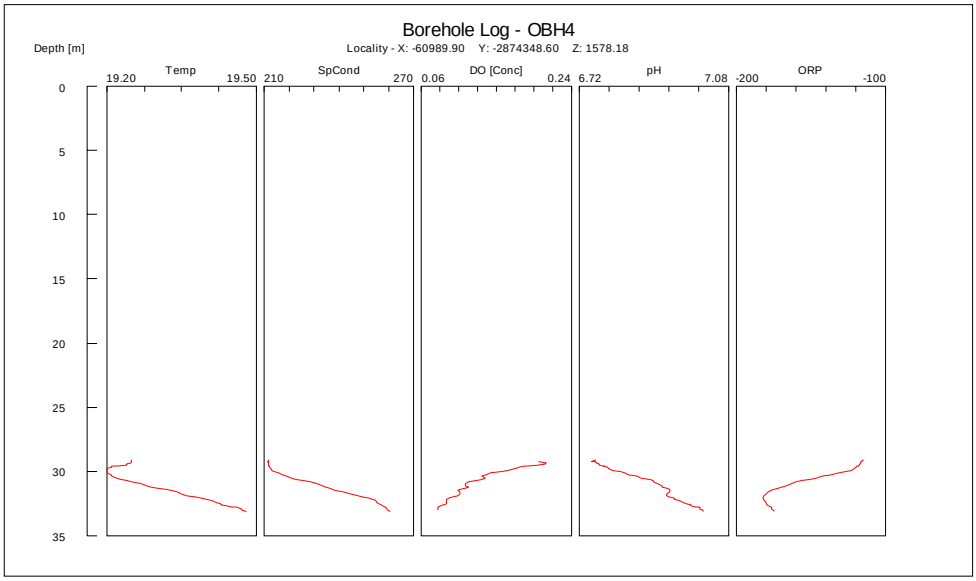


Figure e. Hydrochemical logs of spoil water

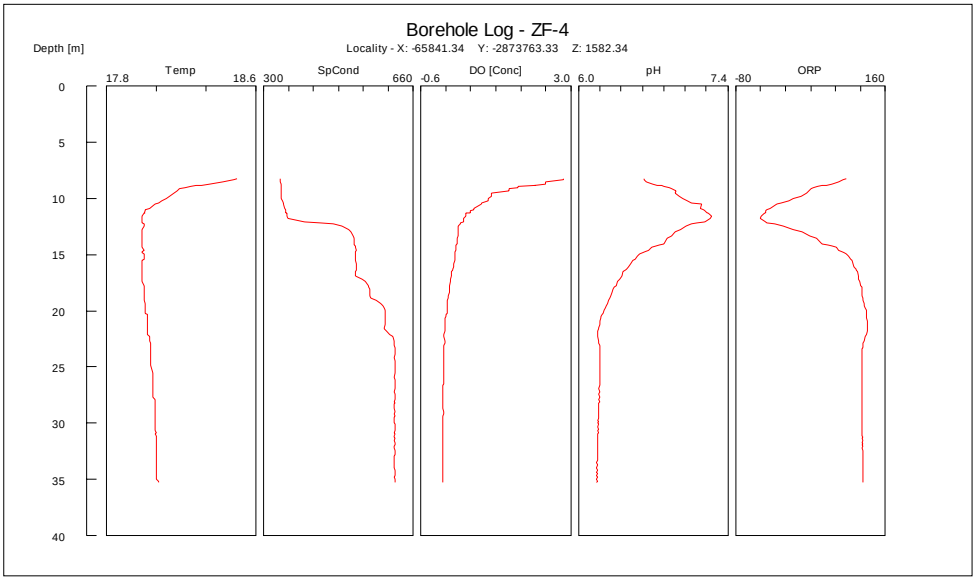


Figure f.Hydrochemical logs of spoil water.

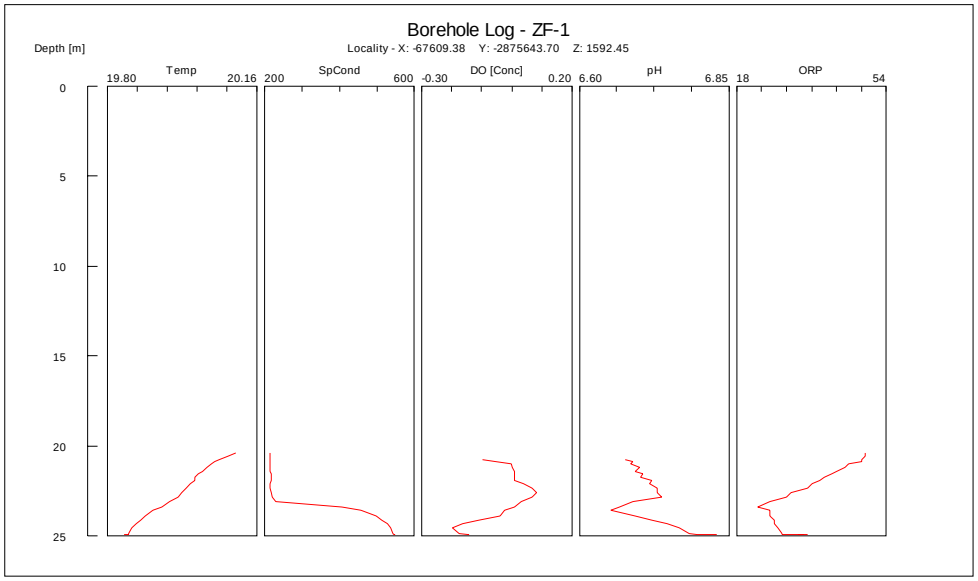


Figure g. Hydrochemical logs of spoil water.

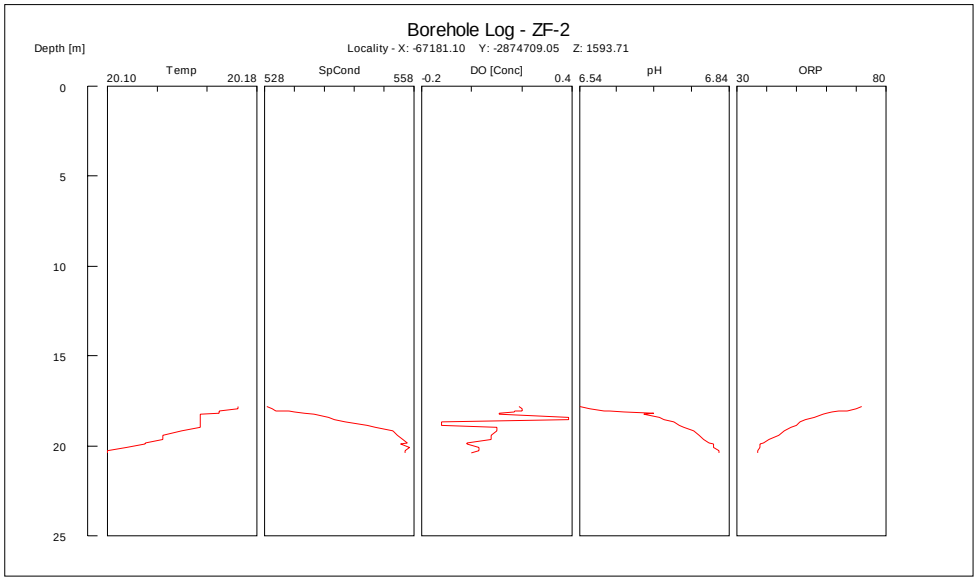


Figure h. Hydrochemical logs of spoil water.

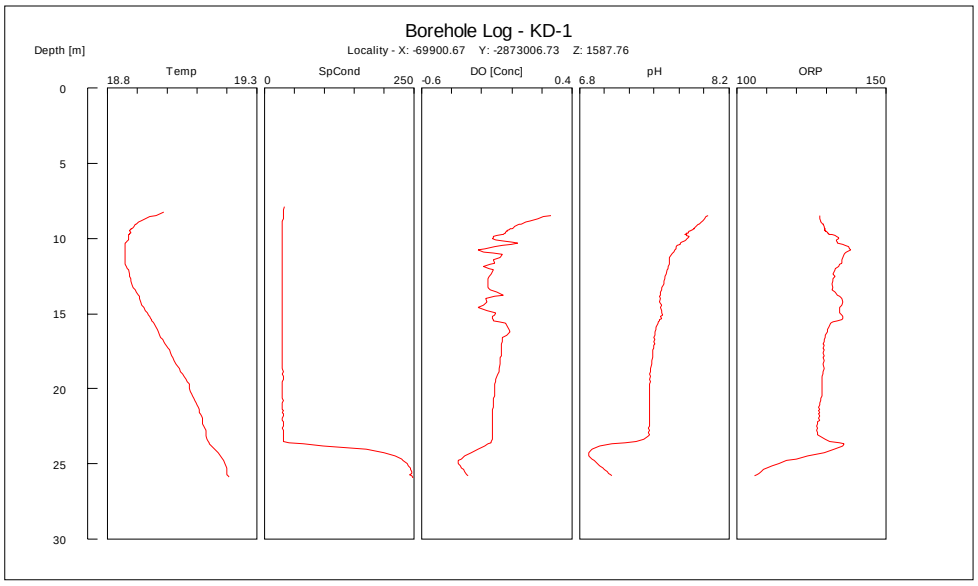


Figure i. Hydrochemical logs of spoil water.

Site	Site Name	Paste/Initial pH	Final pH	Interpretation
Optimum	BG10-1	7.27	3.74	Medium Risk Acid Generation
Optimum	BG10-2	6.9	2.91	Higher Risk Acid Generation
Optimum	BG10-3	8.11	3.58	Medium Risk Acid Generation
Optimum	BG10-4	7.75	2.62	Higher Risk Acid Generation
Optimum	BG10-5	8.29	6.03	Lower Acid Risk
Optimum	BG10-6	7.75	3.13	Higher Risk Acid Generation
Optimum	BG10-7	8.44	7.73	Lower Acid Risk
Optimum	BG10-8	8.3	2.16	Higher Risk Acid Generation
Site	**Site Name**	**Paste/Initial pH**	**Final pH**	**Interpretation**
Optimum	BG11-1	8.42	6.8	Lower Acid Risk
Optimum	BG11-2a	7.39	3	Higher Risk Acid Generation
Optimum	BG11-2b	7.62	2.92	Higher Risk Acid Generation
Optimum	BG11-3	8.2	2.16	Higher Risk Acid Generation
Optimum	BG11-4	8.35	2.25	Higher Risk Acid Generation
Optimum	BG11-5	7.93	4.87	Medium Risk Acid Generation
Optimum	BG11-6	8.19	3.36	Higher Risk Acid Generation
Optimum	BG11-7	9.17	7.74	Lower Acid Risk
Optimum	BG11-8	8.32	2.67	Higher Risk Acid Generation
Optimum	BG11-9	6.11	2.15	Higher Risk Acid Generation
Optimum	BG11-10	9.24	5.43	Medium Risk Acid Generation
Site	**Site Name**	**Paste/Initial pH**	**Final pH**	**Interpretation**
Optimum	BG1-1	7.95	4.54	Medium Risk Acid Generation
Optimum	BG1-2	6.95	1.86	Higher Risk Acid Generation
Optimum	BG1-3	7.57	3.37	Higher Risk Acid Generation
Optimum	BG1-4	8.08	2.79	Higher Risk Acid Generation
Optimum	BG1-5	6.51	2.21	Higher Risk Acid Generation
Optimum	BG1-6	8.26	1.79	Higher Risk Acid Generation
Optimum	BG1-7	8.22	1.94	Higher Risk Acid Generation

Site	Site Name	Paste/Initial pH	Final pH	Interpretation
Optimum	BG4-1	6.63	3.58	Medium Risk Acid Generation
Optimum	BG4-10	5.08	1.78	Higher Risk Acid Generation
Optimum	BG4-2	6.36	1.94	Higher Risk Acid Generation
Optimum	BG4-3	3.4	1.96	Higher Risk Acid Generation
Optimum	BG4-4	6.02	2.7	Higher Risk Acid Generation
Optimum	BG4-5	7.99	2.98	Higher Risk Acid Generation
Optimum	BG4-6	7.66	1.77	Higher Risk Acid Generation
Optimum	BG4-7	8.23	2.49	Higher Risk Acid Generation
Optimum	BG4-8	7.89	6.58	Lower Acid Risk
Optimum	BG4-9	7.99	7.94	Lower Acid Risk
Site	**Site Name**	**Paste/Initial pH**	**Final pH**	**Interpretation**
Optimum	BG5-1	7.15	3.78	Medium Risk Acid Generation
Optimum	BG5-2	5.09	2.49	Higher Risk Acid Generation
Optimum	BG5-3	7.59	2.16	Higher Risk Acid Generation
Optimum	BG5-4	8	2.48	Higher Risk Acid Generation
Optimum	BG5-5	8.78	5.7	Lower Acid Risk
Optimum	BG5-6	8.83	7.74	Lower Acid Risk
Optimum	BG5-7	8.54	2.34	Higher Risk Acid Generation
Site	**Site Name**	**Paste/Initial pH**	**Final pH**	**Interpretation**
Optimum	BG6-1	7.6	3.39	Higher Risk Acid Generation
Optimum	BG6-2	8.86	7.84	Lower Acid Risk
Optimum	BG6-3	6.23	1.64	Higher Risk Acid Generation
Optimum	BG6-4	9.17	6.93	Lower Acid Risk
Optimum	BG6-5	7.28	3.81	Medium Risk Acid Generation
Optimum	BG6-6	8.74	6.59	Lower Acid Risk
Optimum	BG6-7	8.37	2.24	Higher Risk Acid Generation

Site	Site Name	Paste/Initial pH	Final pH	Interpretation
Optimum	BG6-1	7.6	3.39	Higher Risk Acid Generation
Optimum	BG6-2	8.86	7.84	Lower Acid Risk
Optimum	BG6-3	6.23	1.64	Higher Risk Acid Generation
Optimum	BG6-4	9.17	6.93	Lower Acid Risk
Optimum	BG6-5	7.28	3.81	Medium Risk Acid Generation
Optimum	BG6-6	8.74	6.59	Lower Acid Risk
Optimum	BG6-7	8.37	2.24	Higher Risk Acid Generation
Site	**Site Name**	**Paste/Initial pH**	**Final pH**	**Interpretation**
Optimum	BG7-1	8.75	4.65	Medium Risk Acid Generation
Optimum	BG7-2	8.43	7.64	Lower Acid Risk
Optimum	BG7-3	8.38	3.96	Medium Risk Acid Generation
Optimum	BG7-4	8.3	7.68	Lower Acid Risk
Optimum	BG7-5	6.6	2.13	Higher Risk Acid Generation
Optimum	BG7-6	6.87	2.18	Higher Risk Acid Generation
Optimum	BG7-7	6.66	2.42	Higher Risk Acid Generation
Optimum	BG7-8	7.84	2.44	Higher Risk Acid Generation
Optimum	BG7-9	8.4	2.04	Higher Risk Acid Generation
Site	**Site Name**	**Paste/Initial pH**	**Final pH**	**Interpretation**
Optimum	BG8-1	6.76	4.92	Medium Risk Acid Generation
Optimum	BG8-2	7.01	2.61	Higher Risk Acid Generation
Optimum	BG8-3	7.52	2.78	Higher Risk Acid Generation
Optimum	BG8-4	7.72	2.59	Higher Risk Acid Generation
Optimum	BG8-5	9.36	4.5	Medium Risk Acid Generation
Optimum	BG8-6	8.35	3.66	Medium Risk Acid Generation
Site	**Site Name**	**Paste/Initial pH**	**Final pH**	**Interpretation**
Optimum	BG9-1	5.76	1.75	Higher Risk Acid Generation
Optimum	BG9-2	7.75	2.59	Higher Risk Acid Generation
Optimum	BG9-3	8.24	6.45	Lower Acid Risk
Optimum	BG9-4	8.12	6.3	Lower Acid Risk
Optimum	BG9-5	9.08	7.19	Lower Acid Risk
Optimum	BG9-6	7.73	2.12	Higher Risk Acid Generation
Optimum	BG9-7	7.61	2.45	Higher Risk Acid Generation
Optimum	BG9-8	7.34	1.6	Higher Risk Acid Generation

Site Name	Acid Potential (Open)	Acid Potential (Closed)	Base Potential	NNP(Open)	NNP (Closed)	Interpretation
BG10-1	1.208265988	2.416531975	0.702	-0.506265988	-1.714531975	Verify with other tests
BG10-2	8.725048208	17.45009642	4.2936	-4.431448208	-13.15649642	Verify with other tests
BG10-3	12.21933825	24.4386765	15.09168	2.87234175	-9.3469965	Verify with other tests
BG10-4	38.88752242	77.77504483	33.0852	-5.802322417	-44.68984483	Potential Acid Generator
BG10-5	1.559217475	3.11843495	12.67368	11.11446253	9.55524505	Verify with other tests
BG10-6	10.0727555	20.145511	5.94792	-4.1248355	-14.197591	Verify with other tests
BG10-7	3.35532445	6.7106489	31.72056	28.36523555	25.0099111	Excess Neutralising Minerlas
BG10-8	10.17718329	20.35436658	10.55424	0.377056708	-9.800126583	Verify with other tests
Site Name	**Acid Potential (Open)**	**Acid Potential (Closed)**	**Base Potential**	**NNP(Open)**	**NNP (Closed)**	**Interpretation**
BG11-1	3.981515438	7.963030875	14.06112	10.07960456	6.098089125	Verify with other tests
BG11-2a	3.824639025	7.64927805	3.18168	-0.642959025	-4.46759805	Verify with other tests
BG11-2b	3.806177421	7.612354842	2.85624	-0.949937421	-4.756114842	Verify with other tests
BG11-3	17.75940792	35.51881583	16.38912	-1.370287917	-19.12969583	Verify with other tests
BG11-4	36.36505033	72.73010067	10.31424	-26.05081033	-62.41586067	Potential Acid Generator
BG11-5	4.324681375	8.64936275	6.25056	1.925878625	-2.39880275	Verify with other tests
BG11-6	10.39453588	20.78907175	5.94792	-4.446615875	-14.84115175	Verify with other tests
BG11-7	4.641694125	9.28338825	29.86272	25.22102588	20.57933175	Probably Excess Neutralising Minerlas
BG11-8	45.62934958	91.25869917	36.37608	-9.253269583	-54.88261917	Potential Acid Generator
BG11-9	24.36208075	48.7241615	-1.10328	-25.46536075	-49.8274415	Potential Acid Generator
BG11-10	1.984131217	3.968262433	8.41584	6.431708783	4.447577567	Verify with other tests
Site Name	**Acid Potential (Open)**	**Acid Potential (Closed)**	**Base Potential**	**NNP(Open)**	**NNP (Closed)**	**Interpretation**
BG1-1	1.758881363	3.517762725	6.27336	4.514478638	2.755597275	Verify with other tests
BG1-2	13.29525431	26.59050863	-0.80496	-14.10021431	-27.39546863	Potential Acid Generator
BG1-3	5.373960333	10.74792067	6.192	0.818039667	-4.555920667	Verify with other tests
BG1-4	22.54681229	45.09362458	8.96256	-13.58425229	-36.13106458	Potential Acid Generator
BG1-5	53.36776104	106.7355221	0.27984	-53.08792104	-106.4556821	Potential Acid Generator
BG1-6	14.44153365	28.88306729	8.4312	-6.010333646	-20.45186729	Potential Acid Generator
BG1-7	9.897009938	19.79401988	8.11752	-1.779489938	-11.67649988	Verify with other tests

Site Name	Acid Potential (Open)	Acid Potential (Closed)	Base Potential	NNP(Open)	NNP (Closed)	Interpretation
BG2-1	0.52416336	1.048326721	3.64272	3.11855664	2.594393279	Verify with other tests
BG2-2	2.447353846	4.894707692	12.62376	10.17640615	7.729052308	Verify with other tests
BG2-3	15.74798783	31.49597567	25.91688	10.16889217	-5.579095667	Verify with other tests
BG2-4	54.93893797	109.8778759	25.8312	-29.10773797	-84.04667594	Potential Acid Generator
BG2-5	52.05225646	104.1045129	10.31424	-41.73801646	-93.79027292	Potential Acid Generator
Site Name	**Acid Potential (Open)**	**Acid Potential (Closed)**	**Base Potential**	**NNP(Open)**	**NNP (Closed)**	**Interpretation**
BG3-1	4.294724354	8.589448708	14.9832	10.68847565	6.393751292	Verify with other tests
BG3-2	22.514848	45.029696	5.6496	-16.865248	-39.380096	Potential Acid Generator
BG3-3	17.48880304	34.97760608	6.33192	-11.15688304	-28.64568608	Potential Acid Generator
BG3-4	17.98486694	35.96973388	6.11064	-11.87422694	-29.85909388	Potential Acid Generator
BG3-5	7.018436708	14.03687342	11.02368	4.005243292	-3.013193417	Verify with other tests
BG3-6	32.70314563	65.40629125	61.10928	28.40613438	-4.29701125	Verify with other tests
BG3-7	4.840756729	9.681513458	7.82352	2.982763271	-1.857993458	Verify with other tests
BG3-8	2.438240652	4.876481304	31.2096	28.77135935	26.3331187	Probably Excess Neutralising Minerlas
BG3-9	14.375	28.75	6.84288	-7.53212	-21.90712	Potential Acid Generator
Site Name	**Acid Potential (Open)**	**Acid Potential (Closed)**	**Base Potential**	**NNP(Open)**	**NNP (Closed)**	**Interpretation**
BG4-1	1.421387892	2.842775783	0.79056	-0.630827892	-2.052215783	Verify with other tests
BG4-10	18.39581812	36.79163624	-0.53376	-18.92957812	-37.32539624	Potential Acid Generator
BG4-2	8.75	17.5	5.89368	-2.85632	-11.60632	Verify with other tests
BG4-3	68.14061906	136.2812381	-18.40584	-86.54645906	-154.6870781	Potential Acid Generator
BG4-4	4.900964104	9.801928208	-0.08448	-4.985444104	-9.886408208	Verify with other tests
BG4-5	23.86125175	47.7225035	16.77744	-7.08381175	-30.9450635	Potential Acid Generator
BG4-6	17.375	34.75	3.52248	-13.85252	-31.22752	Potential Acid Generator
BG4-7	24.91956988	49.83913975	10.35	-14.56956988	-39.48913975	Potential Acid Generator
BG4-8	2.653043315	5.306086629	7.95912	5.306076685	2.653033371	Verify with other tests
BG4-9	2.784075296	5.568150592	44.12304	41.3389647	38.55488941	Probably Excess Neutralising Minerlas

Site Name	Acid Potential (Open)	Acid Potential (Closed)	Base Potential	NNP(Open)	NNP (Closed)	Interpretation
BG5-1	0.041666667	0.083333333	0.33408	0.292413333	0.250746667	Verify with other tests
BG5-2	17.9918606	35.98372121	1.33752	-16.6543406	-34.64620121	Potential Acid Generator
BG5-3	37.7752221	75.55044421	-0.20832	-37.9835421	-75.75876421	Potential Acid Generator
BG5-4	22.49632335	44.99264671	4.94448	-17.55184335	-40.04816671	Potential Acid Generator
BG5-5	16.6071496	33.21429921	15.22728	-1.379869604	-17.98701921	Verify with other tests
BG5-6	1.171882638	2.343765275	19.76064	18.58875736	17.41687473	Verify with other tests
BG5-7	30.53298146	61.06596292	0.74088	-29.79210146	-60.32508292	Potential Acid Generator

Site Name	Acid Potential (Open)	Acid Potential (Closed)	Base Potential	NNP(Open)	NNP (Closed)	Interpretation
BG6-1	2.920465773	5.840931546	3.7512	0.830734227	-2.089731546	Verify with other tests
BG6-2	1.340366648	2.680733296	33.84024	32.49987335	31.1595067	Probably Excess Neutralising Minerlas
BG6-3	24.75214927	49.50429854	0.25272	-24.49942927	-49.25157854	Potential Acid Generator
BG6-4	5.246322077	10.49264415	27.8424	22.59607792	17.34975585	Verify with other tests
BG6-5	12.19374263	24.38748525	7.28112	-4.912622625	-17.10636525	Verify with other tests
BG6-6	5.429569354	10.85913871	11.322	5.892430646	0.462861292	Verify with other tests
BG6-7	32.64995908	65.29991817	17.86896	-14.78099908	-47.43095817	Potential Acid Generator
Site Name	**Acid Potential (Open)**	**Acid Potential (Closed)**	**Base Potential**	**NNP(Open)**	**NNP (Closed)**	**Interpretation**
BG7-1	1.619353352	3.238706703	1.0392	-0.580153352	-2.199506703	Verify with other tests
BG7-2	7.339380021	14.67876004	39.15144	31.81205998	24.47267996	Probably Excess Neutralising Minerlas
BG7-3	8.911532521	17.82306504	9.53208	0.620547479	-8.290985042	Verify with other tests
BG7-4	11.56565375	23.1313075	19.5936	8.02794625	-3.5377075	Verify with other tests
BG7-5	102.0736544	204.1473088	-0.9948	-103.0684544	-205.1421088	Potential Acid Generator
BG7-6	5.351389869	10.70277974	0.44256	-4.908829869	-10.26021974	Verify with other tests
BG7-7	14.36536285	28.73072571	1.47312	-12.89224285	-27.25760571	Potential Acid Generator
BG7-8	4.252058246	8.504116492	3.53424	-0.717818246	-4.969876492	Verify with other tests
BG7-9	12.00435556	24.00871113	5.32416	-6.680195563	-18.68455113	Verify with other tests

Site Name	Acid Potential (Open)	Acid Potential (Closed)	Base Potential	NNP(Open)	NNP (Closed)	Interpretation
BG8-1	3.543127643	7.086255285	9.01248	5.469352357	1.926224715	Verify with other tests
BG8-2	1.322127108	2.644254217	1.66728	0.345152892	-0.976974217	Verify with other tests
BG8-3	1.450380883	2.900761767	3.8868	2.436419117	0.986038233	Verify with other tests
BG8-4	3.131033367	6.262066733	5.78952	2.658486633	-0.472546733	Verify with other tests
BG8-5	0.477171125	0.95434225	6.20064	5.723468875	5.24629775	Verify with other tests
BG8-6	2.107777696	4.215555392	1.06632	-1.041457696	-3.149235392	Verify with other tests
Site Name	**Acid Potential (Open)**	**Acid Potential (Closed)**	**Base Potential**	**NNP(Open)**	**NNP (Closed)**	**Interpretation**
BG9-1	7.0682185	14.136437	-0.37104	-7.4392585	-14.507477	Verify with other tests
BG9-2	15.31544742	30.63089483	8.30736	-7.008087417	-22.32353483	Potential Acid Generator
BG9-3	3.845831817	7.691663633	12.07704	8.231208183	4.385376367	Verify with other tests
BG9-4	2.399607221	4.799214442	8.18952	5.789912779	3.390305558	Verify with other tests
BG9-5	0.902191296	1.804382592	78.81816	77.9159687	77.01377741	Probably Excess Neutralising Minerlas
BG9-6	69.84072542	139.6814508	28.272	-41.56872542	-111.4094508	Potential Acid Generator
BG9-7	1.927742846	3.855485692	2.78352	0.855777154	-1.071965692	Verify with other tests
BG9-8	5.428665531	10.85733106	0.9036	-4.525065531	-9.953731062	Verify with other tests
BG9-9	33.74625983	67.49251967	6.92424	-26.82201983	-60.56827967	Potential Acid Generator
BG9-10	3.505166817	7.010333633	10.64832	7.143153183	3.637986367	Verify with other tests

Site Name	Neutralising Potential Ratio(NP/AP) for Open System	Neutralising Potential Ratio(NP/AP) for Closed System	Interpretation Open System	Interpretation Closed System
BG10-1	0.580997899	0.290498949	Likely Acid Generator	Likely Acid Generator
BG10-2	0.492100433	0.246050216	Likely Acid Generator	Likely Acid Generator
BG10-3	1.235065246	0.617532623	Acid under certain conditions	Likely Acid Generator
BG10-4	0.850792181	0.42539609	Likely Acid Generator	Likely Acid Generator
BG10-5	8.128231118	4.064115559	No Acid Potential	No Acid Potential
BG10-6	0.590495818	0.295247909	Likely Acid Generator	Likely Acid Generator
BG10-7	9.453798127	4.726899063	No Acid Potential	No Acid Potential
BG10-8	1.037049221	0.51852461	Acid under certain conditions	Likely Acid Generator
Site Name	**Neutralising Potential Ratio(NP/AP) for Open System**	**Neutralising Potential Ratio(NP/AP) for Closed System**	**Interpretation Open System**	**Interpretation Closed System**
BG11-1	3.53160002	1.76580001	Acid under certain conditions	Acid under certain conditions
BG11-2a	0.831890272	0.415945136	Likely Acid Generator	Likely Acid Generator
BG11-2b	0.750422191	0.375211096	Likely Acid Generator	Likely Acid Generator
BG11-3	0.922841577	0.461420788	Likely Acid Generator	Likely Acid Generator
BG11-4	0.283630571	0.141815286	Likely Acid Generator	Likely Acid Generator
BG11-5	1.445322663	0.722661331	Acid under certain conditions	Likely Acid Generator
BG11-6	0.572216025	0.286108012	Likely Acid Generator	Likely Acid Generator
BG11-7	6.433582049	3.216791025	No Acid Potential	Acid under certain conditions
BG11-8	0.797207945	0.398603972	Likely Acid Generator	Likely Acid Generator
BG11-9	0.000410474	0.000205237	Likely Acid Generator	Likely Acid Generator
BG11-10	4.241574312	2.120787156	No Acid Potential	Acid under certain conditions

Site Name	Neutralising Potential Ratio(NP/AP) for Open System	Neutralising Potential Ratio(NP/AP) for Closed System	Interpretation Open System	Interpretation Closed System
BG1-1	3.566676033	1.783338016	Acid under certain conditions	Acid under certain conditions
BG1-2	0.000752148	0.000376074	Likely Acid Generator	Likely Acid Generator
BG1-3	1.15222287	0.576111435	Acid under certain conditions	Likely Acid Generator
BG1-4	0.397508964	0.198754482	Likely Acid Generator	Likely Acid Generator
BG1-5	0.005243615	0.002621808	Likely Acid Generator	Likely Acid Generator
BG1-6	0.58381611	0.291908055	Likely Acid Generator	Likely Acid Generator
BG1-7	0.820199237	0.410099619	Likely Acid Generator	Likely Acid Generator
Site Name	**Neutralising Potential Ratio(NP/AP) for Open System**	**Neutralising Potential Ratio(NP/AP) for Closed System**	**Interpretation Open System**	**Interpretation Closed System**
BG2-1	6.949589145	3.474794573	No Acid Potential	Acid under certain conditions
BG2-2	5.158126203	2.579063101	No Acid Potential	Acid under certain conditions
BG2-3	1.645726443	0.822863221	Acid under certain conditions	Likely Acid Generator
BG2-4	0.470180185	0.235090092	Likely Acid Generator	Likely Acid Generator
BG2-5	0.19815164	0.09907582	Likely Acid Generator	Likely Acid Generator
Site Name	**Neutralising Potential Ratio(NP/AP) for Open System**	**Neutralising Potential Ratio(NP/AP) for Closed System**	**Interpretation Open System**	**Interpretation Closed System**
BG3-1	3.488745438	1.744372719	Acid under certain conditions	Acid under certain conditions
BG3-2	0.250927743	0.125463872	Likely Acid Generator	Likely Acid Generator
BG3-3	0.362055653	0.181027826	Likely Acid Generator	Likely Acid Generator
BG3-4	0.33976565	0.169882825	Likely Acid Generator	Likely Acid Generator
BG3-5	1.570674562	0.785337281	Acid under certain conditions	Likely Acid Generator
BG3-6	1.868605568	0.934302784	Acid under certain conditions	Likely Acid Generator
BG3-7	1.616177064	0.808088532	Acid under certain conditions	Likely Acid Generator
BG3-8	12.80004907	6.400024537	No Acid Potential	No Acid Potential
BG3-9	0.476026435	0.238013217	Likely Acid Generator	Likely Acid Generator

Site Name	Neutralising Potential Ratio(NP/AP) for Open System	Neutralising Potential Ratio(NP/AP) for Closed System	Interpretation Open System	Interpretation Closed System
BG4-1	0.556188782	0.278094391	Likely Acid Generator	Likely Acid Generator
BG4-10	0.000543602	0.000271801	Likely Acid Generator	Likely Acid Generator
BG4-2	0.673563429	0.336781714	Likely Acid Generator	Likely Acid Generator
BG4-3	0.000146755	7.33777E-05	Likely Acid Generator	Likely Acid Generator
BG4-4	0.002040415	0.001020207	Likely Acid Generator	Likely Acid Generator
BG4-5	0.703124889	0.351562445	Likely Acid Generator	Likely Acid Generator
BG4-6	0.202732662	0.101366331	Likely Acid Generator	Likely Acid Generator
BG4-7	0.415336222	0.207668111	Likely Acid Generator	Likely Acid Generator
BG4-8	2.999996252	1.499998126	Acid under certain conditions	Acid under certain conditions
BG4-9	15.84836447	7.924182235	No Acid Potential	No Acid Potential
Site Name	**Neutralising Potential Ratio(NP/AP) for Open System**	**Neutralising Potential Ratio(NP/AP) for Closed System**	**Interpretation Open System**	**Interpretation Closed System**
BG5-1	8.01792	4.00896	No Acid Potential	No Acid Potential
BG5-2	0.074340282	0.037170141	Likely Acid Generator	Likely Acid Generator
BG5-3	0.000264724	0.000132362	Likely Acid Generator	Likely Acid Generator
BG5-4	0.219790582	0.109895291	Likely Acid Generator	Likely Acid Generator
BG5-5	0.916911111	0.458455556	Likely Acid Generator	Likely Acid Generator
BG5-6	16.8623029	8.431151451	No Acid Potential	No Acid Potential
BG5-7	0.024264908	0.012132454	Likely Acid Generator	Likely Acid Generator

Site Name	Neutralising Potential Ratio(NP/AP) for Open System	Neutralising Potential Ratio(NP/AP) for Closed System	Interpretation Open System	Interpretation Closed System
BG6-1	1.28445265	0.642226325	Acid under certain conditions	Likely Acid Generator
BG6-2	25.24700242	12.62350121	No Acid Potential	No Acid Potential
BG6-3	0.010210022	0.005105011	Likely Acid Generator	Likely Acid Generator
BG6-4	5.307032163	2.653516081	No Acid Potential	Acid under certain conditions
BG6-5	0.597119377	0.298559689	Likely Acid Generator	Likely Acid Generator
BG6-6	2.085248251	1.042624126	Acid under certain conditions	Acid under certain conditions
BG6-7	0.547288894	0.273644447	Likely Acid Generator	Likely Acid Generator
Site Name	**Neutralising Potential Ratio(NP/AP) for Open System**	**Neutralising Potential Ratio(NP/AP) for Closed System**	**Interpretation Open System**	**Interpretation Closed System**
BG7-1	0.641737641	0.320868821	Likely Acid Generator	Likely Acid Generator
BG7-2	5.334434229	2.667217114	No Acid Potential	Acid under certain conditions
BG7-3	1.069634205	0.534817102	Acid under certain conditions	Likely Acid Generator
BG7-4	1.694119539	0.84705977	Acid under certain conditions	Likely Acid Generator
BG7-5	9.79685E-05	4.89842E-05	Likely Acid Generator	Likely Acid Generator
BG7-6	0.082700011	0.041350005	Likely Acid Generator	Likely Acid Generator
BG7-7	0.102546661	0.051273331	Likely Acid Generator	Likely Acid Generator
BG7-8	0.831183346	0.415591673	Likely Acid Generator	Likely Acid Generator
BG7-9	0.443519019	0.221759509	Likely Acid Generator	Likely Acid Generator
Site Name	**Neutralising Potential Ratio(NP/AP) for Open System**	**Neutralising Potential Ratio(NP/AP) for Closed System**	**Interpretation Open System**	**Interpretation Closed System**
BG8-1	2.543650952	1.271825476	Acid under certain conditions	Acid under certain conditions
BG8-2	1.261058781	0.630529391	Acid under certain conditions	Likely Acid Generator
BG8-3	2.679847787	1.339923893	Acid under certain conditions	Acid under certain conditions
BG8-4	1.84907643	0.924538215	Acid under certain conditions	Likely Acid Generator
BG8-5	12.99458344	6.497291721	No Acid Potential	No Acid Potential
BG8-6	0.505897753	0.252948876	Likely Acid Generator	Likely Acid Generator

Site Name	Neutralising Potential Ratio(NP/AP) for Open System	Neutralising Potential Ratio(NP/AP) for Closed System	Interpretation Open System	Interpretation Closed System
BG9-1	0.001414784	0.000707392	Likely Acid Generator	Likely Acid Generator
BG9-2	0.542417063	0.271208531	Likely Acid Generator	Likely Acid Generator
BG9-3	3.140293329	1.570146665	Acid under certain conditions	Acid under certain conditions
BG9-4	3.412858542	1.706429271	Acid under certain conditions	Acid under certain conditions
BG9-5	87.36302419	43.68151209	No Acid Potential	No Acid Potential
BG9-6	0.404806792	0.202403396	Likely Acid Generator	Likely Acid Generator
BG9-7	1.443927029	0.721963514	Acid under certain conditions	Likely Acid Generator
BG9-8	0.166449746	0.083224873	Likely Acid Generator	Likely Acid Generator
BG9-9	0.205185405	0.102592703	Likely Acid Generator	Likely Acid Generator
BG9-10	3.037892505	1.518946252	Acid under certain conditions	Acid under certain conditions

APPENDIX 6

Detailed interpretation of acid-base accounting results for Optimum