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## WILL IT GENERATE AMD?

### AN OVERVIEW OF METHODS TO PREDICT ACID MINE DRAINAGE

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#### INTRODUCTION

Many believe that mining effluents always contain metals. While technically correct most mine effluents contain either high or low levels though the concentration and loading of metals varies from mine to mine. Acid mine drainage (AMD) is usually the cause of high metal concentrations in contaminated effluents. Mines that have AMD have difficulty in meeting environmental standards and usually expend large financial resources on pollution control. It is imperative that mining companies and regulatory agencies attempt to predict AMD prior to mining so that mines can be designed that are cost effective and compatible with the environment. If AMD is generated, then companies should identify the source so that mitigation measures can be accomplished for minimal cost. In this paper, we discuss the prediction of AMD prior to mining and the identification of acid sources after drainage has become contaminated.

#### Formation of AMD

Prediction of acid mine drainage must be based on a thorough knowledge of the process of formation and the factors that control it. Unfortunately, the process is complex and not completely understood

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despite several decades of intense study. The knowledge base is considerable, however, and growing as illustrated below.

Kleinmann et al., 1981, identified three stages in the generation of acid mine drainage. In the first stage, chemical and, or, biological oxidation of pyrite and other sulfide minerals slowly produces acid (Figure 1). This acid may initially be neutralized by carbonate minerals in the rock. After the carbonates are consumed, the process enters the second stage. As the pH drops in the microenvironment around the sulfide minerals, populations of acid loving (acidophilic) bacteria such as Thiobacillus ferrooxidans begin to multiply. These bacteria cause a further decrease in pH, causing the process to enter the third stage. When the pH around the sulphides decreases to below 3, ferric iron remains in solution. Ferrous iron is converted by the bacteria to ferric iron which in turn oxidizes the sulphide minerals. The rate of acid formation is rapid in the last stage and is limited by the concentration of ferric iron.

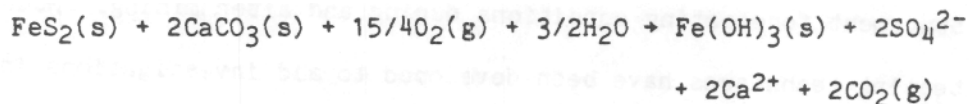
The four equations in Figure 1 generally describe the acid production process with pyrite ( $\text{FeS}_2$ ) as occurs at coal mines, but, describe only a few of the many sulphide oxidation reactions at metal mines. The mix of sulphide minerals at metal mines accounts for the diversity in AMD quality.

Ferguson and Erickson (1986) classified the factors that control AMD formation as primary, secondary, and tertiary. The primary factors are those directly involved in the acid production process. Secondary factors control the consumption or alteration of the products from the acid generation reactions, while tertiary factors are the physical

aspects of the waste materials or minesite that Influence acid production, migration, and consumption.

The primary factors include pyrite and other sulfide minerals, oxygen, water, ferric iron, and iron-oxidizing bacteria (Figure 1). The physical relationship of these factors in an acid generating mine spoil is shown in Figure 2. Here, water and oxygen are provided by the external environment to the acid generating sites within the spoil. The massive transfer of reactants supports rapid acid production.

Regardless of the presence of pyrite and other sulfide minerals, AMD may not be a problem at a minesite due to secondary factors. The most important secondary factor is the neutralization of acid by alkalinity released from carbonate minerals in the mine waste, such as calcite ( $\text{CaCO}_3$ ) and dolomite [ $\text{CaMg}(\text{CO}_3)_2$ ] as described previously. The neutralization by calcite of acidity produced from pyrite oxidation may be represented as follows (Williams et al., 1982):



Other secondary factors include alteration of oxidation products by further reaction, such as ion exchange on clay surfaces, gypsum precipitation, and acid-induced dissolution of other minerals.

The physical characteristics of a mining waste, the spatial relationship between wastes, and the hydrologic regime are some of the tertiary factors that affect the AMD process. The important physical characteristics include particle size, physical weathering tendency, and mine waste permeability. The rate of acid production is a function of

the particle surface area since that property reflects the amount of sulphide exposed for reaction.

Water serves several roles in the acid production system, acting as a reactant, as a reaction medium, and as a product transport solvent.

The overriding principle in the generation of acid mine water is that if the alkalinity released by minerals or already present in the contacting water exceeds the acidity produced then the system remains neutral or basic and the process does not enter Stage II. In this case, the bacteria responsible for catalyzing the acid generation reactions are inhibited and the solubilities of ferrous and ferric iron are reduced - both factors inhibit acid production.

The prediction of acid mine drainage involves the consideration of the few important factors that might control the acid production and consumption reactions at a minesite and the synthesis into a qualitative statement forecasting conditions during and after mining. Models and testing techniques have been developed to aid investigations in making this forecast.

#### Pre-Mine Prediction of AMD

Methods to predict acid mine drainage can be divided into five groups (Ferguson and Erickson, 1986).

1. geographical mining comparisons
2. paleoenvironmental and geological models
3. geochemical static tests
4. geochemical kinetic tests
5. mathematical models

Geographical mining comparisons involve examining and sampling drainage from abandoned or operating mines near the project under study. Simple extrapolations are made for similar mining operations in related geological environments.

Paleoenvironmental models examine the regional depositional environment of the sulphide minerals. Pyritic sulphur formed in marine or brackish water may have a greater tendency to generate AMD than that formed in fresh water environments (Caruccio et al., 1977, Williams et al., 1982). Geological models of a sedimentary sequence or igneous/metamorphic orebody are valuable in estimating the location and size of potentially acid generating zones.

Geochemical static tests simply compare the amount of potentially acid generating sulphides to acid consuming carbonates in a rock sample (Figure 3). The acid/base accounting and APP: Sulphur Ratio tests are used frequently for coal mines in the United States while the B.C. Research Initial Test is used frequently for metal mines in Canada. The acid potential determinations are similar for the three tests, but, the neutralization potentials are different. The acid/base account neutralization potential involves a stronger digestion of carbonate minerals and may produce a slightly higher value than the other two procedures (Ferguson, 1982, Caruccio et al., 1977).

The acid/base account includes a format for presenting AMD prediction data useful for surface coal mines disturbing many lithologie groups (Figure ^). The net neutralization potentials of the individual groups may be used to develop a waste management plan for attempting to prevent AMD formation.

These tests are called static as they do not consider the relative rates of acid production and consumption. The rate of release of acidity from sulphide oxidation, and alkalinity from carbonate dissolution may be quite different and could affect the generation of acid mine drainage. Geidel (1979) suggests that the release of alkalinity is limited to a maximum value by the partial pressure of carbon dioxide while the buildup of acidity is not constrained. Various investigators have criticized the use of static tests and suggested they are only applicable to obvious cases where the quantity of acid producing or acid consuming material is in significant excess (Caruccio, et al., 1980; Williams et al., 1982; SENES, 1984). However, Ferguson and Erickson (1986) in their review of AMD prediction techniques, found that static tests were often accurate in predicting drainage quality and were particularly valuable as screening tests to determine if more sophisticated procedures should be used.

Static tests have been modified to account for possible differences in pyrite reactivity at coal mines. Caruccio et al., (1977) used reflected light microscopy to determine the morphology of pyrite which correlated with drainage quality from leaching tests. The fine grained "framboidal" pyrite was found to be the most reactive. Hammack (1986) used an evolved gas technique to provide a rapid determination of pyrite availability for oxidation. Samples were placed in a furnace, heated in an oxidizing atmosphere, and the evolved sulphur dioxide monitored at various temperatures. The pyrite oxidized from 150° C to 555° C, but only that which ignited below 220° C significantly affected drainage quality in parallel laboratory leaching tests.

Kinetic test methods attempt to model the acid producing and consuming processes in the laboratory or field. Various protocols have been developed as shown in Table 1. Kinetic tests might be expected to more accurately model the acid production and consumption processes though interpretation can be difficult. Kinetic tests are not commonly used because of their higher cost and longer duration, compared to static tests. B.C. Research has developed a type of kinetic test which assesses the ability of bacteria to oxidize sulphide minerals in a rock sample (Test 1 in Table 1). This test is of particular value in determining whether a mineral constituent of the waste is toxic to the microorganisms and inhibits their growth. Other kinetic tests follow the change in leachate quality over time and use the results in a physical or mathematical model of the AMD process. Mathematical models have recently been developed to quantitatively predict mine drainage quality (Carucclo, 1984; Jaynes et al., 1984; Ricca and Shultz, 1979; Halbert et al., 1983; Nicholson, 1984; Cathles, 1979; Davis and Ritchie, 1983). These models are rather complex and have not been extensively verified or used for prediction to date.

A major difficulty with prediction techniques is the lack of verification of test results with field experience. Two recent studies, one of metal mines and one of coal mines, examined the accuracy of some AMD prediction techniques.

Static (acid/base accounting) and kinetic (humidity cell) tests were conducted on 22 rock samples from seven metal mines in British Columbia and Yukon (Ferguson, 1985). Samples of tailings and waste rock were obtained from both active and abandoned minesites. The total sulfur

contents ranged from 0.13 to 49.2 percent, and neutralization potentials ranged from 0 to 258 tonnes  $\text{CaCO}_3$  equivalent per 1,000 tonnes of material. The very high percent sulfur contents of some samples yielded a definite prediction for acid production according to static methods. The static and kinetic tests correctly predicted the formation of AMD in all but six cases - three were incorrect and three were inconclusive. A few results from the kinetic tests (humidity cells) were difficult to interpret due to indefinite pH trends. The results supported the use of static tests for predicting AMD, but suggested there was only a poor relationship between the magnitude of the net base value (net neutralization potential) and the amount of acidity produced during the initial stage of the AMD process. The static tests may be useful for qualitative AMD predictions but not for estimates of actual mine water quality.

Correlations between the static test results (percent sulphur, neutralization potential, and net neutralization potential) and the kinetic test results (sulphate production rate, cumulative acidity production, initial leachate pH and final leachate pH) provided some insight into the geochemical processes involved in acid generation. As expected, the sulphate production rate increased with percent sulphur and was a good indicator of the sulphide oxidation rate. The initial pH of the leachate decreased with increased percent sulphur probably reflecting an increase in soluble metal salts in the samples at the start of the experiment. The cumulative acidity production and final leachate pH, however, correlated with the neutralization potential rather than the net neutralization potential as might be expected from



static test prediction theory. In these tests, the quantity of neutralizing minerals in the samples appeared to play the critical role in initially controlling the acid generation process. In the longer term, acid production from sulphide minerals would be expected to "outlast" the alkalinity from carbonate minerals in potentially acid generating rocks and the AMD process would enter Stage II. These findings agree with results from other short-term (up to 6 months) kinetic tests where little acid was produced from samples exhibiting a strong acid potential according to static tests. Trends in sulphate production, acidity, and pH from kinetic tests must be examined together with the static test results to forecast the long term leachate quality at a mine.

An analogous study evaluated the predictive capability of static (acid-base account) and kinetic (a modified humidity cell procedure) tests applied to coal overburden (Erickson, 1986). Sites were deliberately selected to focus on hard-to-predict cases. In the preliminary analysis, 25 sites were analyzed by the static test; 14 of these were also subjected to the kinetic test.

A simple type of interpretation was applied to acid-base account data. The net neutralization potential (NNP) was calculated for each lithologie unit and the values for individual units were combined to generate a thickness-weighted average NNP to represent the whole overburden column. Thickness-weighted NNP values ranged from -20 to +250 tonnes  $\text{CaCO}_3$  per 1,000 tonnes of overburden. These values were then compared to flow-weighted net alkalinity in drainage from reclaimed mine sections (Table 2). There is no linear correlation between

observed drainage alkalinity and thickness-weighted NNP (Figure 5). NNP values greater than 33 tonnes/1,000 tonnes were always associated with alkaline drainage while NNP values less than 22 tonnes/1,000 tonnes were predominantly associated with acid drainage. The validity of a boundary between 22 and 33 tonnes/1,000 tonnes to distinguish sites that will not produce acidic drainage is uncertain because only 4 of 25 sites had higher NNP values. Further analyses are in progress to test other methods of evaluating overburden analysis data for water quality predictions.

Kinetic tests were conducted on overburden from 14 of these sites. The cumulative alkaline loads produced by each lithologie unit during the simulated weathering test were averaged for the whole overburden column on a thickness-weighted basis and compared to actual drainage quality. As with the acid-base account results, no linear correlation was found. Attempts to use the thickness-weighted alkaline load from the kinetic test to predict acid or alkaline drainage when the NNP value from the acid-base account was less than 22 tonnes/1,000 tonnes were unsuccessful.

These findings are not surprising in light of the high geochemical variability in coal overburden strata. Tests on individual lithologie units fail to account for interactions between potential acid- and alkaline-producing materials.

#### Uncertainty In AMD Production

The production of acid mine drainage is complex and yet, important factors can be modelled for prediction. However, uncertainty is always present and varies according to the nature of the waste material and its

deposition and reclamation history. The range in uncertainty is illustrated in the four simple cases of waste rock disposal in Figure 6. Case one represents the most certain prediction where the waste is either completely composed (1a) or devoid (1b) of sulphide minerals; cases rarely seen at real mines. Uncertainty increases In case two where the sulphide content has increased or decreased from the two extremes In case one. The potential for AMD can be predicted with reasonable certainty by static tests in either high (2a) or low sulphide content (2c) samples. Predictions are more difficult when the sulphide and carbonate content are in critical balance (carbonates 3.125 times sulphides by weight) as shown in 2b. If every particle contains a balance of sulphide and carbonate minerals then theoretically, the two mineral types would be balanced. However, the maximum amount of pyrite that can be oxidized is unlimited, while carbonate dissolution is governed by equilibria. Further, coatings on both sulphide and carbonate mineral surfaces will form and affect the chemical reactions and ultimate drainage quality. Kinetic tests would be valuable in assessing reaction rates.

Homogeneous wastes are rarely found at real mines. More frequently, the acid generation potential will range reflecting spatial differences in geological environments. The numerical balance of the acid generation potential of the entire rock column would be assessed as part of the AMD prediction in acid/base accounting. This balance is important, but, the position of the waste types within the dump may ultimately determine drainage quality (Case 3). Potentially acid generating waste deposited on the exterior of a dump may generate AMD

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that may be only partially neutralized by carbonate minerals in the interior (3a). Coatings would form on carbonate minerals diminishing neutralization capability. In some cases, the sulphide minerals may be randomly distributed in the dump (3b). Acid generation may occur in only isolated zones and seep quality will vary depending upon its source. Potentially acid generating waste should be placed in the interior of the dump where only alkaline groundwater contacts the high sulphide waste (3c). This is AMD prevention by segregation. However, with large quantities, or highly reactive sulphides, the AMD may form despite the alkaline cover due to geochemical limitations on the maximum amount of alkalinity that can be delivered to the sulphide minerals, as discussed previously. A combination of static and kinetic tests, the latter using a simulated stacking sequence of wastes, might be valuable in assessing the relative rates of reaction.

Heterogeneous geochemistry, randomly distributed particles, and an overall sulphide/carbonate balance represents one of the most difficult predictions (Case 1). Very high uncertainty would be associated with a prediction in this case and must be supported by comprehensive kinetic tests on samples that simulate quantity and placement of various lithologie units. Case four describes the sites selected for the coal mine drainage prediction study described earlier. The inaccurate predictions identified in that study may demonstrate the role of spoil placement.

#### Determining the Source of AMD

The overall cost of AMD control would decrease if the most active areas within acid generating wastes could be identified and mitigation

measures targeted for maximum benefit. Locating and sampling the seeps from mining wastes is usually the first step that companies and regulatory agencies take to identify acid generating zones. The pH, acidity, sulphate, metal, and microbial content, and flow of the seeps indicate the geochemical and hydrological processes within the waste. For example, sampling at an abandoned waste rock dump in British Columbia indicated that flow and quality of seeps varied, but their location remained the same; neutralization agents could be applied at these specific sites to reduce contaminant loading (Figure 7). The majority of copper released from the dump originated from two of the four drainage zones in the dump (zones BB and CC in Figure 7). Mitigation measures should be targeted to those areas.

At these sites, seasonal variation in AMD quantity and quality requires monitoring over a wide range of hydrologic conditions to quantify loadings to the receiving environment. Contaminated seeps are usually most readily identified in the spring and fall coincident with maximum melt or precipitation events following prolonged dry periods.

Yellow or red staining of rock and leachate may also indicate the source of AMD. AMD containing only ferrous iron is clear, but shows a red or yellow tint downstream as the ferrous iron is oxidized to the ferric form. AMD from metal mines may be blue-green reflecting high copper values. Dead vegetation near a seep may be an early indicator of contamination.

Characteristics of the waste such as total and sulphate sulphur, neutralization potential, and paste pH indicate the progress of AMD formation reactions. Samples of metal mine tailings can be obtained at

various depths and analyzed by these geochemical tests to determine the depth of oxidation and other information useful in designing alkaline or impermeable covers for AMD control.

The partial pressure of oxygen available in the pore spaces throughout the waste indicates both oxygenated zones that can support acid production and zones where oxidation is occurring. Several oxygen profiles (O<sub>2</sub> partial pressure versus depth) are typical for mine wastes (Harris and Ritchie, 1985; Erickson, 1985). When oxygen is supplied by diffusion (induced by concentration differential) from the atmosphere, the profile shows decreasing oxygen with increasing depth. Active oxidation zones are reflected as sharp partial pressure gradients. When advection (induced by thermal or pressure differential) supplies oxygen to the mine waste, high partial pressures are observed at intermediate depths. Gradients are less easily correlated with active oxidation in these cases. However, the availability of oxygen in advection zones indicates that, if present, pyritic material will likely undergo oxidation.

Variations in the surface or interior temperatures of mining wastes can indicate acid generation since the reactions are exothermic. Temperatures up to 55° C were recorded by thermister strings buried in a very active acid generating waste rock dump in British Columbia (Patterson, 1986). A significant drop in temperature following reclamation of a waste rock dump was recorded by Harris and Ritchie (1986) using thermister probes in wells. Thermography (infrared imaging) was used to identify acid generating zones at three waste rock dumps and open pits in British Columbia. A related, but simpler

approach, involved locating bare spots on a waste rock dump following the first snowfall of winter., In all cases, heat generation correlated with observed differences in water quality of seeps.

Remote detection of acid sources is possible with the geophysical method of electromagnetic induction measurements. This means of surveying detects terrain conductivity anomalies. In several surveys conducted at regraded coal mines, anomalies were observed and later confirmed to reflect pyrite oxidation, changes in saturation state, and disturbed area boundaries (Watzlaf and Ladwig, 1987). The method was found to be most useful as a reconnaissance tool preceding application of detailed monitoring methods.

#### Summary

Though the acid mine drainage process is complex and not completely understood, prediction techniques are available that are successful for many mining projects. Considerable skill and experience is required to conduct some tests and interpret results for accurate forecasts of mine drainage quality. Uncertainty is always present, and should be estimated and acknowledged in the prediction statement.

The location of acid generating zones within a mining waste can be determined by both simple and sophisticated techniques. In general, it is easier to locate the source of AMD than predict prior to mining if drainage will be acidic. Success in both of these areas of prediction are required if mining is to be conducted in an environmentally sound manner.

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TABLE 1. - KINETIC ACID MINE DRAINAGE PREDICTION TECHNIQUES

(Adapted from Ferguson, 1985 and Ferguson and Erickson, 1986)

| TEST                               | DESCRIPTION   | USE  | REFERENCES  |
|------------------------------------|---|--|---|
| 1. B.C. Research Confirmation Test | <ul style="list-style-type: none"> <li>- Sample placed in 250 ml Erlenmeyer flask with 70 ml nutrient media, culture of Thiobacillus ferrooxidans at pH 2.2-2.5.</li> <li>- Flask placed on gyratory shaker at 35° C in CO<sub>2</sub> enriched atmosphere.</li> <li>- pH monitored and additional sample added.</li> <li>- If pH rises substantially then sample non-acid producer.</li> <li>- If pH remains low then sample potential acid producer.</li> </ul> | Frequently used for metal mines in Canada                            | Bruynesteyn and Hackl (1984)                                  |
| 2. Shake Flasks                    | <ul style="list-style-type: none"> <li>- Sample placed in 1L Erlenmeyer flask with 600 ml of water or nutrient solution.</li> <li>- Series of samples tested at various starting pH, inoculation, and temperature.</li> <li>- Samples incubated for up to 3 months.</li> <li>- Leachates analyzed weekly and bi-weekly for range of parameters.</li> </ul>  | Infrequently used for metal mines in Canada                          | Davidge (1984)<br>Halbert, et al., (1983)                     |
| 3. Soxhlet Reactor                 | <ul style="list-style-type: none"> <li>- Standard or modified Soxhlet reactor used.</li> <li>- Water placed in reservoir, vaporized and passed into condenser. Condensed liquid drips into thimble with sample and thence back into the reservoir.</li> <li>- Leachate analyzed after 64-192 hrs. for a range of parameters.</li> </ul>   | Infrequently used in coal fields of Appalachia, U.S.A.               | Sullivan and Sobek (1982)<br>Renton (1983)                    |
| 4. Humidity Cell                   | <ul style="list-style-type: none"> <li>- Sample placed in plexiglass container connected to humidified air.</li> <li>- Humidified air passed over sample for 3 days.</li> <li>- Dry air passed over sample for 3 days and 200 ml of water added on seventh day.</li> <li>- Leachate removed and analyzed for range of parameters.</li> <li>- Procedure repeated for 8-10 weeks.</li> </ul>  | <p>Relatively common in coal fields</p> <p>of Appalachia, U.S.A.</p> | <p>Caruccio et al., (1977)</p> <p>Caruccio et al., (1980)</p> |

TABLE 1. - KINETIC ACID MINE DRAINAGE PREDICTION TECHNIQUES (Continued)

(Adapted from Ferguson, 1985 and Ferguson and Erickson, 1986)

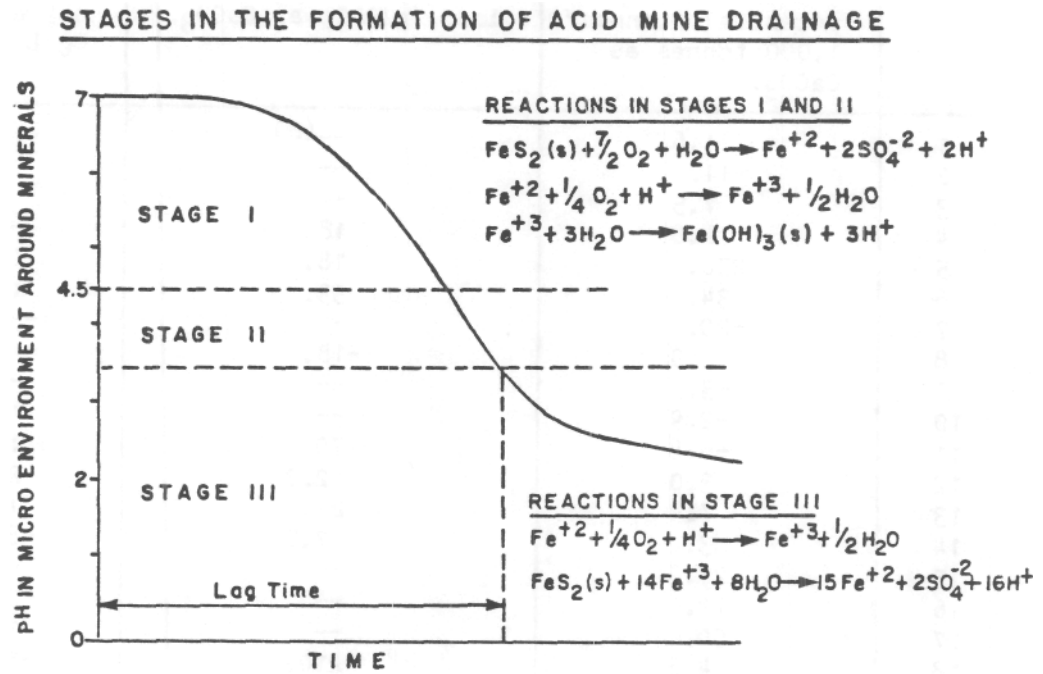
| TEST                         | DESCRIPTION   | USE   | REFERENCES   |
|------------------------------|---|---|--|
| 5. Columns/<br>Lysimeters    | <ul style="list-style-type: none"> <li>- Sample placed in column and periodically leached by distilled water.</li> <li>- Samples of leachate analyzed for range of parameters.</li> <li>- Usually leached for 8-10 weeks minimum.</li> <li>- Several variations of set-up and leaching procedures in literature.</li> </ul> | Relatively common in Canada and U.S.A.      | <p>Sturey et al., (1982)</p> <p>Apel (1983)<br/>Ritcey and Silver (1981)</p> |
| 6. Test Plots/<br>Pits/Piles | <ul style="list-style-type: none"> <li>- Run of mine or modified sample placed on impervious surface.</li> <li>- Precipitation provides leachate which is collected in sump.</li> <li>- Samples of collected leachate analyzed for range of parameters.</li> <li>- Test usually run for at least 1 year.</li> </ul>         | Very infrequently used in Canada and U.S.A. | <p>Eger et al., (1981)</p> <p>Murray and Okuhara (1980)</p>                  |

TABLE 2. - COMPARISON OF OVERBURDEN ANALYSIS  
AND POST-MINING DRAINAGE QUALITY FOR  
25 U.S. COAL MINES<sup>(1)</sup>

| SITE | ACID-BASE ACCOUNT<br>Thickness-weighted<br>net neutralization<br>potential, tonnes/<br>1,000 tonnes as<br>CaCO <sub>3</sub> . | MODIFIED HUMIDITY CELL<br>Thickness-weighted<br>cumulative net alkaline<br>load, g/300g as CaCO <sub>3</sub> . | POST-MINING<br>DRAINAGE QUALITY<br>Flow-weighted<br>net alkalinity,<br>mg/L as CaCO <sub>3</sub> . |
|------|---|--|--|
| 1    | -1.6  | --(2)  | -120.  |
| 2    | -11.  | --   | 7.6  |
| 3    | 7.5   | --   | 65.  |
| 4    | 4.8   | 18.  | -72.   |
| 5    | 250.  | 18.  | 170.   |
| 6    | 34.   | 33.  | 110.   |
| 7    | -20.  | --   | -340.  |
| 8    | -2.9  | -18.   | -110.  |
| 9    | -3.5  | --   | -85.   |
| 10   | -2.9  | --   | -100.  |
| 11   | -6.8  | -170.  | 100.   |
| 12   | 3.0   | 2.2  | -290.  |
| 13   | 7.4   | 23.  | 110.   |
| 14   | 3.2   | 7.7  | -860.  |
| 15   | 22.   | --   | -13.   |
| 16   | 11.   | --   | -240.  |
| 17   | 150.  | --   | 100.   |
| 18   | -4.6  | -210.  | -500.  |
| 19   | 2.7   | -24.   | -190.  |
| 21   | 3.2   | 27.  | -8.7   |
| 22   | 90.   | -280.  | 430.   |
| 25   | 20.   | 21.  | 310.   |
| 27   | 9.8   | --   | 52.  |
| 29   | 3.6   | -42.   | -610.  |
| 30   | -0.49   | --   | 38.  |

(1) All values have been rounded to 2 significant figures.

(2) Dashes indicate that the kinetic test was not performed.



**OVERALL PROCESS (Stumm and Morgan, 1981)**

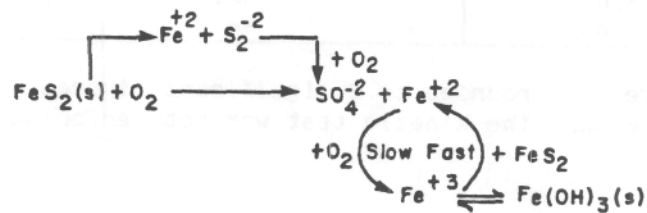


FIGURE 1 FORMATION OF ACID MINE DRAINAGE FROM PYRITE OXIDATION



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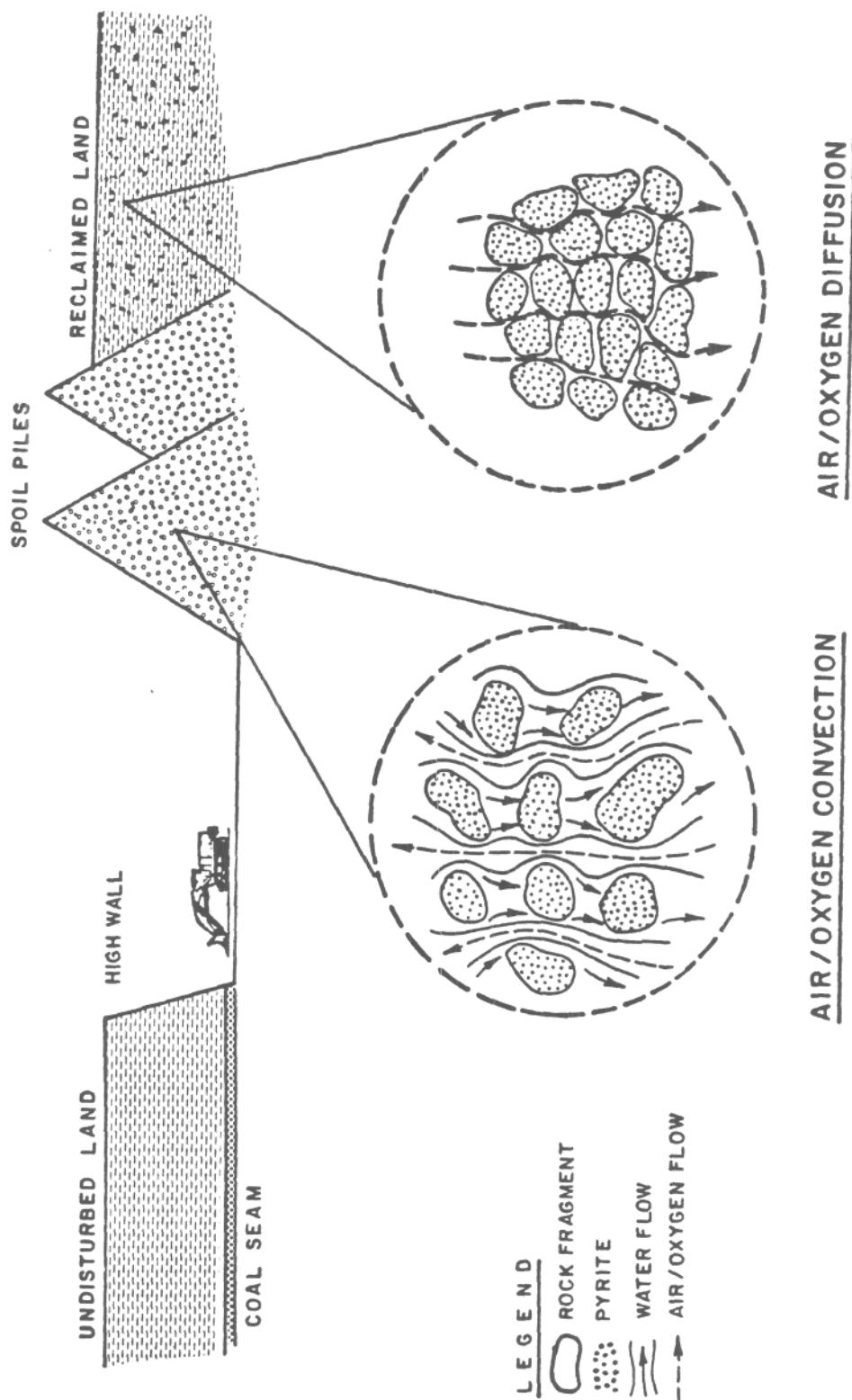


FIGURE 2 PRODUCTION OF ACID MINE DRAINAGE IN POROUS WASTE DUMPS (AFTER CATHLES 1982)

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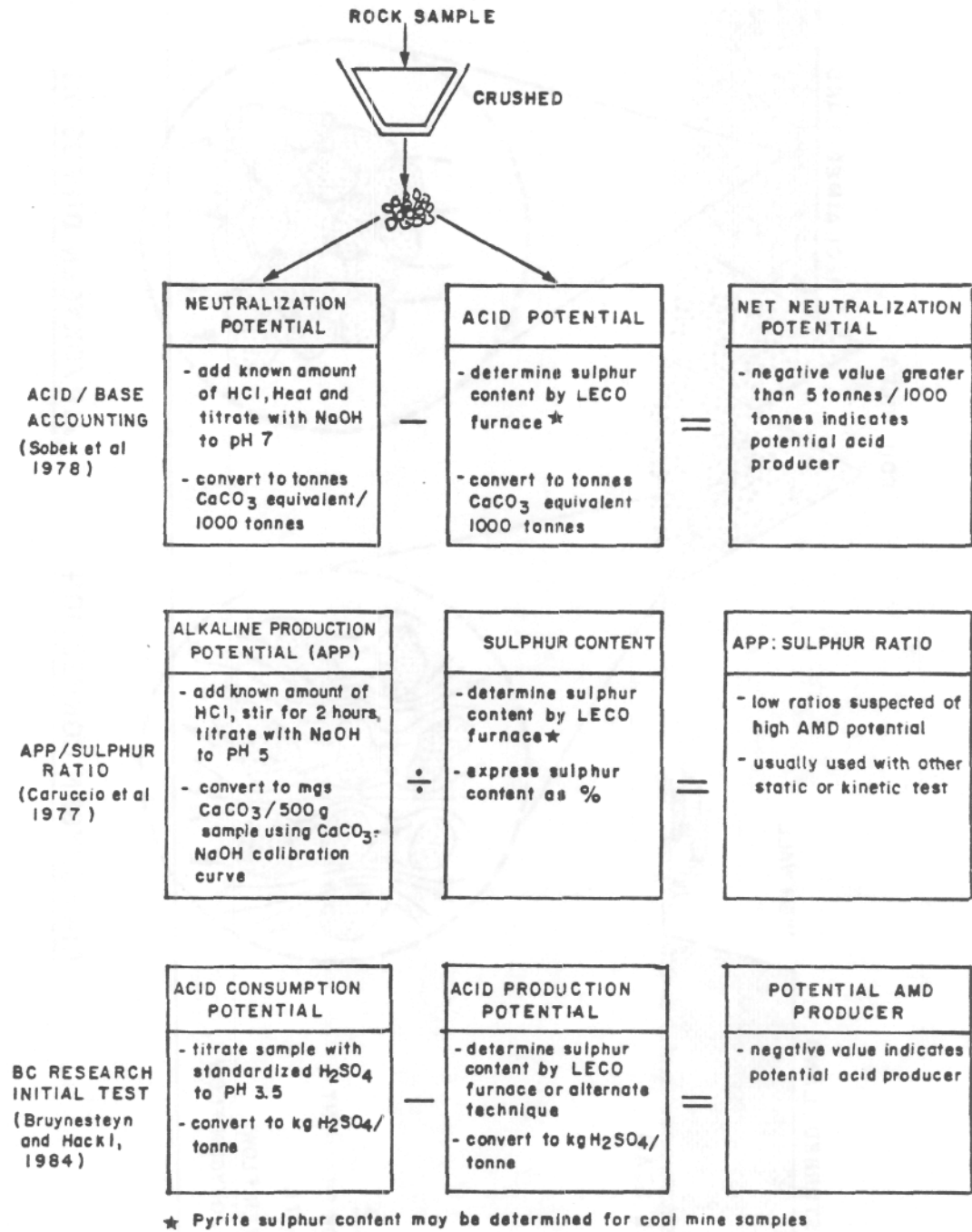
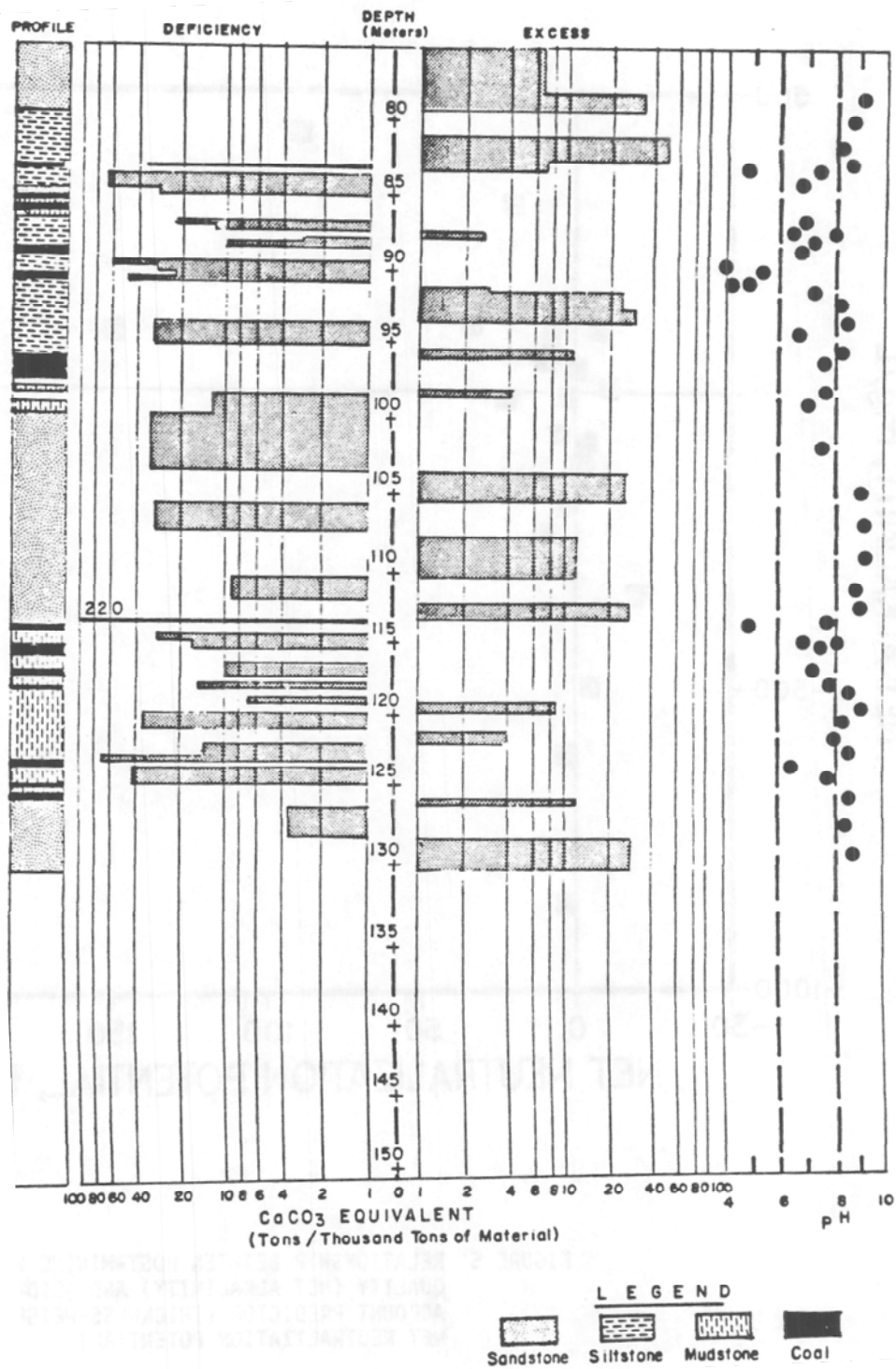


FIGURE 3 STATIC ACID MINE DRAINAGE PREDICTION TECHNIQUES



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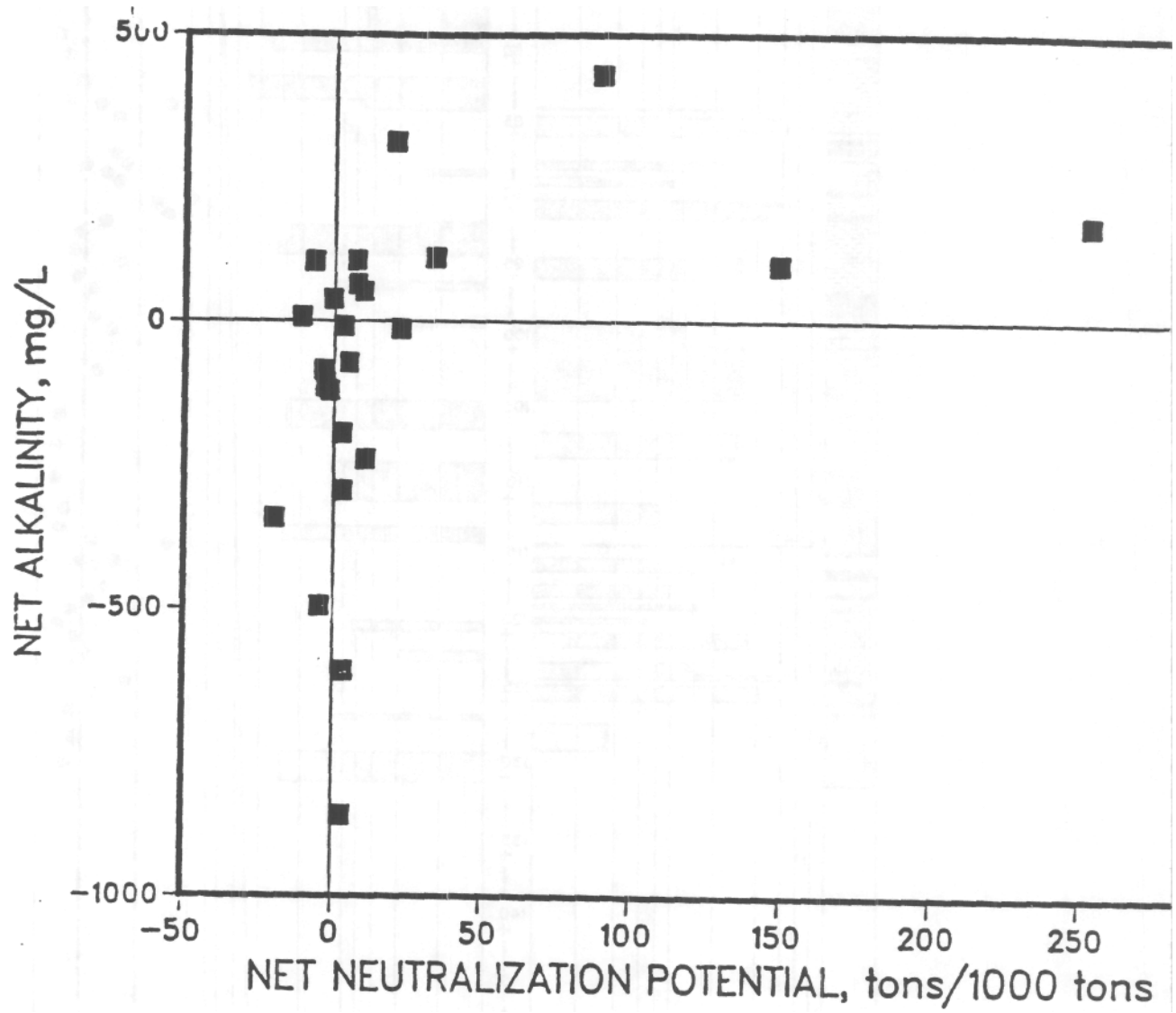


FIGURE 5 RELATIONSHIP BETWEEN POST-MINING WATER QUALITY (NET ALKALINITY) AND ACID-BASE ACCOUNT PREDICTOR (THICKNESS-WEIGHTED NET NEUTRALIZATION POTENTIAL)

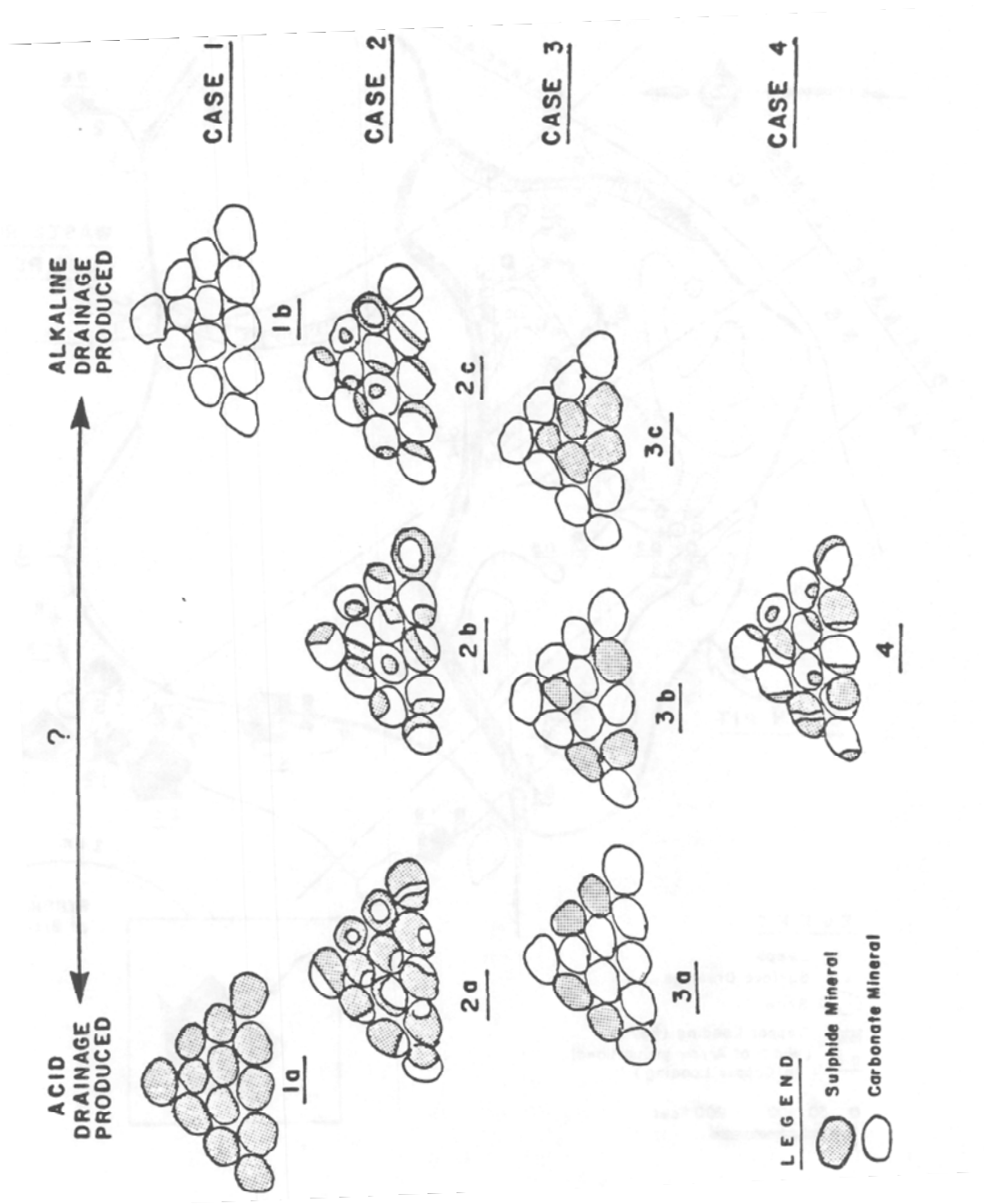


FIGURE 6 UNCERTAINTY IN AMD PREDICTION

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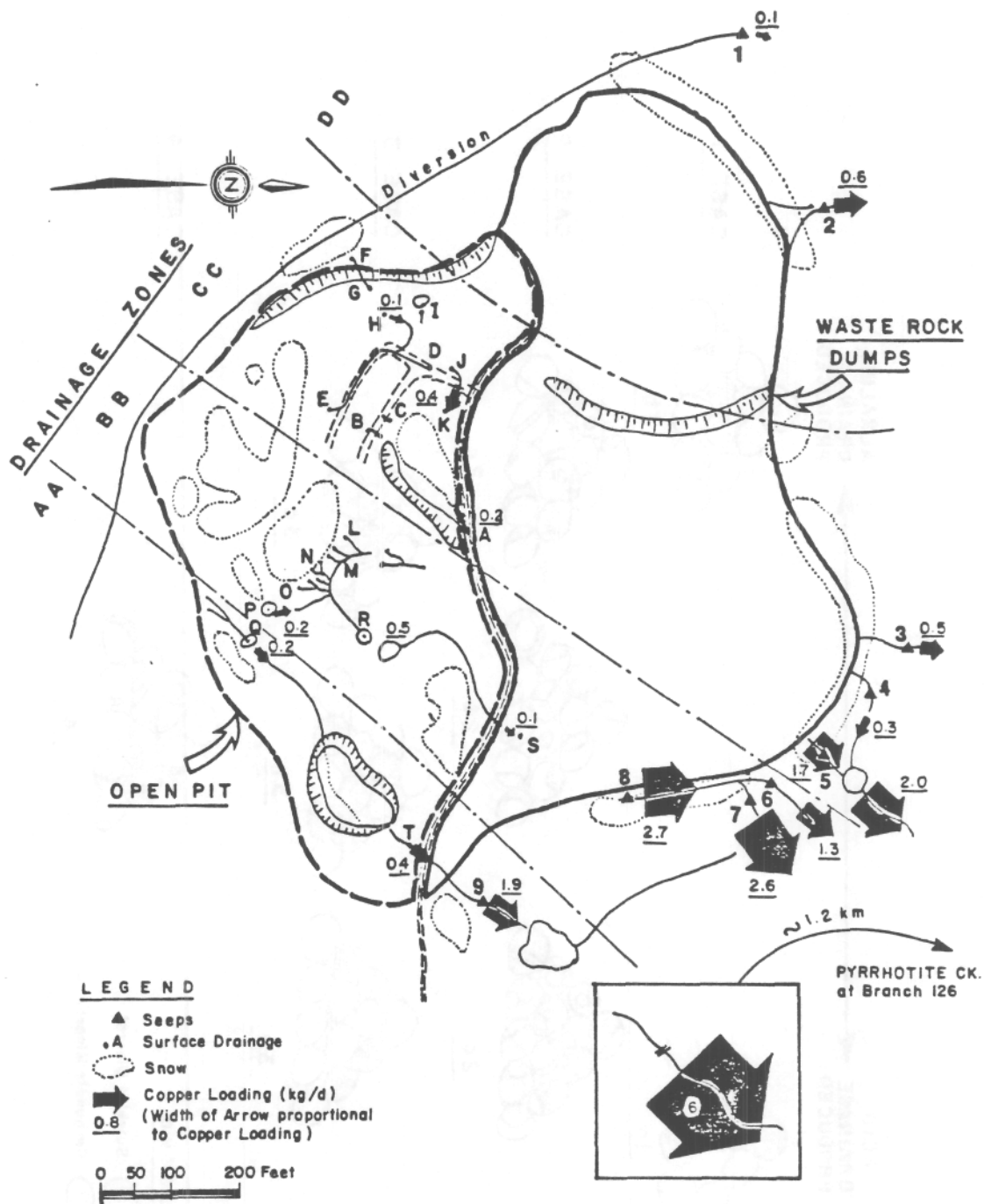


FIGURE 7 METAL MINE OPEN PIT AND WASTE ROCK DUMP - SURFACE DRAINAGE AND SEEPAGE COPPER LOADINGS