LONG TERM ACID GENERATION STUDIES: CINOLA PROJECT, QUEEN CHARLOTTE ISLANDS, BRITISH COLUMBIA

MEND Project 1.19.1

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FINAL REPORT
LONG TERM ACID GENERATION STUDIES
CINOLA PROJECT, QUEEN CHARLOTTE ISLANDS
BRITISH COLUMBIA

Contract: 23440-2-9271/01-SQ

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EXECUTIVE SUMMARY

In 1987, City Resources (Canada) Limited initiated a program of acid generation testing as part of feasibility studies for the Cinola Gold Project located on the Queen Charlotte Islands, off the north coast of British Columbia. The program was designed to quantify acid generation potential and evaluate waste rock management options for the proposed open pit gold mine. In 1990, the Mine Environment Neutral Drainage (MEND) Program and the BC Acid Mine Drainage Task Force began funding further monitoring of tests to evaluate long term weathering conditions in five humidity cells, five leach columns and four on-site waste rock pads. The study was concluded in 1993.

The project area experiences mild damp maritime conditions. Most precipitation occurs in the winter, primarily as rain. Bedrock in the area is mantled by thin till deposits. The Cinola deposit was formed by localization of relatively low temperature hydrothermal fluids along a fault system. During mineralization, the surrounding conglomerates, sandstones, siltstones and mudstones were altered to clay minerals (kaolinite and illite, a low temperature form of muscovite) and pyrite was disseminated throughout the rock mass at concentrations typically in the range of 1 to 2%. Calcite occurs at similar or lower concentrations. Several rock types were classified as potentially acid generating based on conventional acid-base accounting.

The study yielded important data on long term weathering trends for tests conducted at different scales. Five humidity cells (four of which contained acid generating waste rock) were continued for 140 weeks and showed three distinctive stages in pH and sulphate production rate. In Stage 1, leachate pH was near 7.0 and sulphate production was slow (less than 20 mg SO_4/kg/week). As readily available neutralizing minerals were removed, leachate pH decreased to less than 3 and sulphate production increased rapidly (to greater than 1000 mg SO_4/kg/week). In Stage 3, sulphate production slowly decreased and leachate pH slowly increased to between 3 and 4. After more than 100 weeks of leaching, sulphate production decreased by one or two orders of magnitude and leachate continued to be acidic (leachate pH<4). Trends in waste rock pad leachate were less apparent due to annual flushing events related to late summer and fall rainfall. However, a qualitatively similar long term decrease in sulphate production and increase in leachate pH was observed. After five years, the waste pad leachate continued to be strongly acidic for three test piles and concentrations of iron, copper, zinc and arsenic were indicative of acidic weathering conditions.

The leach column study evaluated the delay in release of heavy metals and acid drainage achieved by addition of varying concentrations of crushed limestone to waste rock. Long term trends were very similar to humidity cells. Two simple relationships were defined relating limestone content (ie. neutralization potential) to (1) time elapsed until the first indications of net acid generation were observed; and (2) time elapsed until peak acid generation was observed. Release of zinc followed the first type of relationship whereas release of iron and copper followed the second relationship. The study showed that although limestone addition delayed full acid generation and release of copper and iron according to an exponential relationship, significant zinc loads may be released in pH-neutral drainage several years before acid drainage is produced.

When comparing different types of weathering tests, the study demonstrated that the small- and large-scale tests produced similar results for qualitative long term trends, sulphide oxidation reaction kinetics, and

average sulphate release rates expressed as estimates of exposed particle surface areas. The test results were dissimilar for metal release rates probably due to complex mineral precipitation controls operating under widely varying solid-to-liquid ratios. These conclusions apply to the Cinola epithermal deposit where sulphide mineralogy is simple relative to complex deposits containing two or more different types of iron sulphide in a variety of forms.

It was concluded that further research is needed to address a number of issues. These include: evaluation of solid weathering products; long term kinetics of weathering in mineralogically complex materials; long term kinetics of weathering in marginally-acid generating materials; long term leachate quality for sulphide-depleted weathered waste rock; application of small-scale test results to large scale waste rock piles; and evaluation of the effect of heterogeneities in mixing of calcareous and potentially acid generating waste rock.

RÉSUMÉ

En 1987, City Resources (Canada) Limited a lancé un programme d'essais portant sur la production d'acides, dans le cadre des études de faisabilité associées au projet d'exploitation de la mine d'or de Cinola. Le gisement se trouve dans les îles de la Reine-Charlotte, au large de la côte nord de la Colombie-Britannique. Ce programme d'essais visait à quantifier le potentiel acidogène des stériles que produirait cette mine à ciel ouvert, et à évaluer les moyens qui s'offriraient pour la gestion de ces stériles. En 1990, le Programme de neutralisation des eaux de drainage dans l'environnement minier (NEDEM) et le *BC Acid Mine Drainage Task Force* ont commencé à financer des activités complémentaires de surveillance des essais, pour évaluer les effets à long terme de l'altération météorologique, à l'aide de cinq cellules hygrométriques, de cinq colonnes de lixiviation et de quatre haldes constituées sur le terrain. L'étude a pris fin en 1993.

La région étudiée connaît un climat maritime doux et humide. Les précipitations, constituées surtout de pluie, y tombent en majeure partie pendant l'hiver. Le substratum rocheux est recouvert de minces dépôts de till. Le gisement Cinola s'est formé par la concentration de fluides hydrothermaux à température relativement basse le long d'un système de failles. Pendant la minéralisation, les conglomérats, le grès, les siltstones et les mudstones encaissants ont été altérés en minéraux argileux (de la kaolinite et de l'illite, qui est une forme de muscovite de basse température), et de la pyrite a été disséminée dans la masse rocheuse en concentrations de l'ordre de 1 à 2 %. On y trouve aussi de la calcite en concentrations similaires ou inférieures. Plusieurs types de roches y ont été classés comme potentiellement acidogènes, d'après la méthode conventionnelle de détermination de l'acido-alcalinité.

L'étude a permis de recueillir, au moyen d'essais effectués à diverses échelles, des données importantes sur les tendances à long terme de l'altération météorologique. Pendant 140 semaines, on a observé cinq cellules hygrométriques (dont quatre contenaient des stériles acidogènes), qui ont mis en évidence trois stades distincts dans la variation du pH et la production des sulfates. Au stade 1, le pH du lixiviat se situait autour de 7, et la production de sulfates était lente (moins de 20 mg de SO_4/kg/semaine). Au stade 2, une fois enlevés les minéraux neutralisants les plus accessibles, le pH du lixiviat a baissé à moins de 3, et la production de sulfates s'est accrue rapidement pour atteindre plus de 1 000 mg de SO_4/kg/semaine. Au stade 3, la production de sulfates a un peu ralenti et le pH du lixiviat a lentement augmenté pour se situer entre 3 et 4. Après plus de 100 semaines de lixiviation, la production de sulfates a baissé d'un ou deux ordres de grandeur et le lixiviat est demeuré acide (pH inférieur à 4). Dans les lixiviats des haldes extérieures, les tendances étaient moins évidentes en raison des phénomènes de lessivage annuels dus aux pluies qui tombent à la fin de l'été et en automne. Cependant, à long terme, la baisse de production des sulfates et la hausse du pH du lixiviat étaient qualitativement comparables à celles observées dans les cellules hygrométriques. Après cinq ans, le lixiviat était toujours très acide dans trois des haldes, et les concentrations de fer, de cuivre, de zinc et d'arsenic indiquaient une altération par des acides.

Les colonnes de lixiviation ont servi à évaluer dans quelle mesure l'addition de diverses concentrations de calcaire aux stériles retarde la mobilisation des métaux lourds et l'acidification des eaux de mine. À long terme, les courbes étaient très semblables à celles observées dans les cellules hygrométriques. On a établi deux corrélations simples : d'abord entre la teneur en calcaire (c'est-à-dire le potentiel de neutralisation) et le temps écoulé jusqu'aux premiers signes de production nette d'acides, puis entre la teneur en calcaire et le temps écoulé jusqu'à la production maximale d'acides. La mobilisation du zinc est déterminée par la relation du premier type, et celle du cuivre et du fer, par la relation du second type. L'étude a montré que, même si l'addition de calcaire a retardé la production nette d'acides et la libération du cuivre et du fer suivant une relation exponentielle, de grandes quantités de zinc peuvent être libérées dans des eaux de mine à pH neutre plusieurs années avant l'acidification de ces eaux.

On a comparé divers types d'essais d'altération et découvert que les essais à petite et à grande échelle donnaient des résultats similaires en ce qui concerne les tendances quantitatives à long terme, la cinétique de l'oxydation des sulfures et les taux moyens de libération des sulfates, exprimés en fonction de la surface estimée des particules exposées. Les résultats des essais diffèrent cependant sur le taux de mobilisation des métaux, probablement en raison de la complexité des facteurs qui interviennent dans la précipitation des minéraux lorsque les ratios solide/liquide sont très variables. Ces conclusions s'appliquent au gisement épithermal Cinola, dont la minéralogie des sulfures est simple par rapport à celle d'autres gisements complexes qui peuvent contenir deux ou plusieurs types de sulfure de fer sous diverses formes.

On a conclu qu'il faudra continuer la recherche, car il reste de nombreux aspects à évaluer : les produits d'altération solides; la cinétique de l'altération à long terme dans les matériaux qui ont une minéralogie complexe; la cinétique de l'altération à long terme dans les matériaux peu acidogènes; la qualité à long terme du lixiviat produits par les de stériles altérés appauvris en sulfures; l'application des résultats des essais à petite échelle aux haldes; l'effet des hétérogénéités dans le mélange de stériles calcaires avec des stériles potentiellement acidogènes.

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LONG TERM ACID GENERATION STUDIES
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BRITISH COLUMBIA

1.0 INTRODUCTION

1.1 BACKGROUND AND PROJECT HISTORY

The Cinola Gold Deposit, formerly known as the Specogna Deposit, is located on Graham Island, one of the two major islands of the Queen Charlotte Islands group (Figure 1-1). Mineral claims in the area were first staked in 1970. In the late 1970's, mineral exploration was completed to an advanced stage by the Cinola Operating Company. Metallurgical testing of bulk samples obtained from an exploration adit indicated that recovery of gold would be difficult due to the association of gold with sulphide minerals. Tests also showed that acid generation was likely in mineral wastes. Development activity occurred at the property until 1986 when City Resources (Canada) Inc. initiated several major engineering and environmental study programs to assess the feasibility of developing the Cinola deposit using different mining and milling methods.

As part of environmental studies, City Resources initiated a program of static and kinetic weathering tests to evaluate the potential for acid generation from waste rock, pit walls and mill tailings, and to test different acid rock drainage (ARD) prevention strategies. The results of these studies were compiled in 1988 and 1989, and were reviewed under the Mine Development Review Process (MDRP) administered by the British Columbia Ministry of Energy, Mines and Petroleum Resources. Subsequently, in May 1990, City Resources decided to cease feasibility studies due to unfavourable economic conditions for mine development.

At that time, the B.C. Acid Mine Drainage (AMD) Task Force and the Mine Environment Neutral Drainage program (MEND) recognised that continued monitoring of selected weathering experiments could provide important additional information regarding long term weathering mechanisms in waste rock and the use of kinetic prediction tests. Therefore, the Task Force and MEND committed to a further three years of monitoring three limestone/waste rock mixing laboratory experiments, and four on-site waste rock pads. The additional studies were initiated in May 1990, and are referred to in the remainder of this report as "the MEND/BC AMD Task Force projects".

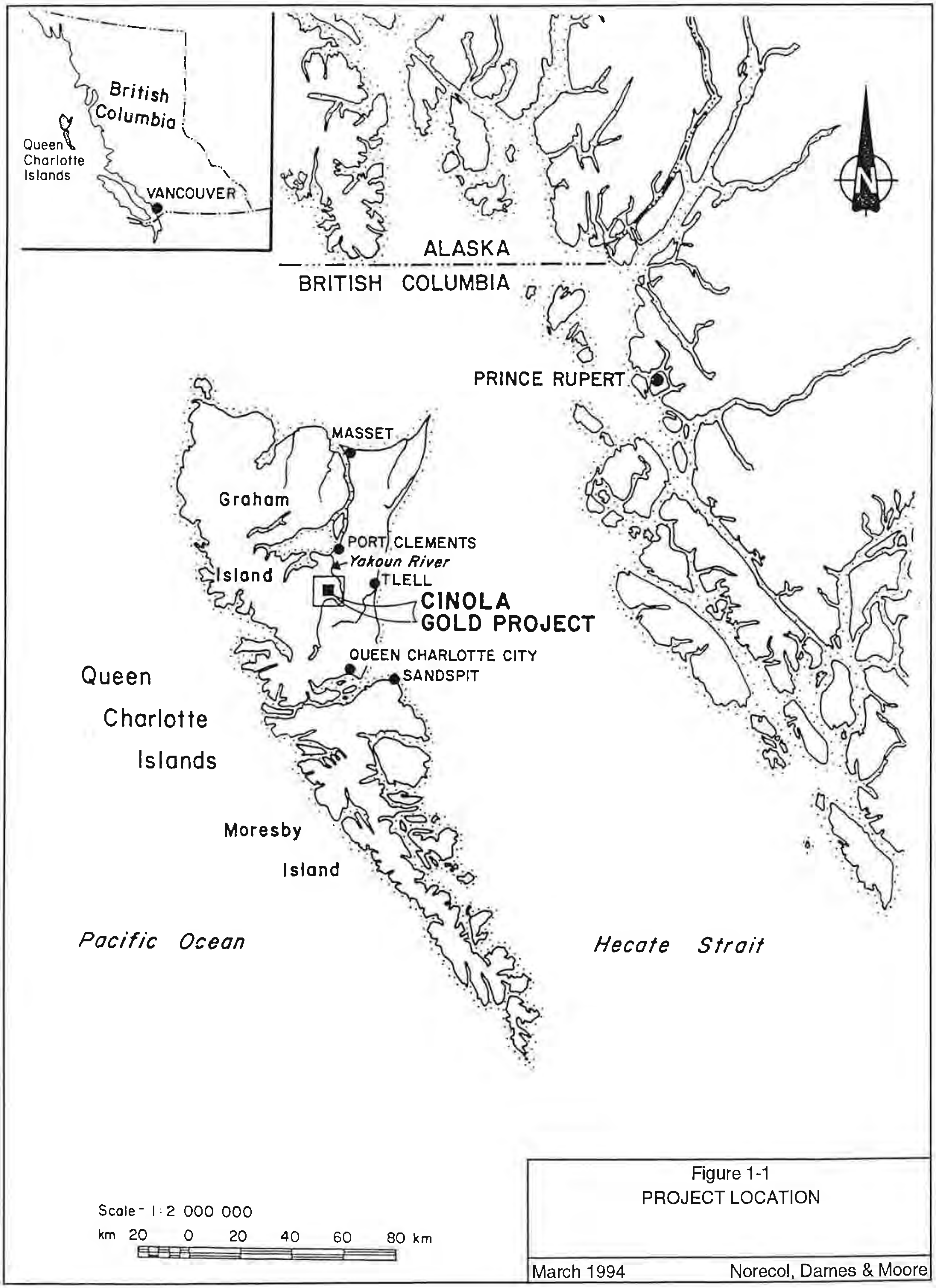

Figure 1-1
PROJECT LOCATION

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1.2 OBJECTIVES OF THE ACID ROCK DRAINAGE TEST PROGRAMS

1.2.1 City Resources Program

Data obtained for the Cinola deposit in the early 1980's (IEC Beak 1982 for the Cinola Operating Company) indicated that there was a potential for ARD at the site. Additional assessment was required to evaluate the potential for impacts on the quality of surface water and groundwater, and to determine potential costs of mitigation and control. The general objective was to quantify, to the extent possible, the potential rate and degree of acid generation in rock disturbed by mine development. Specific objectives to be addressed by the City Resources test program were to:

- characterize all the rock types in the project area and determine their potential for acid generation;
- quantify the total capacity of various rock types to generate acid;
- determine the temporal changes in rates of acid generation in different rock types;
- determine the rates of acid generation for varying conditions involving differences in exposure to air and water;
- determine the effect of mixing limestone with waste rock on the delay or prevention of acid generation; and
- determine the metal leaching characteristics of the different rock types.

1.2.2 MEND/BC AMD Task Force Project

Since the MEND/BC AMD Task Force project was conducted using tests initiated by City Resources, the scope of the MEND/BC AMD Task Force project was limited by the available tests and their experimental design in operation in May 1990. At that time, four on-site waste rock pads were intact, and five humidity cells and five leach column tests were being run by Norecol Environmental Consultants Ltd. and B.C. Research Corp, respectively. In addition, most of the data collected for other aspects of the project were available. The following project objectives were defined for the MEND/BC AMD Task Force work: (Annex "A", Supply and Services Canada Contract No. 23440-2-9271/01-SQ, Appendix A, this report).

"• characterize six years of weathering in the four on-site waste rock pads and apply the results to understanding rock dump acid generation processes;

- evaluate the results of a column study of mixing calcareous rock with mine waste rock as a means to prevent the formation of acid drainage;

- characterize material that has undergone over three years of weathering in humidity cells; and

- evaluate and compare the performance of the various ARD test methods used in the project".

Three previous progress reports (Norecol Environmental Consultants Ltd. (1991a; 1991b; 1992) summarized results of the MEND/BC AMD Task Force project. This is the final report and follows the dismantling of all remaining laboratory experiments, analysis of experimental residues and compilation of data (as defined in Appendix "A").

1.3 SOURCES OF DATA AND LIMITATIONS

This final report represents a compilation of data collected over two distinct phases of the project:

- prior to 1990, the project was directed by City Resources; and

- between 1990 and 1993, control of the ARD aspects of the project passed to MEND and the BC AMD Task Force.

This imposed several limitations on the project. These limitations do not reflect on the ability of the researchers involved, but the state of understanding of this type of program design in the late 1980's. Firstly, prior to 1990, the test methodologies were not recorded in as much detail as would have been desirable. Secondly, some of the data required to fully understand the results was not collected prior to initiation of the tests in 1987 and 1988. This limits the ability to compare fresh materials with weathered materials. Thirdly, it is now known that certain test procedures are not as accurate as other more recently developed procedures. However, the same (or very similar) procedures have been used throughout the project for continuity.

1.4 PERSONNEL

Personnel involved in the project are listed in Appendix B.

2.0 SITE DESCRIPTION

2.1 REGIONAL ENVIRONMENT

2.1.1 General

The Cinola Gold Deposit is located on Graham Island, 18 km south of Port Clements (Figure 1-1). The topography to the west of the study area is mountainous with elevations rising to more than 625 m. Topography to the north and east is rolling with elevations of 120 to 150 m. Seasonal weather patterns are typical of coastal western Canada. Annual precipitation varies from 1700 to 2200 mm, most of which occurs as rain during October to March.

The Queen Charlotte Islands lie within the Coastal Western Hemlock biogeoclimatic zone. Much of the project area former cover of mature western hemlock, western red cedar and sitka spruce has been clearcut.

2.1.2 Climatic Baseline

Monthly precipitation data for the closest AES station representative of site conditions at Sewall Masset Inlet (Station 105PA91) are shown in Figure 2-1. The annual pattern of precipitation is repeated consistently from year-to-year. The wettest month of the year is October or November, and high precipitation persists through December and January. The driest months of the year are usually May to August. Average daily temperatures at the AES station are always above freezing, and long term snow does not accumulate throughout the winter, though it may persist for a few weeks in mid-winter. The coldest month of year is usually January or February with average daily temperatures less than 3°C. In November 1990, average daily temperatures were 0°C. The warmest months are June to August, without exception. Maximum daily average temperatures exceed 14°C in mid-summer.

Detailed site-specific baseline precipitation data were required to interpret tests at the site. A wedge rain gauge at the site was monitored for about a year beginning in February 1987, although comparable temperature data were not collected. To estimate precipitation at the site from 1987 to 1992, monthly precipitation at Sewall Masset Inlet was regressed against site precipitation from the wedge rain gauge, corrected for evaporation. The Cinola data were collected from February 1987 to January 1988. The relationship obtained was:

$$\mathrm{Log(Cinola)} = 2.07\ \mathrm{Log(Sewall)} - 2.32 \quad (n=11)$$

The Pearson linear correlation coefficient (r) for this relationship is 0.835, which is significantly different from zero, with a confidence level of better than 95%. The correlation line is not affected by any outlying anomalies. The defined relationship is therefore considered to provide statistically reliable predictions 95% of the time. The equation implies that winter rainfall is on average greater at Cinola than at Sewall Masset Inlet, but summer

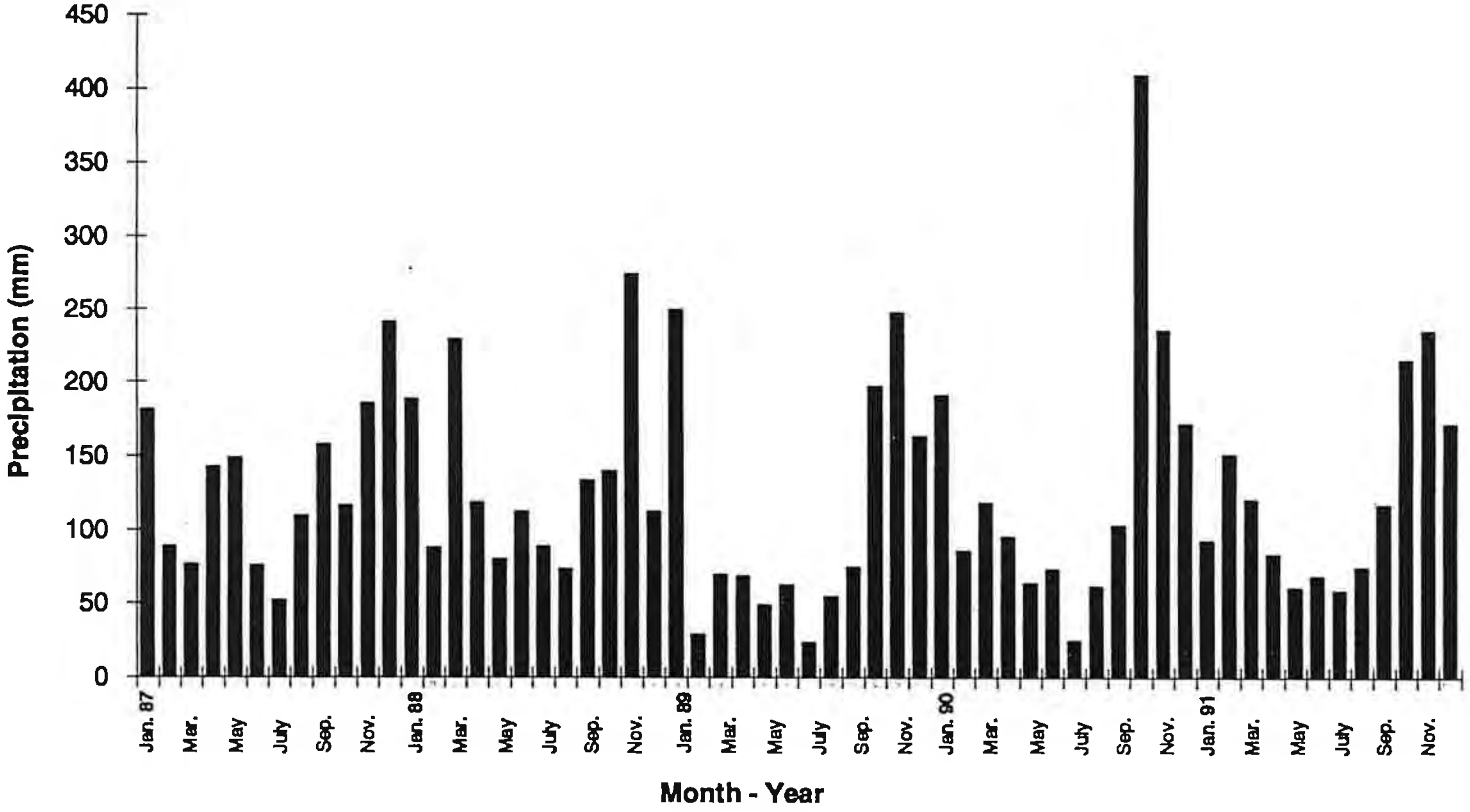

Figure 2-1
PRECIPITATION RECORD
SEWALL MASSETT INLET

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precipitation are typically lower at Cinola. This relationship was used to predict precipitation rates and drainage volumes.

2.2 SURFICIAL GEOLOGY AND SOILS

The vicinity of the proposed open pit and waste rock dumps is mantled by a thin blanket of morainal sandy-silt till, less than 2 m thick. These deposits are typical of the region. Thicker (greater than 5 m) morainal and fluvial deposits occur nearby.

Soils in the region are classified as various types of podzols (humo-ferric, orthic humic, ferro-humic). These types of soils are indicative of rapid parent material weathering occurring under mild, very wet conditions (Birkeland 1984). They are characterized by thick iron-rich horizons formed by the oxidation of iron silicate minerals. In poorly drained areas, these soils are gleyed meaning that they are saturated continuously or periodically. Dystric brunisols and regosols occur at scattered locations in association with the other soils and are indicative of less developed soils in locally dry, cooler or unstable slope conditions.

2.3 BEDROCK GEOLOGY

2.3.1 General

The Cinola deposit was classified as epithermal Carlin-type by Champigny (1981) and Pantaleyev (1988) due to the small (<0.5 μm) particle size of gold, age of about 14 Ma, the presence of argillic[1] alteration, association with faults and felsic intrusions, and porosity of the host rock.

A simplified version of the formation of the deposit is given below. In the following description, rock types referred to in the report are shown in **bold**. Geological times are given with reference to the Miocene epoch which began and ended 24 and 5 million years ago, respectively. In early Middle Miocene time, the Cinola area was covered by fluvial (river) sediments (referred to as the **Skonun Sediments**) deposited on a basement of earlier (144 to 208 million years) rocks referred to as the **Haida Mudstone**. During Middle Miocene time, the partly consolidated, saturated Skonun Sediments were intruded by a small stock of molten felsic (that is, rich in quartz and feldspars) material (**rhyolite**). The molten rock was forced between and across layers in the sediments, and also caused the sediments to breakup and flow locally. The heat associated with this stock caused heating and circulation of water. The heated rock was focussed in fault systems in the area of the Cinola deposit, and gold mineralization occurred. Interaction between the heated fluids and sediments caused

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[1] The terms "argillic" and "argillically-altered" are used throughout this report. They refer to a very common type of rock alteration produced by hot water in which primary framework silicate minerals (such as feldspars) have been changed to clay minerals. The diagnostic clay minerals are kaolinite ($Al_2Si_2O_5(OH)_4$) and illite (a general term for mica-like clay minerals). Sericite ($KAl_2(AlSi_3O_{10})(OH)_2$), a fine grained form of muscovite mica, and alunite ($KAl_3(SO_4)_2(OH)_6$) may also occur.

the original rock forming minerals to be altered. Typical products of this alteration were phyllosilicates, a mineral group which includes mica (for example, sericite) and clay (for example, kaoloinite) minerals. The heated fluids were commonly under pressure resulting in explosive fracturing of the rock to form **breccias**. The rock fragments within the fractures were also altered by the hot fluids.

Figure 2-2 illustrates a typical vertical cross-section through the deposit. The Specogna Fault is the dominant structural feature of the deposit. The older Haida Mudstone rocks are located beneath (to the left of) the fault. Above the fault, City Resources geologists divided the Skonun Sediments into a sequence of sub-horizontal layers. Layers of mudflow breccia are located between the layers.

Rhyolite has intruded near the fault. Also, near the fault the rocks were inundated with quartz from mineralizing fluids. This is indicated by "pervasive silification" on the cross-section. Further from the fault, the primary rock-forming silicates have been argillically-altered to varying degrees. The actual contact between these alteration types is gradational.

The following section provides a summary of available information on the properties of the various rock types.

2.3.2 Specific Properties of Rock Types

General Characteristics

Available data on the lithological and mineralogical characteristics of the major rock types at Cinola relevant to assessment of acid generation potential are summarized in Table 2-1. The table was compiled from City Resources geology reports. Thin section reports are contained in Appendix C. Distinctive features of each of the rock types are summarized below.

Rhyolite

This rock type is composed of quartz (SiO_2), and feldspars ($KAlSi_3O_8$, $NaAlSi_3O_8$, $CaAl_2Si_2O_8$). Calcite ($CaCO_3$) is absent. Pyrite (FeS_2) may be present in concentrations varying from 1 to 10%. No information is available in the occurrence of the pyrite. The mineral grains are generally too small to be distinguished with the naked eye (referred to as aphanitic). Occasionally, some of the grains may be visible (referred to as porphyritic).

Skonun Sediments

The Skonun Sediments consists of consolidated layers and lenses of mudstone (fine component particles), siltstone, sandstone and conglomerate (very coarse component particles). The individual particles are composed of quartz, potassium feldspar, hornblende ($(Ca,Na)_{2\text{-}3}(Mg,Fe,Al)_5Si_6(Si,Al)_2O_{22}(OH)_2$) and biotite mica ($K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$). These mineralogies reflect the provenance area of the sediments. As described above, this rock type may be partly or completed altered to quartz and kaolinite. The altered rock

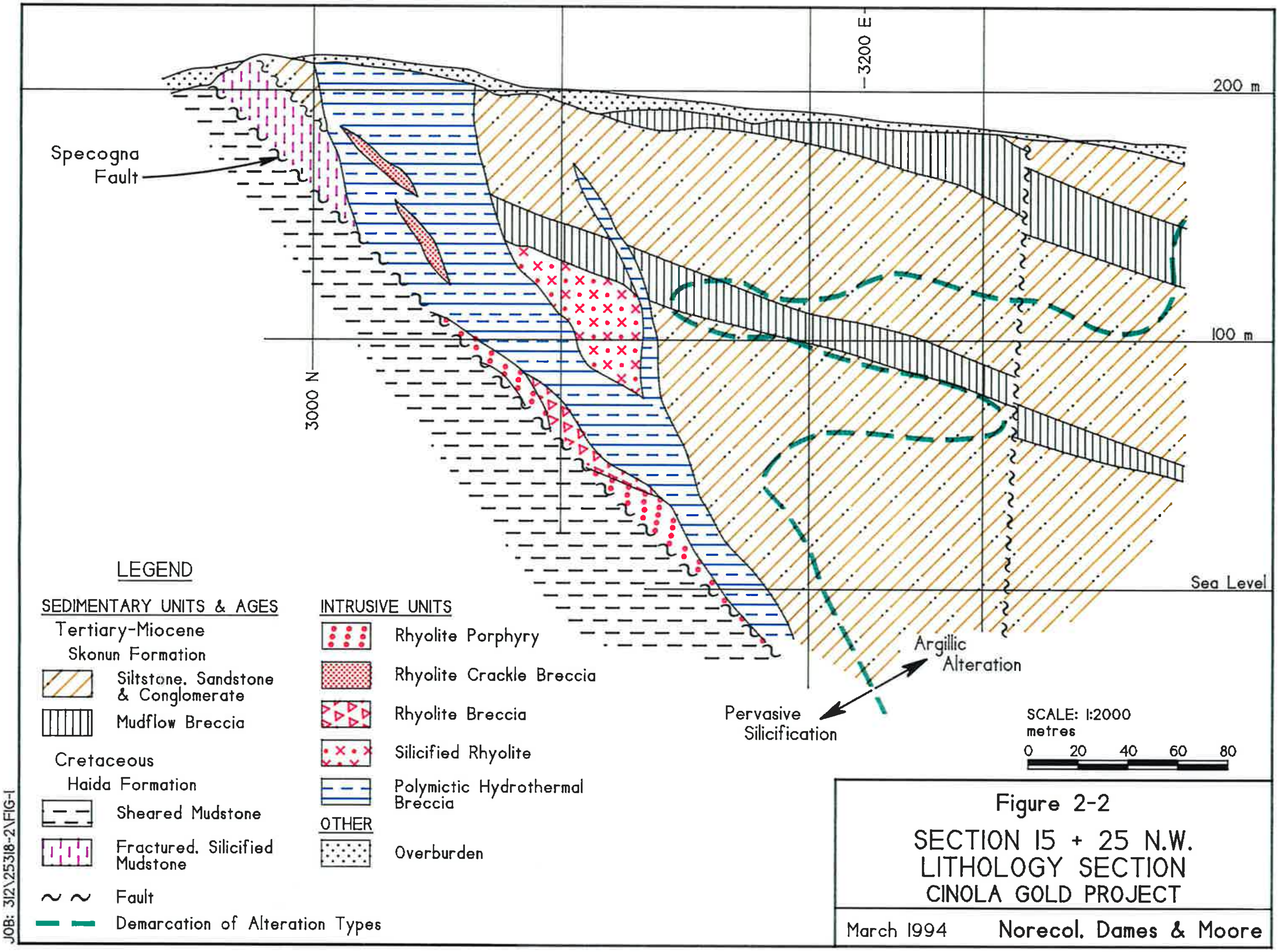


Figure 2-2

SECTION 15 + 25 N.W.
LITHOLOGY SECTION
CINOLA GOLD PROJECT

March 1994 Norecol, Dames & Moore

TABLE 2-1
SUMMARY OF ROCK TYPE CHARACTERISTICS

Rock Type	Lithologies	Alteration Types	Position in Geology	Abundance in Waste Rock %	Abundance in Pit Walls %	Primary Mineralogy	Secondary Mineralogy
Rhyolite	Rhyolite porphyry	No data	Intrusions in Skonun Sediments	6	ND	Quartz, feldspar	Calcite absent, pyrite (1 to 10%)
Skonun Sediments	Mudstone, siltstone, sandstone, conglomerate	Unaltered	Main host rock for Cinola Deposit	56	?40%	Components of clasts include quartz, K-feldspar, hornblende, biotite	None
		Argillic	Distant from Specogna Fault	6	?10%		Pyrite (2%, 1 to 5 um disseminated grains), calcite (<1%, absent), alunite
		Silicic	Near Specogna Fault		No data		Quartz overprinting of primary textures
Breccias		Silicic	Composed of other rock units, near Specogna Fault	4	Included in Skonun	ND	ND
Haida Mudstone	Mudstone, siltstone	Unaltered	Footwall of Specogna Fault	22	?50%	Probably quartz, illite, fine and coarse calcite	Pyrite (<<1% 2 to 25 um disseminated spheroids), kaolinite
		Silicic	Near Specogna Fault			Quartz	ND
Overburden	Till	None	Overlying deposit	6	Negligible	No data	No data

Notes:
1. Majority of data obtained from examination of polished thin sections by City Resources.
2. "?" indicates data uncertain. ND indicates data not available.

appears similar to the unaltered rock in that original features such as layering and grain boundaries are preserved. In the unaltered rock, pyrite is absent. In the altered rock it occurs as very small (1 to 5 μm) grains scattered throughout (disseminated).

Breccias

The breccias are composed of fragments of other rock types (primarily Skonun Sediments) fractured and cemented by quartz during mineralization. Larger fragments (framework) are surrounded by smaller fragments (matrix). Pyrite occurs as fine disseminated grains.

Haida Mudstone

These mudstones are black to dark grey. Siltstone and sandstone are minor components. Typically, the main component of mudstone is the mineral illite. Pyrite generally occurs in very low concentrations (much less than 1%) as disseminated small (2 to 25 μm) spherical grains. Calcite occurs either as fine grains disseminated in the matrix or as coarse crystals.

Characteristics Relevant to Acid Generation

Notably, there is a lack of useful quantitative data on sulphide and carbonate mineral occurrence in relation to fractures. This information would assist in understanding the susceptibility of the rock to weathering. Weathered rock at surface (gossan) has apparently not been studied but would perhaps have provided useful data on long term weathering characteristics (Day and Cowdery 1990). The majority of characteristics recorded by City Resources' geologists and Champigny (1981) relate to the primary environment of rock formation and the relationships between economic minerals and alteration features.

In summary, the following characteristics of the rock are relevant to acid generation potential:

- Pyrite occurs at concentrations near 2%, and is the most abundant sulphide. Marcasite (FeS_2) abundance is about one tenth that of pyrite. Other sulphide minerals (chalcopyrite, $CuFeS_2$; sphalerite, ZnS; galena, PbS; pyrrhotite, $Fe_{1-x}S$; cinnabar, HgS) occur in concentrations much less than 1%.

- Pyrite occurs as disseminated grains generally less than 25 μm in diameter. The form has been described as spherulitic (spherical clusters with radiating crystals) and framboidal ("raspberry-like"). The term framboidal refers to its appearance rather than possible genesis.

- Skonun Sediments contain the highest concentrations of pyrite. The Haida Mudstones contain much lower concentrations of pyrite.

- Carbonate minerals were rarely observed in the Skonun Sediments, and are thus unlikely to have a significant effect on acid generation.

- In places, the Haida Mudstones contain significant concentrations (several percent) of carbonates, primarily calcite.

- Silicified rocks are extremely competent, making the exposure of sulphide minerals between fractures unlikely.

- Argillically-altered rocks typically contain the alteration products kaolinite and illite. However, the concentrations and identities of these minerals were not confirmed. These rocks slake (breakdown in water) readily, potentially leading to exposure of pyrite to weathering.

In summary, the most abundant unit is the Skonun Sediments. This unit contains insignificant amounts of calcite, and 2% pyrite present as finely (<5 µm) disseminated grains. Marcasite abundance is about a tenth that of pyrite.

Haida Mudstone is the other significant rock unit. This rock type typically contains small (<1%) amounts of pyrite, also as finely disseminated grains. Calcite is described as being much more abundant than pyrite, although amounts were not quantified.

Little data on rock competency were available. However, silicified rocks tend to be extremely competent. Breakage is likely to occur along fractures rather than through unfractured rock. Argillically-altered rock tends to be somewhat softer and slakes readily leading to rapid breakdown during weathering. The argillic and silicic alteration types overlap leading to a varying competency depending on the degree and predominant type of alteration.

2.3.3 Rock Type Terminology in this Report

The remainder of this report refers to the major rock types: Haida Mudstone and Skonun Sediments. Other rock, such as rhyolite and breccia, are smaller components of the waste rock and pit walls and are therefore addressed to a much lesser degree.

3.0 EXPERIMENTAL DESIGN OF THE ACID GENERATION TEST PROGRAMS

3.1 CITY RESOURCES' PROGRAM

The objectives of the City Resources program listed in Section 1.2.1 resulted in a series of studies, each composed of a number of laboratory tests. These studies are tabulated below.

Study	Description
A	Screen Acid Generation Potential. Initial classification of rocks according to acid generation potential using static geochemical approaches.
B	Calibrate Acid-Base Accounting and Leachate Water Quality. Comparison of results from static and various kinetic tests to determine the usefulness of static tests as screening tools.
C	Quantify Acid Generation Potential. Estimate the long term rates of acid production, metal leaching and acid neutralization.
D	Compare Wet-Dry and Wet Humidity Cells. Comparison of conventional humidity cell procedures (using alternating wet-dry air cycles) with humidity cells more representative of actual site conditions (continuous moist air).
E	Compare Field and Laboratory Acid Generation Rates. Calibrate laboratory test results to assess potential water quality impacts.
F	Compare Sub-aqueous and Sub-aerial Leaching Rates. Evaluate underwater disposal of waste rock.
G	Evaluate Limestone Addition. Evaluate addition of limestone to waste rock stockpiles as a means to prevent or delay release of acid drainage.

A variety of different types of laboratory and field tests were selected for each study. These tests were:

Acid-base Accounting (ABA)	Acid-base accounting (sulphur content and neutralization potential) is a static geochemical method providing rapid screening of the relative quantities of acid generating and acid neutralizing minerals.

Humidity Cells	These laboratory tests were used to indicate acid generation rates under controlled laboratory conditions on well characterized materials. The conventional procedure uses wet-dry cycles. A continuous moist cycle was also used to provide a closer comparison with the extremely moist conditions encountered at the site.
Waste Rock Pads	These field tests were initiated to indicate long term acid generation and metal leaching rates under actual site conditions. The pads were also useful in calibrating weathering rates determined under laboratory conditions.
Columns	Six types of laboratory column tests were designed to evaluate both sub-aerial and sub-aqueous weathering rates, and the effects of adding of limestone to potentially acid generating waste rock.
Shake flasks	These laboratory tests were designed to test short term acid release from argillically altered rock.

The type and number of tests used in the various studies are shown in Table 3-1. For example, calibration of field and laboratory acid generation rates (E) used six wet-dry humidity cells, four wet humidity cells, and the four waste rock pads. It should be noted that many tests were used for more than one study. A complete list of the experimental units and ABA's is shown in Table 3-2.

3.2 MEND/BC AMD TASK FORCE PROJECT

Upon initiation of the MEND/BC AMD Task Force Project, the majority of kinetic tests initiated by City Resources had been terminated. Tests remaining are indicated in Table 3-2 in the column "THIS STUDY". These tests had been continued by City Resources primarily to complete studies C, E and G (Section 3.1). The five remaining humidity cells were terminated at the beginning of the MEND/BC AMD Task Force project because it appeared that water quality trends were well established. The waste rock pads and waste rock and limestone column tests were continued for at least part of the three years of the MEND/BC AMD Task Force project to complete studies E and G.

TABLE 3-1
SUMMARY OF TYPE AND NUMBER OF TESTS FOR EACH STUDY

STUDIES / TESTS		Acid-base Accounting	Humidity Cells Wet-dry	Humidity Cells Wet	Waste Rock Pads	Leach Columns Sub-aerial	Leach Columns Sub-aqueous	Leach Columns Limestone Mix
A	Screen Acid Generation Potential	197	0	0	0	0	0	0
B	Calibrate ABA and Water Quality	44	6	38	4	5	8	5
C	Quantify acid generation potential	10	6	38	4	5	8	5
D	Compare wet-dry and wet humidity cells	0	6	4	0	0	0	0
E	Compare field and laboratory acid generation rates	0	6	4	4	0	0	0
F	Compare sub-aqueous and sub-aerial leaching	13	0	0	0	5	8	0
G	Evaluate limestone addition	5	0	0	0	0	0	5
	TOTAL NUMBER OF TESTS	269	6	38	4	5	8	5

TABLE 3-2
LIST OF EXPERIMENTAL UNITS AND STUDIES

STUDY (1,2)						THIS STUDY	TEST (3)	TYPE	#	ROCK TYPE	COMMENTS	POWDER pH	TOTAL S (%)	kg CaCO3/t			NP/MPA (5)
B	C	D	E	F	G									MPA (4)	NP (4)	NNP (4)	
X	X	X	X				HC	Wet-Dry	1-01	Skonun Sediments	WRP-1, Two of same cell	5.3	1.95	60.9	2.16	-58.8	0.04
X	X	X	X				HC	Wet-Dry	1-02	Skonun Sediments	WRP-2, Two of same cell	7.2	2.96	92.5	3.05	-89.5	0.03
X	X	X	X				HC	Wet-Dry	1-03	Skonun Sediments	WRP-4, Two of same cell	7.1	1.75	54.7	0.69	-54.0	0.01
X	X	X	X				HC	Wet	2-01	Skonun Sediments	WRP-1	5.3	1.95	60.9	2.16	-58.8	0.04
X	X	X	X				HC	Wet	2-02	Skonun Sediments	WRP-2	7.2	2.96	92.5	3.05	-89.5	0.03
X	X		X			X	HC	Wet	2-03	Argillically Altered Skonun	WRP-3	3.5	3.06	95.6	-6.37	-102.0	-
X	X	X	X			X	HC	Wet	2-04	Skonun Sediments	WRP-4	7.1	1.75	54.7	0.69	-54.0	0.01
X	X						HC	Wet	3-06	Haida Mudstone		8.2	1.30	40.6	29.7	-10.9	0.73
X	X						HC	Wet	3-17	Haida Mudstone		8.2	1.38	43.1	151	107.9	3.50
X	X						HC	Wet	3-19	Haida Mudstone		8.4	0.87	27.2	49.4	22.2	1.82
X	X					X	HC	Wet	3-20	Haida Mudstone		7.7	1.15	35.9	7.12	-28.8	0.20
X	X					X	HC	Wet	3-22	Haida Mudstone		8.1	1.21	37.8	86.4	48.6	2.28
X	X						HC	Wet	3-31	Haida Mudstone		7.6	1.71	53.4	35.1	-18.3	0.66
X	X						HC	Wet	3-04	Skonun Sediments		5.4	3.01	94.1	1.32	-92.7	0.01
X	X						HC	Wet	3-07	Skonun Sediments		4.9	1.98	61.9	2.47	-59.4	0.04
X	X						HC	Wet	3-16	Skonun Sediments		4.6	3.12	97.5	0.30	-97.2	0.00
X	X						HC	Wet	3-21	Skonun Sediments		4.1	2.46	76.9	-0.45	-77.3	-
X	X						HC	Wet	3-23	Skonun Sediments		5.1	3.84	120	-1.89	-121.9	-
X	X						HC	Wet	3-32	Skonun Sediments		4.1	3.08	96.3	3.04	-93.2	0.03
X	X						HC	Wet	3-01	Skonun Sediments		6.3	0.96	30	1.00	-29.0	0.03
X	X						HC	Wet	3-05	Skonun Sediments		4.7	0.84	26.3	0.50	-25.8	0.02
X	X						HC	Wet	3-08	Skonun Sediments		4.7	2.34	73.1	1.25	-71.9	0.02
X	X						HC	Wet	3-10	Skonun Sediments		4.8	2.16	67.5	0.95	-66.6	0.01
X	X						HC	Wet	3-12	Skonun Sediments		4.9	1.90	59.4	0.57	-58.8	0.01
X	X						HC	Wet	3-27	Skonun Sediments		5.7	2.35	73.4	1.30	-72.1	0.02
X	X					X	HC	Wet	3-11	Skonun Sediments		7.7	2.53	79.1	6.23	-72.8	0.08
X	X						HC	Wet	3-14	Skonun Sediments		7.7	2.61	81.6	13.4	-68.2	0.16
X	X						HC	Wet	3-15	Skonun Sediments		6.4	2.20	68.8	1.74	-67.0	0.03
X	X						HC	Wet	3-18	Skonun Sediments		5.0	1.47	45.9	0.95	-45.0	0.02
X	X						HC	Wet	3-28	Skonun Sediments		6.5	2.55	79.7	2.54	-77.1	0.03
X	X						HC	Wet	3-29	Skonun Sediments		7.6	2.23	69.7	9.33	-60.4	0.13
X	X						HC	Wet	3-30	Skonun Sediments		5.0	1.63	50.9	0.25	-50.7	0.00
X	X						HC	Wet	3-33	Rhyolite		5.0	3.22	101	2.39	-98.2	0.02
X	X						HC	Wet	3-09	Breccia		4.4	1.51	47.2	0.22	-47.0	0.00
X	X						HC	Wet	3-26	Breccia		4.3	2.14	66.9	0.01	-66.9	0.00
X	X						HC	Wet	3-34	Breccia		6.9	3.00	93.8	1.51	-92.2	0.02
X	X						HC	Wet	3-02	Argillically Altered Skonun		4.9	4.10	128	1.32	-126.8	0.01
X	X						HC	Wet	3-03	Argillically Altered Skonun		3.8	6.08	190	0.01	-190.0	0.00
X	X						HC	Wet	3-13	Argillically Altered Skonun		6.5	4.00	125	3.99	-121.0	0.03
X	X						HC	Wet	3-24	Argillically Altered Skonun		6.6	4.05	127	6.58	-120.0	0.05
X	X						HC	Wet	3-25	Argillically Altered Skonun		7.2	4.83	151	7.15	-143.8	0.05
X	X		X			X	WRP		1	Skonun Sediments		5.3	1.95	60.9	2.16	-58.8	0.04
X	X		X			X	WRP		2	Skonun Sediments		7.2	2.96	92.5	3.05	-89.5	0.03
X	X		X			X	WRP		3	Argillically Altered Skonun		3.5	3.06	95.6	-6.37	-102.0	-
X	X		X			X	WRP		4	Skonun Sediments		7.1	1.75	54.7	0.69	-54.0	0.01
X	X			X			LCaq	Sub-aq.	1	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12
X	X			X			LCaq	Sub-aq.	2	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12
X	X			X			LCaq	Sub-aq.	3	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10
X	X			X			LCaq	Sub-aq.	4	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10
X	X			X			LCaq	Sub-aq.	5	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12
X	X			X			LCaq	Sub-aq.	6	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12
X	X			X			LCaq	Sub-aq.	7	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10
X	X			X			LCaq	Sub-aq.	8	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10
X	X			X			LCae	Sub-aer.	9	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12
X	X			X			LCae	Sub-aer.	10	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10
X	X			X			LCae	Sub-aer.	11	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12
X	X			X			LCae	Sub-aer.	12	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10
X	X			X			LCae	Sub-aer.	13	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12
X					X	X	LC	Limestone	1	Skonun Sediments		6.9	2.10	65.6	8	-57.6	0.12
X					X	X	LC	Limestone	2	Skonun Sediments, 6.6% Lst		-	1.98	61.9	69	7.1	1.12
X					X	X	LC	Limestone	3	Skonun Sediments, 3.3% Lst		-	2.05	64.1	38	-26.1	0.59
X					X	X	LC	Limestone	4	Skonun Sediments, 0.84% Lst		-	2.08	65	16	-49.0	0.25
X					X	X	LC	Limestone	5	Skonun Sediments	Limestone in layers	-	2.08	65	19	-46.0	0.29

Notes

1. Refer to Table 3-1 for list of studies and tests.
2. For experiments D to G, "X" means exactly same material used in different tests.
3. HC = Humidity Cell, WRP = Waste Rock Pad, LC = Leach Column, aq = subaqueous, ae = subaerial.
4. MPA - Maximum Potential Acidity, NP - Neutralization Potential, NNP=NP-MPA.
5. "-" indicates value not determined for NP<0.

4.0 TEST MATERIALS AND METHODS

This chapter summarizes the sources of samples used in the testing and standard operational protocols for the tests. Specific variances from, and details of the procedures are included in the subsequent sections, which also describe the outcomes of the experiments.

4.1 SOURCE OF TEST MATERIALS

4.1.1 Acid-Base Accounting Test Work

All samples were obtained from reverse circulation rotary drill cuttings (uncrushed). The locations of the drill holes are shown in Figure 4-1. This method tends to result in losses of soluble components due to flushing during drilling. Fine particles may also be suspended and lost from the sample. Drill cuttings had been stored underwater in buckets for between six months and one year. Water in a few buckets was found to be acidic, but the majority appeared to be unaffected by acid generation during storage. Each sample consisted of approximately 2 m of core.

4.1.2 Humidity Cells

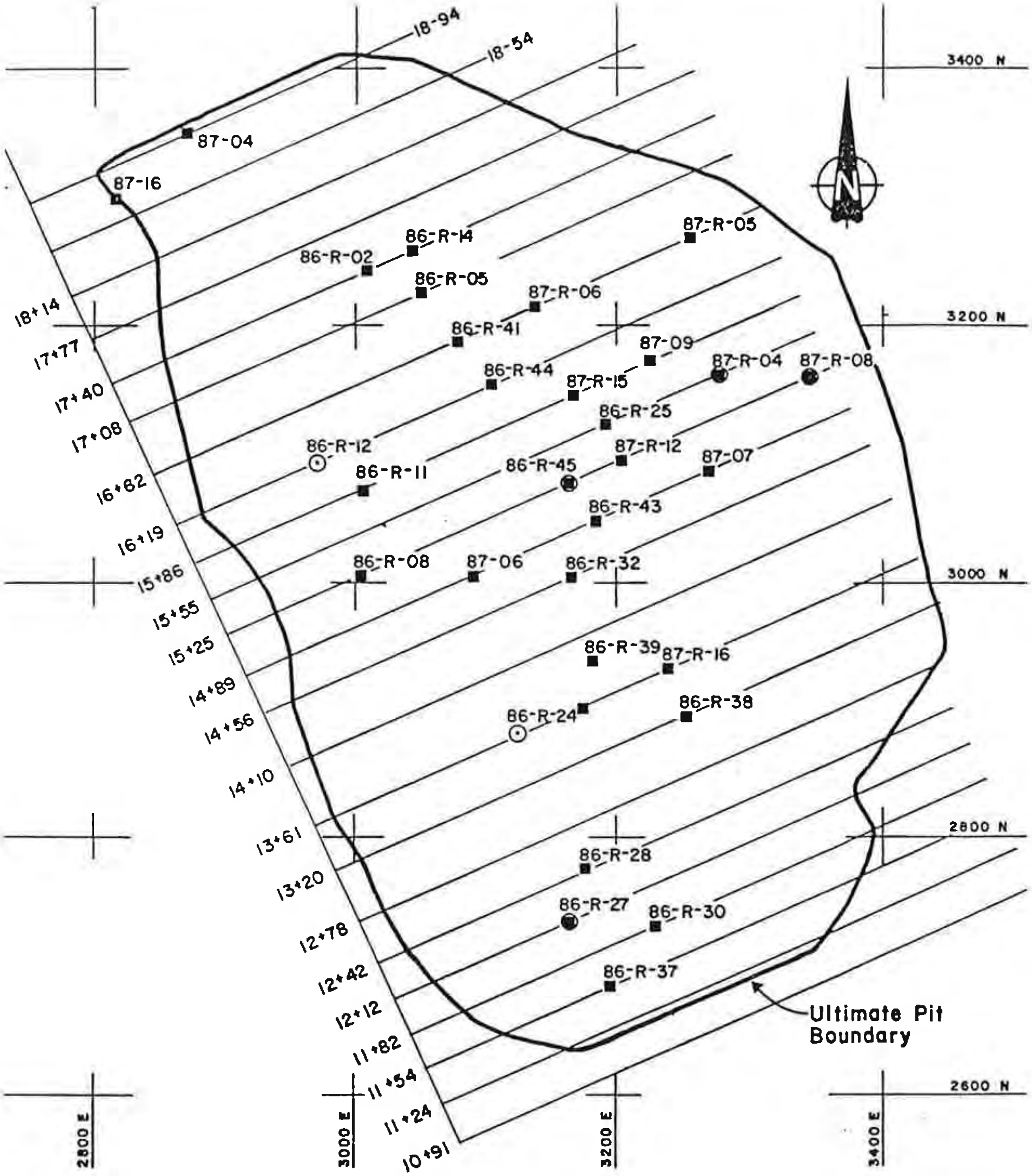
Sample Number Nomenclature

Three different sets of humidity cell tests were conducted (Table 3-2). Set 1 comprised six humidity cells with identification numbers prefixed by "1-". Similarly, sets 2, and 3 were prefixed by "2-", and "3-", respectively. Sets 1 and 2 were conducted on material from the on-site waste rock pads. Set 3 was conducted on samples representative of the waste rock.

Sources of Samples

Set 1 and 2 samples were collected from near the top of each waste rock pad after approximately 1 month of weathering. The samples were screened with a 4 mm hand sieve and stored in airtight plastic bags.

Set 3 samples were composites of drill core (Section 4.1.1). Approximately 6 to 20 m of core was composited to form the test material for each cell.



LEGEND

Waste Rock Samples ■

Overburden Samples ⊙

50 0 50 100 m

Figure 4-1
LOCATION OF DRILL HOLES
WASTE ROCK SAMPLES

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4.1.3 Waste Rock Pads

Four waste rock pads were constructed in February 1987 using rock from two different sources. Pad 1 consisted of Skonun Formation rock (silicified conglomerate) that was removed from the exploration adit in 1982. Throughout this report, this material is referred to as "five-year weathered Skonun Sediments". Pads 2, 3 and 4 were constructed from rock freshly removed from the adit in 1987. After blasting, the rock was not processed in any way. The material contained some large blocks surrounded by visible abundant sandy fine material.

4.1.4 Waste Rock and Limestone Mixing Experiment

Waste rock used in the study was a composite of various sub-groups of the Skonun Sediments mirroring the expected composition of waste rock piles. The rock material was obtained from reverse circulation drill cuttings which had been stored underwater prior to initiating the studies (Section 4.1.1). Prior to loading into the columns, the waste rock was coned three times to ensure thorough mixing.

Limestone for the experiments was obtained from Texada Island, the proposed source of limestone if the deposit were developed. The limestone was dried and crushed to a diameter of 0.6 mm and smaller.

4.2 METHODS FOR CHARACTERIZATION OF TEST MATERIAL

4.2.1 Acid-Base Accounting (ABA), Sulphur and Carbonate

All samples were dried and crushed in two stages using jaw and cone crushers. Sub-samples were pulverized using a ring pulverizer, screened to finer than 0.11 mm and homogenized.

Acid-base accounting followed the standard procedures defined by Sobek *et al.* (1978). The pH of the pulverized sample is referred to subsequently as "powder pH". Selected samples were also analyzed for sulphate-sulphur using a hydrochloric acid leach, sulphide-sulphur using nitric acid, and inorganic CO_2 (carbonate) using a hydrochloric acid leach. Detection limits for methods are provided in Appendix D.

4.2.2 Particle Size Analysis

Particle size analyses were conducted on approximately 500 g of dried material, using 0.053, 0.106, 0.590, 2.0 mm screens. The resulting particle size analyses were used to estimate particle surface areas, by assuming that the particles are spherical and the average diameter of each fraction (D_i) is midway between the two sieves which produced the particular size fraction. The approximate formula used was:

$$\text{Total area} = (3/\text{density}).\Sigma(\text{Mass of fraction})/D_i.$$

The assumption of sphericity may tend to grossly overestimate surface area if particles are long and thin, or underestimate surface area if particles are plate-like. In the absence of specific information on particle shape to generate shape factors, the approach used provides a rough average. This calculation method was also used throughout the City Resources and therefore allows results for test materials and residues to be compared directly.

These estimates were used to estimate sulphate release on a surface area basis for all kinetic tests.

4.2.3 Petrographic Analysis

Small chips and sand size material were mounted on glass slides ground to the standard thickness of 0.03 mm, polished and examined in plane and cross-polarized light using a petrographic microscope. Opaque minerals were examined in reflected light. Transparent minerals were examined in plane polarized and cross-polarized light. Photomicrographs were taken using 200 ASA Kodak Gold film.

4.3 METHODS OF RESIDUE CHARACTERIZATION

In addition to ABA, particle size analysis and petrographic analysis, the residues remaining after testing were characterized using the following methods.

4.3.1 Dismantling of Limestone Mixing Experiment Columns

When the limestone mixing columns were dismantled, the residues were visually examined for changes in colour, observable minerals, and tested for the presence of limestone using hydrochloric acid.

4.3.2 Examination of Waste Rock Pads

In 1993, a trench was excavated in Pad 2 and visual changes in colour, particle size and cementation were described. Grab samples were collected for analysis.

4.3.3 Residue pH

The pH of a leachate formed by shaking 1 part water with 1 part test residue (by volume) was measured. In this report, this is referred to as "residue pH", although it is not the same measurement described by Sobek *et al.* (1987) for powder pH or the soil pH used by soil scientists.

4.3.4 Sequential Leach of Test Residues

Approximately 1 g of pulverized residue from several tests was leached with solutions dissolving specific chemical compounds. The leach solutions were (with species for dissolution in parentheses) 10% hydrochloric acid (sulphates), 10% ammonium oxalate (secondary hydroxides and oxides), concentrated nitric acid and bromine (sulphide minerals), and concentrated nitric and perchloric acids (silicate minerals). Leachates were analyzed for iron, copper and zinc.

4.4 KINETIC TEST PROCEDURES

4.4.1 Humidity Cells

Each humidity cell consisted of a 1 L shallow plastic box with a tight fitting lid, and containing 200 g of rock crushed to pass a 2 mm screen. A tube through the plastic lid supplied humidified or dry air. The equipment is illustrated schematically in Figure 4-2. At the end of every one week cycle, 250 mL of deionized water was added to the rock and then extracted one hour later. This leaching procedure was repeated with a second 250 mL of deionized water. The leachates were combined, and filtered (0.45 µm filter). Some leachates were turbid and were centrifuged prior to filtration. All solid residues collected by decanting following centrifuging were returned to the cells the following week in the first 250 mL of water.

Set 1 humidity cells (Table 3-2) were operated on a 3-day wet, 3-day dry, 1-day leach cycle, as described by Sobek *et al.* (1978). The remaining tests were operated with continuous moist air flow.

A portion of the leachate was preserved with nitric acid for metal analysis. Leachates were typically analyzed for pH, conductivity, sulphate, acidity, alkalinity, and dissolved (after 0.45 µm filtration) arsenic, calcium, copper, iron, mercury, magnesium and zinc. Detection limits for the analyses are shown in Appendix D.

4.4.2 Waste Rock Pads

Pad design and construction details are illustrated in Figures 4-3 and 4-4a&b. The waste rock was placed on a bed of inert quartz sand which in turn covered an impermeable liner. The pads were drained by a perforated pipe wrapped in geotextile fabric through a flow splitter and into a plastic barrel. The flow splitters, intended to continuously separate a portion of the flow for testing, were not effective. Barrels for collection of leachate were covered to keep out precipitation. The barrels had a capacity of 40 litres and had a siphon tube which caused the barrel to decant completely when about one-third full. As the barrels were expected to overflow on many occasions between sampling events, the siphon prevented mixing of leachate produced at different times.

Decanted leachate was channelled over a bed of crushed limestone to partially neutralize the drainage. This bed was periodically turned over and replenished to maintain its neutralization capacity.

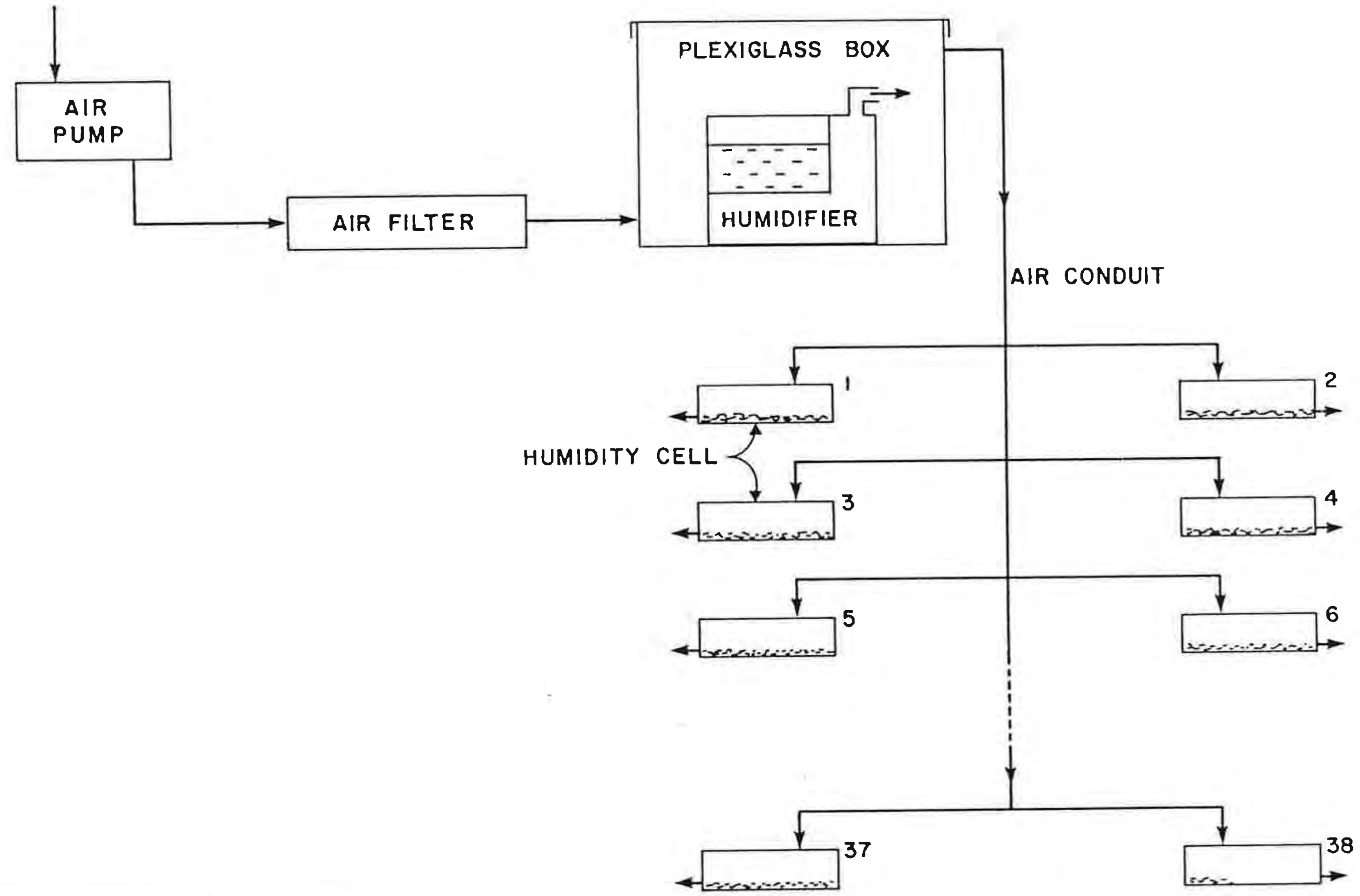

Figure 4-2
HUMIDITY CELL APPARATUS

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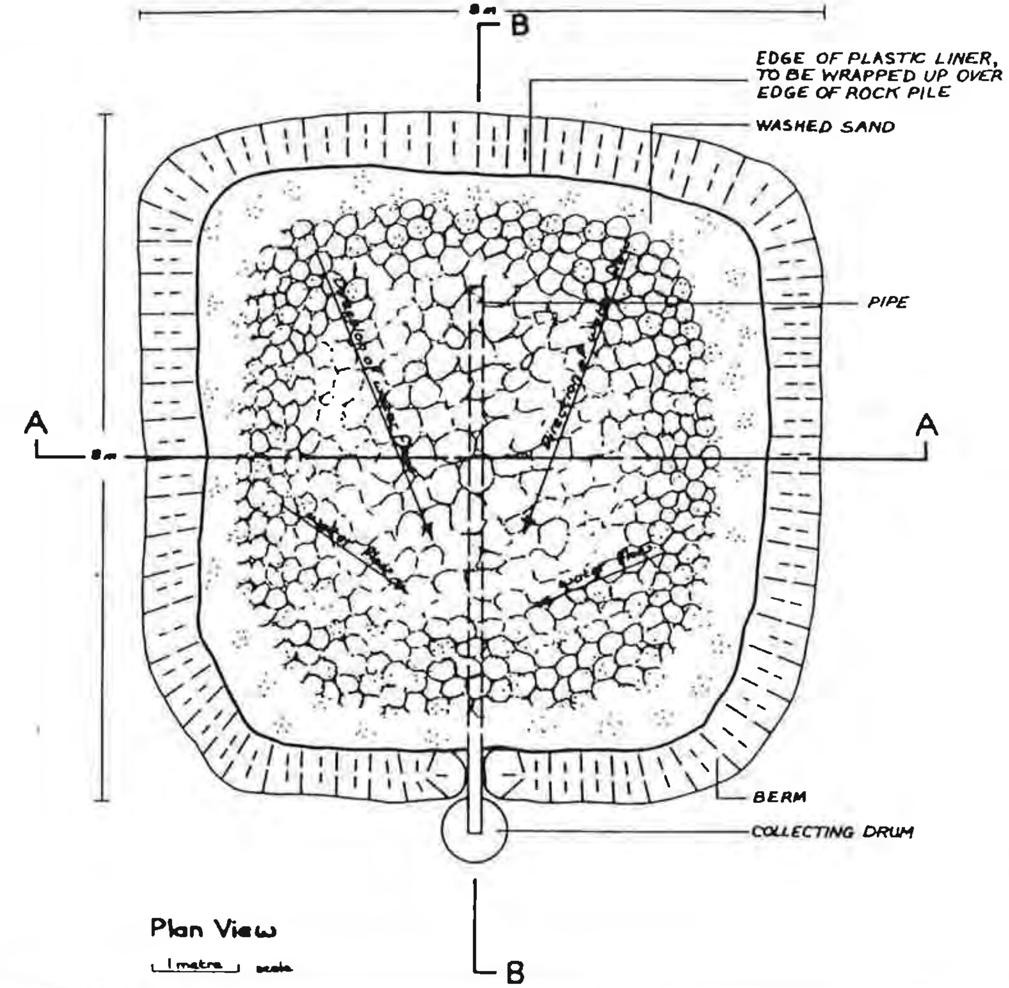
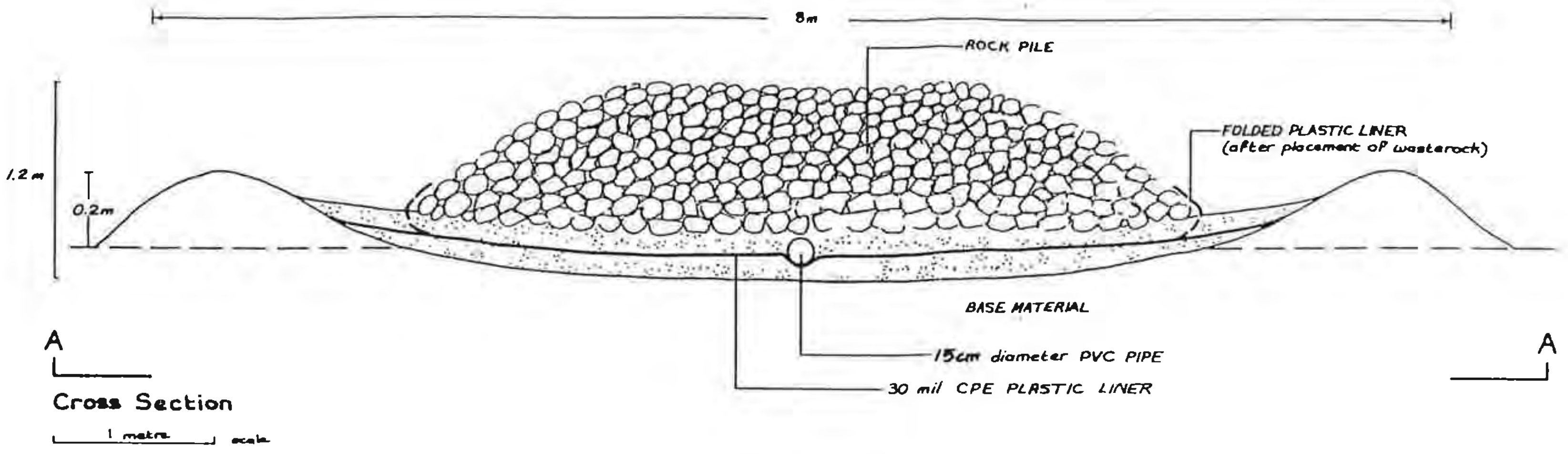
Construction Procedure

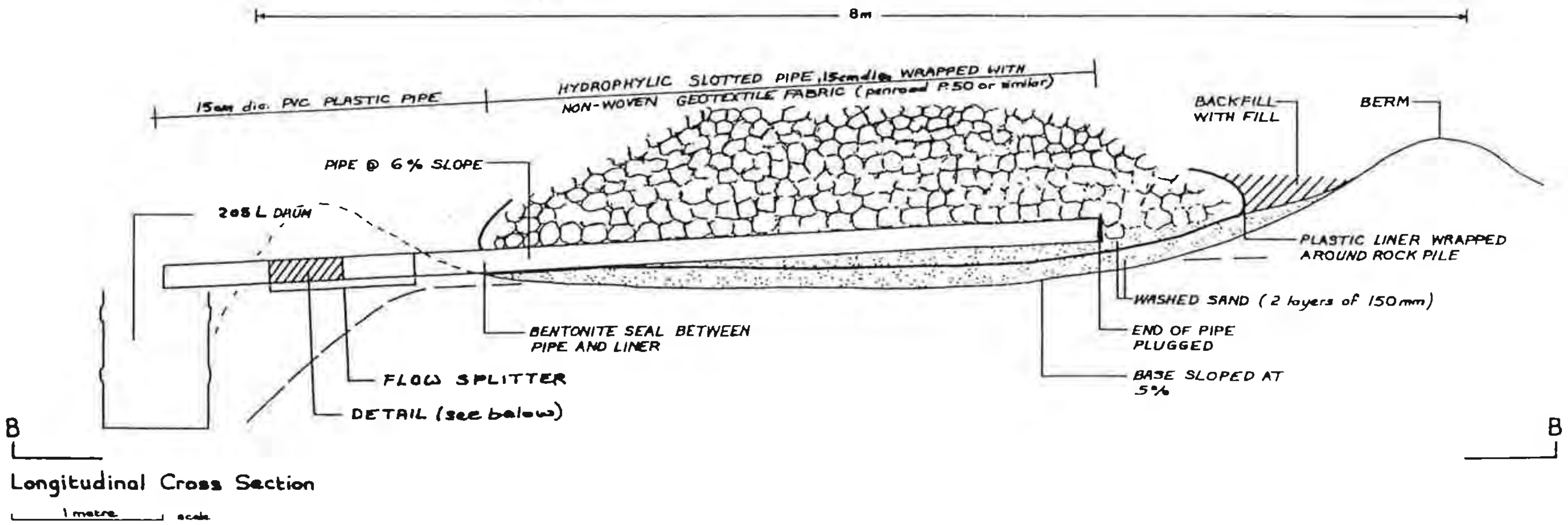
1. Prepare base and side berms.
2. Place 150 mm layer washed sand.
3. Place 30 mil CPE plastic liner.
4. Place 150 mm layer washed sand.
5. Place 15 cm dia. hydrophylic slotted pipe wrapped in geotextile fabric.
6. Place PVC plastic pipe through liner and berm opening and connect to hydrophylic pipe.
7. Form bentonite seal.
8. Place max. 500 mm layer of waste rock by hand on sand and around hydrophylic pipe.
9. Place waste rock in nominal 500 mm lifts.
10. Wrap plastic liner against side and around perimeter of waste rock pile.
11. Prepare water collection system.



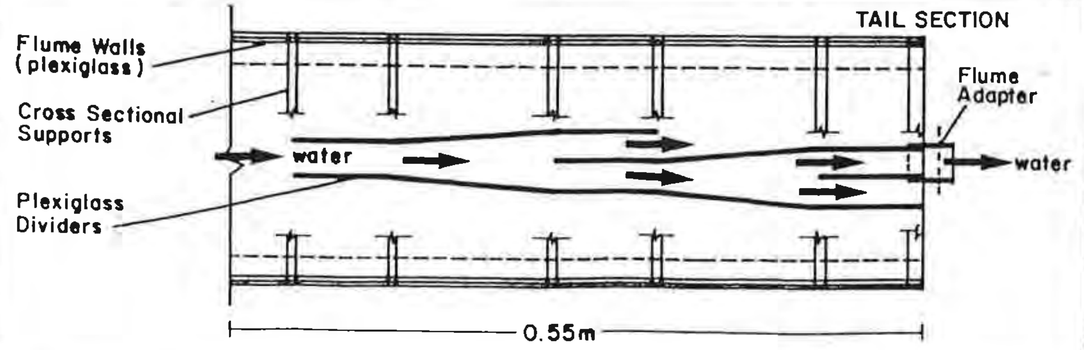
Plan View



Cross Section



Longitudinal Cross Section



DETAIL OF FLOW SPLITTER - PLAN VIEW

Figure 4-3
CONSTRUCTION OF WASTE ROCK PAD

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Figure 4-4a Pad 2 showing overall configuration. White pail is 40 cm high. Photograph taken in September 1990.

Figure 4-4b Close up of rock in Pad 2. Note 5 cm diameter lens gap for scale. Photograph taken in September 1990.

In July 1991, vandals removed the water collection pails from all pads, and the drainage pipe from Pad 1. To discourage future vandalism, a lock was installed on the gate to the site, and a large sign describing the experiment was erected adjacent to the pads.

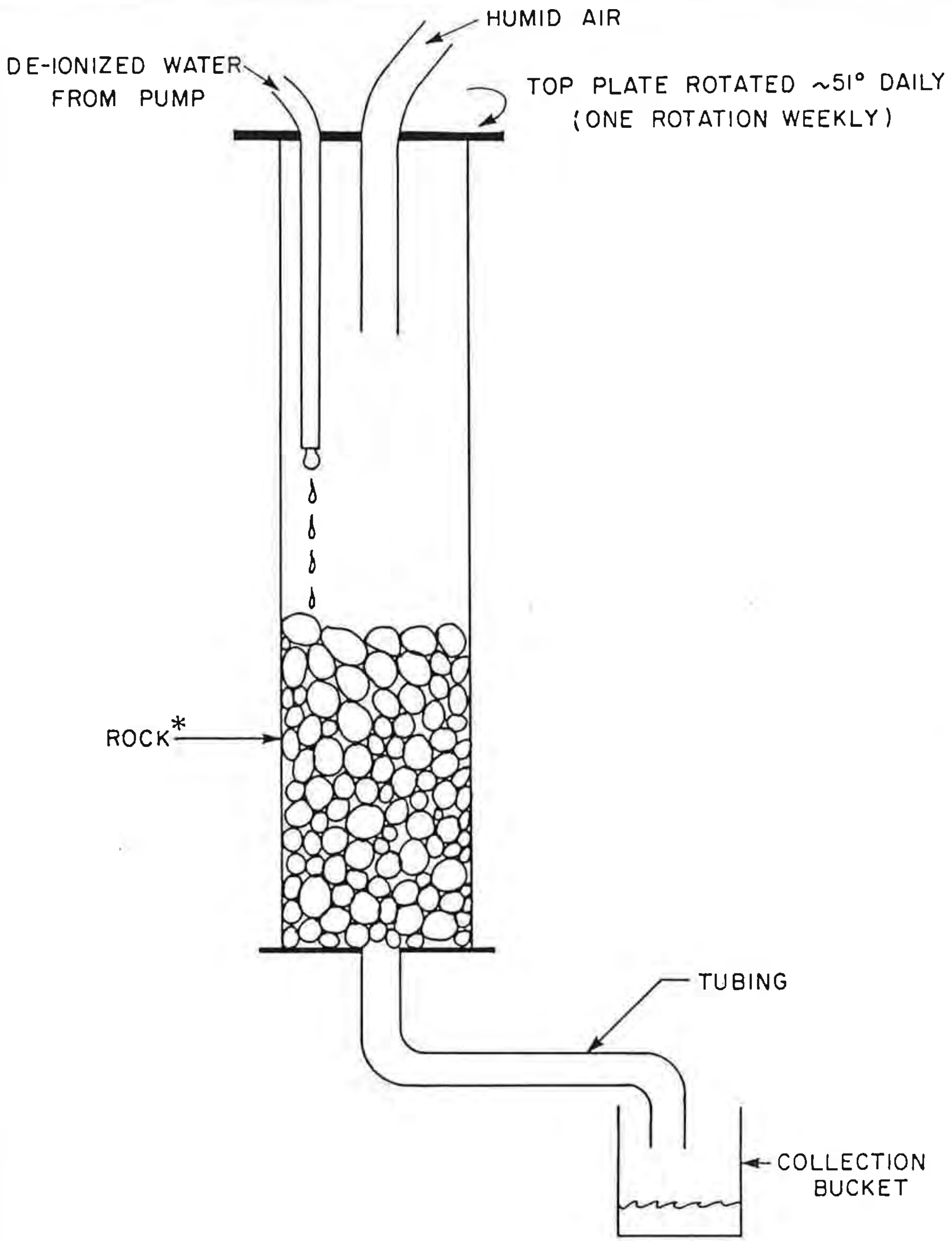
Acid-base accounting (ABA) and size-fraction analyses were conducted on all sub-samples of waste rock prior to initiation of the tests. Four humidity cells were set up using material from each of the four pads, and were operated for 148 weeks. Results from these tests are described in Section 6.0.

From February 1987 to October 1988, pad leachate was collected approximately once every two weeks. The pads were not monitored from October 1988 to September 1990, because leachate data were not requested by City Resources. Sampling was re-initiated in September 1990 as part of the MEND/BC AMD Task Force program. The last set of samples were collected in April 1992. Under City Resources' program, leachate was analyzed for pH, conductivity, alkalinity, sulphate, acidity, total mercury, and dissolved aluminum, arsenic, calcium, cadmium, cobalt, chromium, copper, iron, manganese, nickel, lead, antimony and zinc. Leachates collected in the 1990-91 program were analyzed for the same general parameters but fewer dissolved parameters (aluminum, arsenic, calcium, copper, iron and zinc). The list of dissolved metals was expanded for the 1991-92 program to include silver, aluminum, arsenic, boron, barium, beryllium, calcium, cadmium, cobalt, chromium, copper, potassium, magnesium, iron, manganese, molybdenum, sodium, nickel, lead, antimony, selenium, tin, strontium, titanium, vanadium and zinc, all analyzed by ICP. Detection limits for the parameters determined at each stage of the program are given in Appendix D.

4.4.3 Waste Rock and Limestone Mixing Experiments

Five 15-cm diameter plastic columns approximately 1 m in height were designed, as illustrated in Figures 4-5 and 4-6. The columns were fitted with bottom drains with a short length (30 to 50 cm) of plastic tubing to direct leachate into a collection bucket. The depth of rock in the columns was 0.5 m. Column tops were covered with a plastic plate to minimize evaporation. A hole in the centre of the plate allowed humidified air to be pumped in. A second hole was used to introduce deionized water at a rate of 0.4 to 0.5 mL/minute, which is equivalent to an annual precipitation rate of 14,000 mm. The top plate was rotated 51° daily (full rotation in 1 week) so that the water dripped on seven different locations each week. This design allowed most of the rock to come into contact with the deionized water, while at the same time permitting the development of preferential channels within the column as would be expected in a rock stockpile.

Initially, leachate from both the tubing (at the time of sampling) and the bucket was analyzed. Each week, water collected directly from the tubing was analyzed for pH, Eh, temperature, dissolved oxygen, and conductivity. Filtered (0.45 µm filter) leachate was analyzed for alkalinity, acidity, sulphate and total sulphur, and 30 metals including the same metals measured in the humidity cell leachate. Leachate in the bucket, which represented a weekly composite, was analyzed for pH and sulphate.



Dimensions:
Column - 15 cm diameter, 1 m in height
Height of rock - 50 cm

Figure 4-5
SCHEMATIC DIAGRAM OF
WASTE ROCK/LIMESTONE COLUMNS

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Figure 4-6 Columns 1,2 and 3. For dimensions refer to Figure 4-5.

As the study progressed, City Resources modified the analytical schedule due to financial constraints. Following week 15, samples were analyzed for metals twice a week. Following week 33, all parameters except pH, conductivity and dissolved oxygen were tested every other week, and the quantity of water added and removed from the columns was determined on a weekly basis.

For the first year (1990-91) of the MEND/BC AMD Task Force Project, the following reduced schedule of analyses was adopted:

- pH and conductivity were measured every other week;
- sulphate, acidity (to pH 4.5 and 8.3), alkalinity, and dissolved iron and calcium were measured every four weeks; and
- dissolved copper, zinc, lead, and arsenic concentrations were measured every 12 weeks.

In the second and third years of the MEND/BC AMD Task Force Project, the schedule for general parameters, iron and calcium was continued, however, the list of metals analyzed was expanded to lithium, beryllium, boron, magnesium, aluminum, titanium, vanadium, chromium, manganese, iron, cobalt, nickel, copper, zinc, arsenic, selenium, strontium, molybdenum, silver, cadmium, tin, antimony, barium, mercury, thallium, lead, thorium and uranium. Only leachates in the buckets were analyzed because past data indicated that tubing and bucket results were comparable. Dissolved oxygen was not analyzed because significant changes in this parameter were not observed even when columns generated acidic leachate. Detection limits at various stages of the project are summarized in Appendix D.

5.0 INITIAL SCREENING OF ACID GENERATION POTENTIAL

City Resources collected (see Section 4.1.1) 197 rock samples from within the area of the proposed open pit to characterize typical waste rock and pit wallrocks.

5.1 RESULTS

The various sulphur analyses by City Resources indicate 55 to 96% (average 87%) of the total sulphur occurs as sulphur-sulphide (Table 5-1). The remaining 13% balance is made up principally by organic sulphur, reflecting the elevated organic content, and weak acid-soluble sulphate forms, such as alunite. Means, maxima and minima for the ABA parameters determined by City Resources (1988, Volume V) are shown in Table 5-2. Table 5-2 also contains values for neutralization potential (NP), maximum potential acidity (MPA), net neutralization potential (NNP=NP-MPA) and NP/MPA. Since, the original data were not available, the NP/MPA was calculated using the average values for NP and MPA.

Mean total sulphur concentrations in waste rock and ore varied from 0.7 to 4.7%, with the highest values in the argillically-altered Skonun Formation. Neutralization potentials were very low (0.2 to 5.0 kg $CaCO_3$/t) and are considered negligible. Rock from the pit area had NP/MPA values varying from 0.005 to 0.13. Samples representative of the proposed east pit wall showed similar results. The west pit wall, however, was expected to be composed of Haida mudstone which had higher neutralization potentials than Skonun sediments in the area of the proposed pit (Figure 4-1). Although the NNP's for the mudstone were 24 kg $CaCO_3$/t, the NP/MPA was less than 2.0.

5.2 DISCUSSION

5.2.1 Form of Sulphur

Sulphate present in the samples is thought to represent the oxidation of iron sulphides in the rock mass prior to sampling or during storage prior to analysis. Small amounts of primary sulphate minerals (such as gypsum, $CaSO_4$) may also be present, but none were identified by City Resources. Since the proportion of sulphur in non-sulphide forms was relatively small, City Resources elected to base subsequent acid-base accounting predictions on total sulphur concentrations.

5.2.2 Acid Generation Potential

At the time the Cinola deposit was being developed by City Resources, an NNP of -5 kg $CaCO_3$/t was assumed to represent the threshold between acid generation and acid consumption. This threshold was suggested by Sobek *et al.* (1978). Subsequently, others have suggested the threshold may lie between -20 and 20 kg $CaCO_3$/t (Ferguson and Morin 1991). Recent re-evaluations of the theoretical basis for ABA have concluded that the NP/MPA ratio provides a more reliable way of estimating the acid generation threshold

TABLE 5-1
SULPHUR FORMS IN WASTE ROCK

HOLE NUMBER (1)	APPARENT DEPTH (2) (m)	ROCK TYPE	TOTAL SULPHUR (%)	SULPHUR AS SULPHIDE (%)	SULPHATE (%)	SULPHUR AS ORGANIC (%)	INERT SULPHUR (3) (%)	INERT SULPHUR (3) (as a % of Total S)
86-R-27	54 - 56	Breccia	1.00	0.8	0.02	0.18	0.20	21.2
86-R-38	78 - 80	Breccia	1.10	1.1	0.02	0.03	0.05	4.5
86-R-25	82 - 84	Breccia	2.10	1.7	0.11	0.26	0.37	17.6
86-R-02	82 - 84	Breccia	1.10	0.8	0.04	0.18	0.22	21.8
86-R-32	156 - 158	Haida Mudstone	0.74	0.6	0.03	0.11	0.13	17.9
86-R-02	86 - 88	Haida Mudstone	2.70	2.3	0.06	0.34	0.40	14.8
86-R-02	100 - 102	Haida Mudstone	1.10	0.9	0.04	0.16	0.20	18.0
86-R-37	26 - 30	Skonun Sediments	0.94	0.7	0.02	0.25	0.27	28.6
86-R-30	28 - 30	Skonun Sediments	1.30	1.2	0.03	0.12	0.15	11.3
86-R-45	12 - 14	Skonun Sediments	1.80	1.7	0.07	0.01	0.07	4.2
86-R-45	14 - 16	Skonun Sediments	1.60	1.5	0.03	0.07	0.10	6.3
86-R-45	16 - 18	Skonun Sediments	1.40	1.2	0.04	0.11	0.15	11.1
86-R-02	10 - 12	Skonun Sediments	2.70	2.5	0.14	0.06	0.20	7.4
86-R-02	36 - 38	Skonun Sediments	3.40	3.0	0.09	0.28	0.37	10.9
86-R-15	78 - 80	Till Overburden	1.10	0.6	0.31	0.13	0.44	43.7

NOTES:

1. Drill hole locations are shown on Figure 4-1.
2. Depth interval does not necessarily equate to distance below ground surface, as all holes were not vertical.
3. Inert sulphur = sulphur sulphate + organic sulphur.
4. The summation of sulphur types may not equal total sulphur since the method used for sulphur determination may include reactive sulphides.

TABLE 5-2

SUMMARY OF ACID-BASE ACCOUNTING RESULTS FOR WASTE ROCK REPRESENTATIVE OF THE PIT AND PIT WALLS

									kg CaCO3/t										
WASTE ROCK GROUP	LOCATION	NO. OF SAMPLES	POWDER pH			TOTAL SULPHUR (%)			MPA			NP			NNP			NP/MPA
			MIN	MAX	MEAN	MIN	MAX	MEAN	MIN	MAX	MEAN	MIN	MAX	MEAN	MIN	MAX	MEAN	MEAN
HAIDA MUDSTONE																		
	Pit Rock	3	5.7	7.5	6.8	0.9	1.6	1.2	28	50	38	2.4	8.8	5.0	-49	-25	-33	0.18
	West Pit Wall	30	4.5	8.5	7.6	0.1	2.8	1.3	3	88	41	-0.9	310	65	-69	235	24	3.54
SKONUN SEDIMENTS																		
	Pit Rock	48	3.9	7.9	5.8	0.5	5.4	2.3	16	169	72	-3.3	23.0	2.9	-120	-14	-67	0.14
	East Pit Wall	53	3.3	8.1	5.2	0.8	3.8	2.3	25	119	72	-4.0	12	2.0	-120	-24	-69	0.10
RHYOLITE																		
	Pit Rock	3	5.1	6.6	5.8	1.7	4.0	2.8	53	125	88	1.9	2.8	2.4	-120	-49	-78	0.02
	West Pit Wall	9	4.3	8.3	6.5	0	2.7	0.7	0	84	22	0.8	130	16	-82	120	-5	1.54
MULTIPHASE BRECCIA																		
	Pit Rock	8	2.5	7.0	5.5	0.6	2.4	1.3	19	75	41	-6.7	2.8	0.2	-74	-19	-41	0.04
	West Pit Wall	2	4.8	5.6	5.2	1.0	1.8	1.4	31	56	44	1.3	1.8	1.5	-55	-30	-43	0.03
ARGILLICALLY ALTERED SKONUN SEDIMENTS	Pit Rock	11	3.4	6.7	5.1	1.9	7.2	4.7	59	225	147	-0.1	4.3	2.1	-220	-58	-150	0.02
	East Pit Wall	15	3.0	6.3	4.0	3.7	7.0	5.1	116	219	159	0.1	4.0	2.1	-220	-110	-157	0.02
OTHER (Silica Veins)																		
	Pit Rock	2	4.8	5.2	5.0	0.4	0.9	0.7	13	28	22	0.5	2.6	1.6	-26	-12	-19	0.09
	West Pit Wall	4	6.4	7.9	7.4	0.3	0.9	0.5	9	28	16	1.3	1.7	1.5	-26	-6.2	-13	0.06

NOTES:

1. "MPA" - Maximum Potential Acidity.
2. "NP" - Neutralization Potential.
3. "NNP" - Net Neutralization Potential (NP-MPA). Statistics for this parameter were derived from raw data, not the statistics for MPA and NP.
4. NP/MPA calculated from statistics in this table (that is NP(MEAN)/MPA(MEAN), therefore maximum and minimum values cannot be determined.

(Cravotta *et al.*, 1990). The expected theoretical threshold of NP/MPA, based on Cravotta *et al.*'s literature review would be between 1.0 and 2.0. This range of values was used in this report to assess the Cinola ABA data.

Most rock from the proposed open pit and east pit wall is predicted to be acid generating since NP/MPA is considerably less than 1.0 for Skonun Sediments. Although sulphur concentrations in this waste rock type are relatively low (between 1 and 3%), when compared to some other mineral deposits, reactive acid consuming minerals occur in very low concentrations, and hence acid generation is probable. In contrast, the west pit wall was expected to be composed primarily of Haida Mudstone. The Haida Mudstone contains much higher neutralization potentials than the majority of waste rock and the average NP/MPA is greater 3.0. This rock was therefore expected to be acid consuming.

Strongly argillically-altered Skonun Formation rocks were found to release acid upon contact with water. City Resources (1988, Volume V) speculated that the reaction was due to leaching of naturally acidic pore water. In addition, acidic water may be produced by dissolution of acidic salts produced during hydrothermal alteration.

6.0 LONG TERM WEATHERING TRENDS HUMIDITY CELL STUDY

Forty-four humidity cells were set up by City Resources to address experiments B (Calibrate ABA and Water Quality), C (Quantify Acid Generation Potential), D (Compare Wet-Dry and Wet Humidity Cells) and E (Compare Field and Laboratory Acid Generation Rates), as described in Section 3.1. At the time the MEND/BC AMD Task Force project was initiated, the majority of these tests had been terminated. The following chapter summarizes results from these experiments with particular emphasis on long term weathering trends. The individual tests are listed in Table 6-1.

6.1 APPLICATION OF HUMIDITY CELLS AND MODIFICATION OF PROCEDURES

Humidity cells are the simplest kinetic test type. They are conducted using a small amount of finely (2 mm) crushed material, that can be accurately characterized, and are conducted under experimental conditions that can be controlled. This eliminates random variations due to heterogeneities in the test material, variable exposure of sulphide and carbonate minerals, formation of discrete flow paths and variations in ambient conditions (temperature, oxygen supply and humidity). The main disadvantage of humidity cells is that the test conditions are considerably different from full-size waste rock piles and rock fractures. For example, in a humidity cell test, the leachate to rock ratio is much greater and acidic conditions in the vicinity of each grain must be re-established following each flushing event. Conversely, frequent leaching of weathering products from the humidity cell reduces the effect formation of coatings on reactive mineral grains might have.

The conventional humidity cell procedure (Sobek *et al.*, 1978) uses a three-day dry air cycle followed by a three-day wet air cycle. Significant drying of rock at the Cinola Project was not expected due to the predominance of very humid conditions (refer to Section 2.1.1). Therefore, the wet-dry air cycling was replaced with continuous supply of 100% humidified air. Each cell was also leached twice per week, because one leach was found to incompletely remove accumulated weathering products.

6.2 CHARACTERISTICS OF TEST MATERIAL

Acid-base accounts, particle size distributions and petrography were determined for all humidity cell test materials. Acid-base accounts for the various materials used in humidity cell tests are summarized in Table 6-1. Only three of the humidity cells were run with Haida Mudstone, which was expected to be acid consuming based on ABA. All the other rock types tested had very low neutralization potentials, with NP/MPA ratios, usually less than 0.1.

Particle size distributions for cells 3-11, 3-20 and 3-22, terminated at the start of the MEND/BC AMD Task Force Project, are shown in Figure 6-1.

TABLE 6-1
LIST OF HUMIDITY CELLS AND ACID-BASE ACCOUNTS

LONG TERM (1)	TEST	TYPE	#	ROCK TYPE	COMMENTS	POWDBR pH	TOTAL S (%)	MPA (2)	NP (2)	NNP (2)	NP/MPA (3)
								kg CaCO3/t			
	HC	Wet-Dry	1-01	Skonun Sediments	WRP-1, in duplicate	5.3	1.95	60.9	2.2	-58.8	0.04
	HC	Wet-Dry	1-02	Skonun Sediments	WRP-2, in duplicate	7.2	2.96	92.5	3.1	-89.5	0.03
	HC	Wet-Dry	1-03	Skonun Sediments	WRP-4, in duplicate	7.1	1.75	54.7	0.7	-54.0	0.01
	HC	Wet	2-01	Skonun Sediments	WRP-1	5.3	1.95	60.9	2.2	-58.8	0.04
	HC	Wet	2-02	Skonun Sediments	WRP-2	7.2	2.96	92.5	3.1	-89.5	0.03
X	HC	Wet	2-03	Argillically Altered Skonun	WRP-3	3.5	3.06	95.6	-6.4	-102.0	-
X	HC	Wet	2-04	Skonun Sediments	WRP-4	7.1	1.75	54.7	0.7	-54.0	0.01
	HC	Wet	3-06	Haida Mudstone		8.2	1.30	40.6	29.7	-10.9	0.73
	HC	Wet	3-17	Haida Mudstone		8.2	1.38	43.1	151.0	107.9	3.50
	HC	Wet	3-19	Haida Mudstone		8.4	0.87	27.2	49.4	22.2	1.82
X	HC	Wet	3-20	Haida Mudstone		7.7	1.15	35.9	7.1	-28.8	0.20
X	HC	Wet	3-22	Haida Mudstone		8.1	1.21	37.8	86.4	48.6	2.28
	HC	Wet	3-31	Haida Mudstone		7.6	1.71	53.4	35.1	-18.3	0.66
	HC	Wet	3-04	Skonun Sediments		5.4	3.01	94.1	1.3	-92.7	0.01
	HC	Wet	3-07	Skonun Sediments		4.9	1.98	61.9	2.5	-59.4	0.04
	HC	Wet	3-16	Skonun Sediments		4.6	3.12	97.5	0.3	-97.2	0.00
	HC	Wet	3-21	Skonun Sediments		4.1	2.46	76.9	-0.5	-77.3	-
	HC	Wet	3-23	Skonun Sediments		5.1	3.84	120.0	-1.9	-121.9	-
	HC	Wet	3-32	Skonun Sediments		4.1	3.08	96.3	3.0	-93.2	0.03
	HC	Wet	3-01	Skonun Sediments		6.3	0.96	30.0	1.0	-29.0	0.03
	HC	Wet	3-05	Skonun Sediments		4.7	0.84	26.3	0.5	-25.8	0.02
	HC	Wet	3-08	Skonun Sediments		4.7	2.34	73.1	1.3	-71.9	0.02
	HC	Wet	3-10	Skonun Sediments		4.8	2.16	67.5	1.0	-66.6	0.01
	HC	Wet	3-12	Skonun Sediments		4.9	1.90	59.4	0.6	-58.8	0.01
	HC	Wet	3-27	Skonun Sediments		5.7	2.35	73.4	1.3	-72.1	0.02
X	HC	Wet	3-11	Skonun Sediments		7.7	2.53	79.1	6.2	-72.8	0.08
	HC	Wet	3-14	Skonun Sediments		7.7	2.61	81.6	13.4	-68.2	0.16
	HC	Wet	3-15	Skonun Sediments		6.4	2.20	68.8	1.7	-67.0	0.03
	HC	Wet	3-18	Skonun Sediments		5.0	1.47	45.9	1.0	-45.0	0.02
	HC	Wet	3-28	Skonun Sediments		6.5	2.55	79.7	2.5	-77.1	0.03
	HC	Wet	3-29	Skonun Sediments		7.6	2.23	69.7	9.3	-60.4	0.13
	HC	Wet	3-30	Skonun Sediments		5.0	1.63	50.9	0.3	-50.7	0.00
	HC	Wet	3-33	Rhyolite		5.0	3.22	100.6	2.4	-98.2	0.02
	HC	Wet	3-09	Breccia		4.4	1.51	47.2	0.2	-47.0	0.00
	HC	Wet	3-26	Breccia		4.3	2.14	66.9	0.0	-66.9	0.00
	HC	Wet	3-34	Breccia		6.9	3.00	93.8	1.5	-92.2	0.02
	HC	Wet	3-02	Argillically Altered Skonun		4.9	4.10	128.1	1.3	-126.8	0.01
	HC	Wet	3-03	Argillically Altered Skonun		3.8	6.08	190.0	0.0	-190.0	0.00
	HC	Wet	3-13	Argillically Altered Skonun		6.5	4.00	125.0	4.0	-121.0	0.03
	HC	Wet	3-24	Argillically Altered Skonun		6.6	4.05	126.6	6.6	-120.0	0.05
	HC	Wet	3-25	Argillically Altered Skonun		7.2	4.83	150.9	7.2	-143.8	0.05

Notes:

1. X in LONG TERM column indicates tests continued for 140 weeks.
2. MPA - Maximum Potential Acidity, NP - Neutralization Potential, NNP=NP-MPA.
3. "-" indicates value not determined for NP<0.

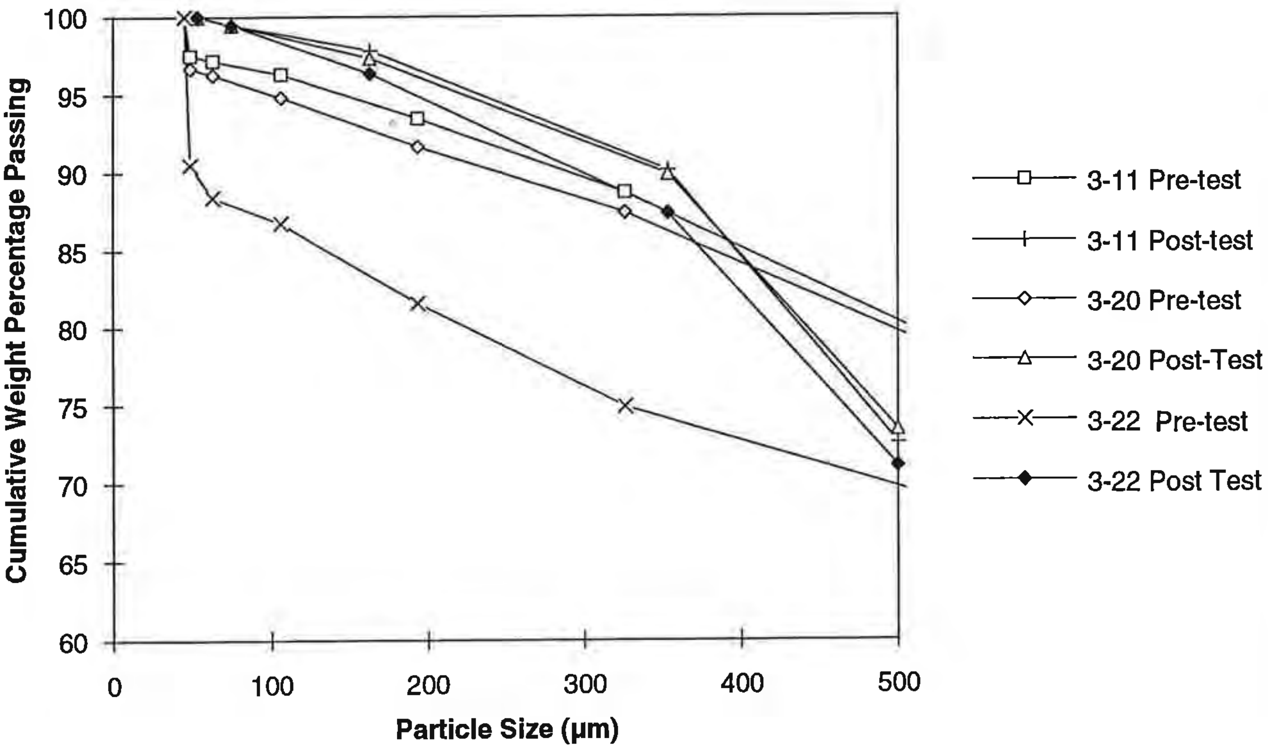

Figure 6-1
PRE- AND POST-TEST
SIZE ANALYSIS
HUMIDITY CELLS

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Particle size distributions were used to estimate the exposed surface area in m^2 per kg of rock, assuming that the rock particles were spherical (Section 4.2.2). The calculated surface areas varied from 5.4 to 48.2 m^2/kg.

6.3 LEACHATE RESULTS

Leachate results are summarized in Figures 6-2 to 6-5. These figures show the following results:

Figure 6-2	Illustrates trends in pH for 20-week humidity cells containing Skonun Sediments. 6-2(a) shows results for samples collected from the waste rock pads and weathered under wet-dry cycles. 6-2(b) shows results for the same samples weathered under continuous moist conditions. 6-2(c) shows results for other samples weathered under continuous moist conditions.
Figure 6-3	Illustrates trends in sulphate loading for 20-week humidity cells containing Skonun Sediments. The separate figures are equivalent to Figure 6-2.
Figure 6-4	Illustrates trends in pH and sulphate for 20-week humidity cells containing Haida Mudstone.
Figure 6-5	Illustrates long term (140 weeks) trends in pH, acidity and sulphate for samples of waste rock pad material weathered under continuous moist conditions ((a), (b) and (c), respectively), and other samples of Skonun sediments and Haida Mudstone ((d), (e) and (f), respectively). The first 20 weeks of (a) and (c) are also shown in Figure 6-2(b) and 6-3(c), respectively. Similarly, the first 20 weeks of (d) and (f) are also shown in Figure 6-4.

Analytical results are also provided on disk in the report pocket.

6.3.1 Indicator Parameters and Major Dissolved Components

Trends in indicator parameters (pH, conductivity, acidity) and major dissolved components (sulphate, alkalinity) can be grouped into three major categories, immediate, delayed and non-acid producers. Characteristic results for these categories are described below.

Category 1 - Immediate Acid Producers

Humidity cells run for this group, which included the majority of Skonun Sediments, rhyolite and argillically-altered Skonun Sediment samples, generated acidic leachate immediately, and continued to do so for the duration of the tests (Figure 6-2). Neutralization potentials were less than 2.5 kg $CaCO_3$/t. Leachate pH's were generally less than 3.0 to 4.0 throughout the tests. Humidity cells containing material from the waste rock pads remained at these levels (Figure 6-2(a)) or increased uniformly (Figure 6-2(b)). In contrast, leachate pH for drill core samples dropped to between 1.9 and 2.4 by the 11th week (Figures 6-2(c) lower lines). By

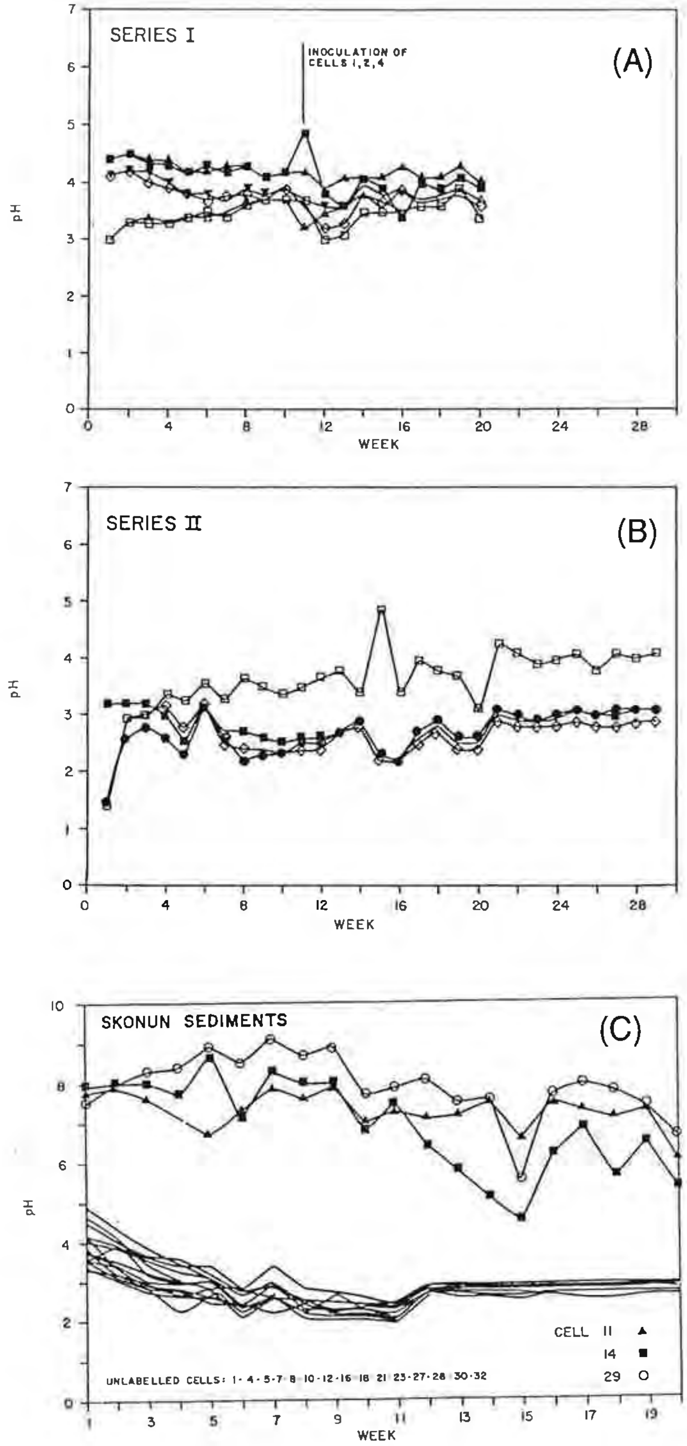

Figure 6-2
pH vs. TIME FOR 20-WEEK HUMIDITY CELLS
CONTAINING SKONUN SEDIMENTS

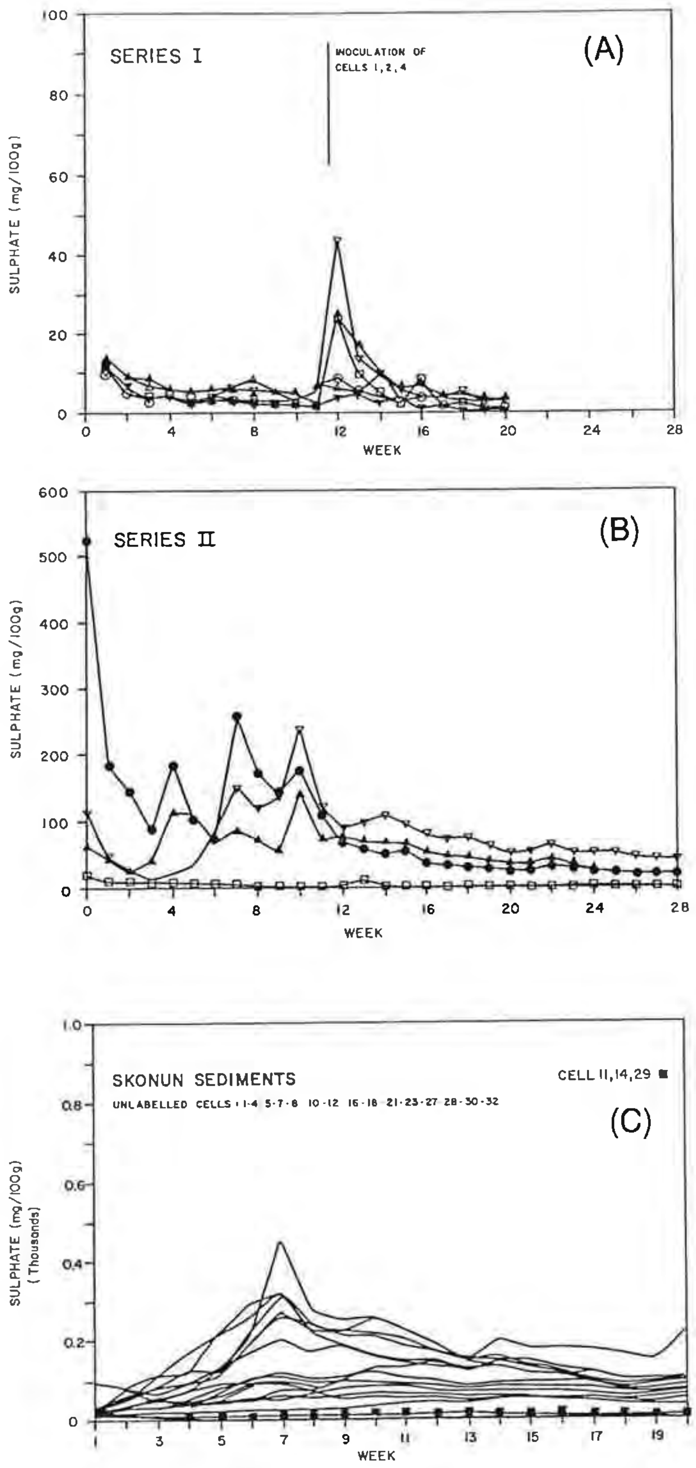

Figure 6-3
SULPHATE vs TIME FOR HUMIDITY CELLS
CONTAINING SKONUN SEDIMENTS

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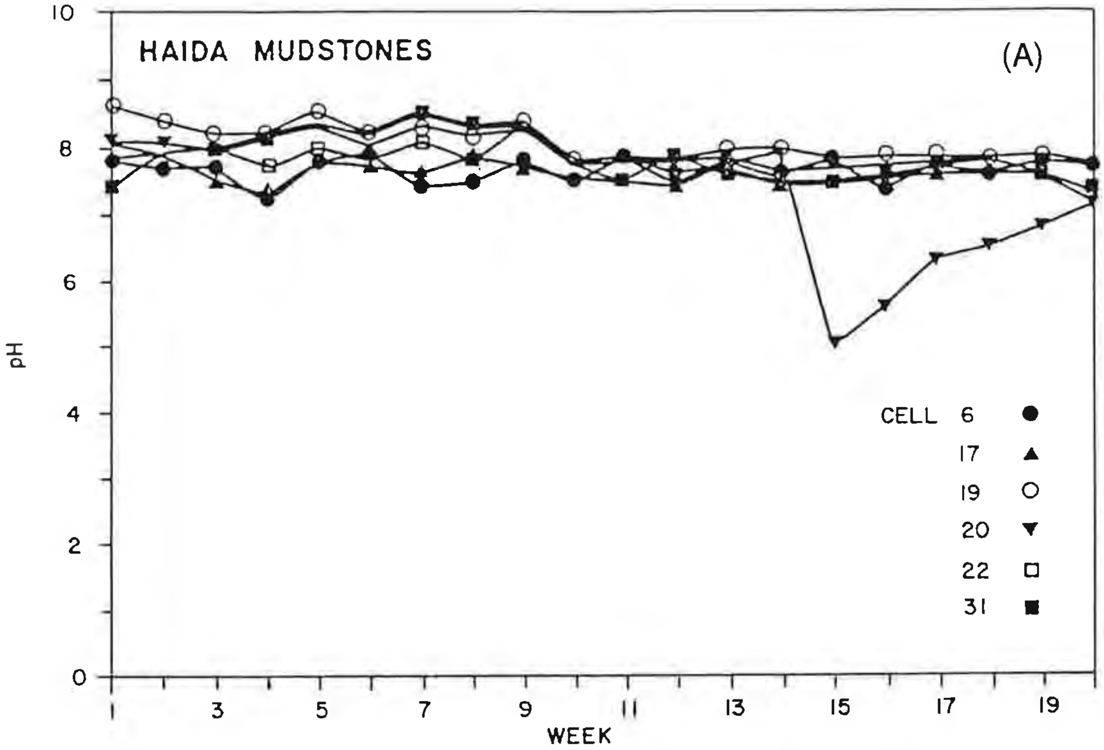

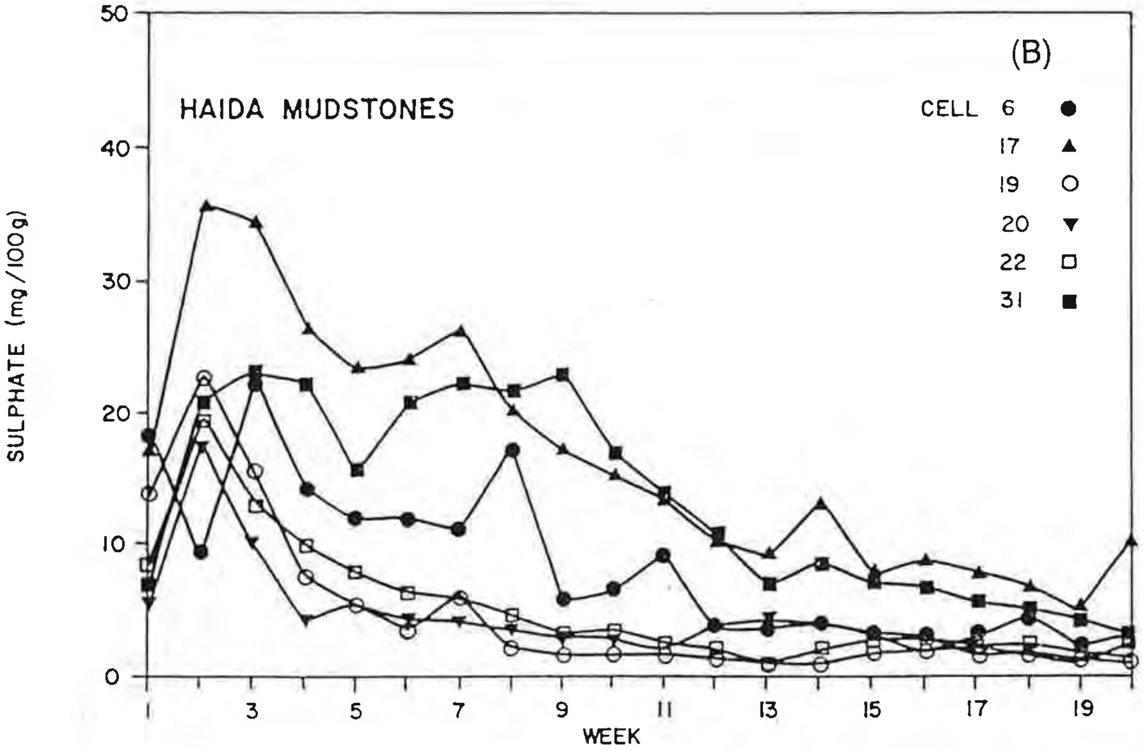

Figure 6-4
SULPHATE & pH vs TIME FOR HUMIDITY CELLS CONTAINING HAIDA MUDSTONE

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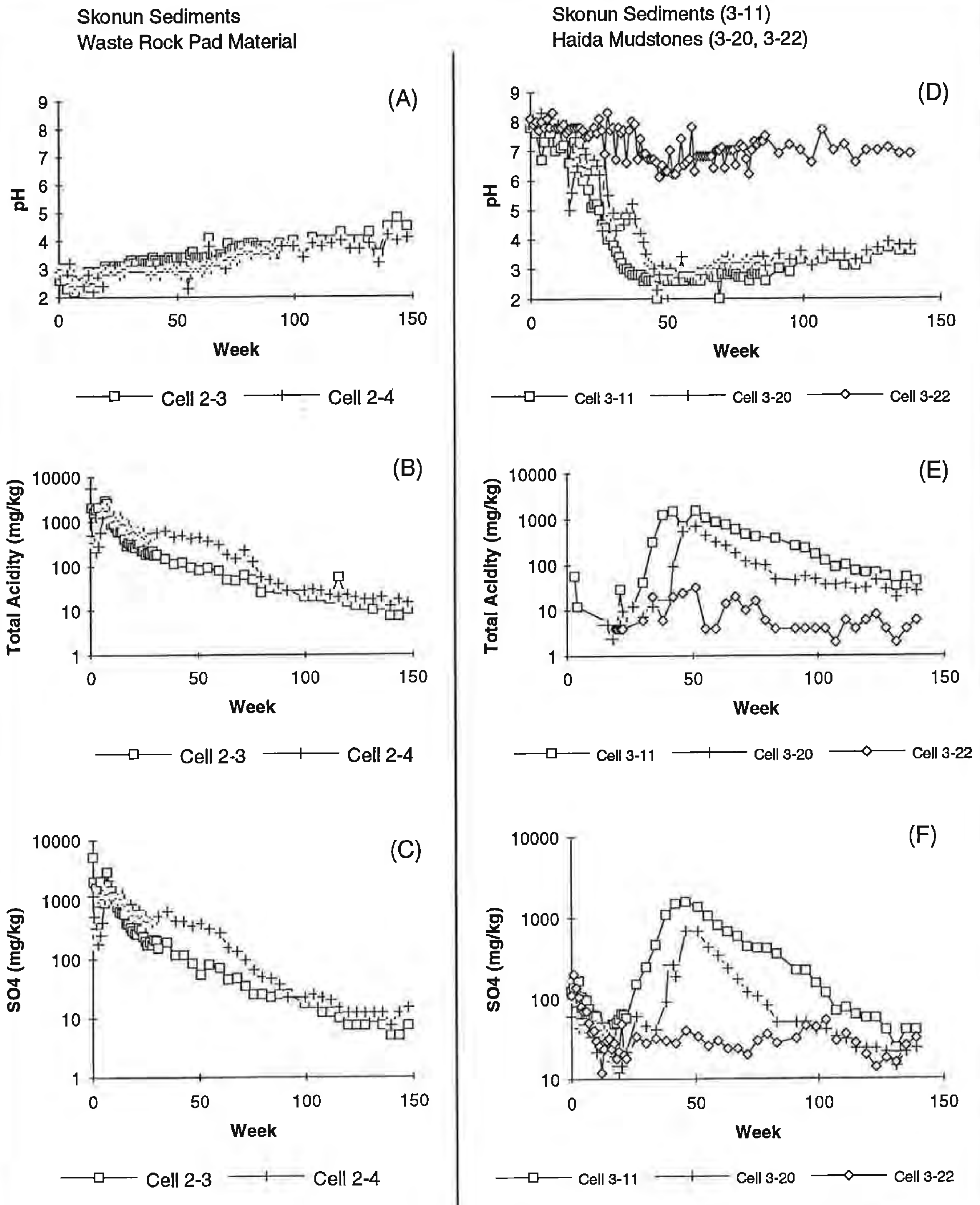

Figure 6-5
RESULTS FOR 140-WEEK
HUMIDITY CELLS

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the 20th week, leachate pH's were constrained to between 2.7 and 2.9. Both sulphate and total acidity concentrations increased to the 7th week and then slowly decreased as available sulphide minerals were consumed (Figures 6-3). These trends continued in the humidity cells operated over 140 weeks (Figure 6-5a,b,c). Leachate pH increased steadily with time due to reduced acid generation and dilution of leachates.

Category 2 - Delayed Acid Producers

Three humidity cells containing potentially acid generating Skonun Formation with NP's greater than 6 kg $CaCO_3$/t did not generate strongly acidic leachate after 20 weeks of weathering (Figure 6-2c, upper lines). However, one of these tests (3-11) was continued and yielded leachate with a pH of 3 by the 40th week (Figure 6-5d; open boxes). For this cell, sulphate and total acidity concentrations peaked between the 50th and 60th weeks, and then decreased exponentially reaching pre-peak concentrations by the 140th week (Figure 6-5e,f).

No samples of potentially acid generating Haida Mudstone produced acidic leachate before week 20. The cell with the lowest NP (3-20, 7 kg $CaCO_3$/t) produced acidic leachate after 14 weeks (Figure 6-4a), then recovered to pH 7 at week 20, but eventually produced strongly acidic leachate after 40 weeks (Figure 6-5d). Thereafter, trends in pH, sulphate and acidity were similar to 3-11. Results for 3-20 were unusual and cannot be explained without data for parameters indicating dissolution of acid-consuming minerals.

Category 3 - Non-Acid Producers

Five Haida Mudstone samples did not generate acidity before being terminated at week 20 (Figure 6-4a). One cell (3-22, Neutralization potential and NP/MPA were 86 kg $CaCO_3$/t and 2.29, respectively) was continued for 140 weeks and continually produced leachate with pH's near 7 (Figure 6-5d). Sulphate concentrations and acidity were relatively constant over this period (Figure 6-5e), and were generally uncorrelated suggesting variations were primarily the result of changes in laboratory conditions.

6.3.2 Minor and Trace Components

Summarized results for these components are not illustrated. Detailed analytical results are provided on the data diskette (in pocket).

Concentrations of dissolved iron, arsenic, copper, mercury and zinc in leachates generally followed similar trends as sulphate and acidity, although concentrations from Category 1 and 2 cells were generally much higher than from cells which did not generate acidic leachate. In Category 3 cells, concentrations of arsenic, copper, mercury and zinc were close to their detection limits of 0.001, 0.05, 0.00005, and 0.03 mg/L, respectively and not correlated with sulphate and acidity. In acidic leachates from Category 1 and 2 cells, concentrations of zinc and arsenic were between 1 and 10 mg/L at peak sulphate production levels. Copper concentrations were between 0.1 and 1 mg/L. The highest arsenic concentrations occurred five weeks later than the peak in zinc.

6.4 RESIDUAL MATERIAL CHARACTERISTICS

Following termination of the cells, acid-base accounts, particle size distributions and petrography were determined for selected residues.

Results of pre- and post-humidity cell acid-base accounts are summarized in Table 6-2. The majority of cell materials showed a drop in total sulphur content, with 140-week cell materials showing the most substantial reduction. The actual reduction is rarely consistent with the expected change as calculated using the sulphate concentrations measured in leachates. This effect is the result of difficulties in obtaining representative results from a small sub-sample of the crushed test material (the "nugget effect") or inaccuracies in the test methods. Neutralization potentials, however, were mostly lower in the post-test materials. The exception was 3-22 (Haida Mudstone) which showed no net change in NP. This material contained occasional fragments of pure calcite leading to a "nugget" effect and resultant sampling variance.

The NP/MPA ratio provides a useful comparison of the different cells. The ratio increased for cells which were not expected to generate acid (based on ABA) and decreased for those which actually generated acid (in humidity cells). This makes sense, theoretically, as NP/MPA would approach infinity for acid consuming rock (as MPA is consumed first and approaches zero), and decreases to zero for acid generating rock (as NP is consumed first and approaches zero). This could be a useful tool for early detection of acid generating materials. However, it would only be useful if a high proportion of the sulphur and neutralization potential is available for reaction.

Post-test size fraction analysis results for materials from cells 3-11, 3-20 and 3-22, weathered for 140 weeks, indicate loss of fines particles during the course of the experiments (Figure 6-1). This could result from preferential oxidation and leaching of finer particles, and/or the slow loss of fines during rock washing, centrifuging and filtration. The latter explanation is more likely.

Rock samples weathered for 20 weeks in humidity cells showed no evidence of oxidation in polished thin section (see Appendix C for Petrographic Reports). For example, pyrite grains did not show any evidence of oxidation rims. However, abundant evidence of oxidation was observed in waste rock pads weathered for 140 weeks. Smaller pyrite grains were completely oxidized, whereas larger grains showed 10 to 20 µm rims of limonite. Based on orange internal reflections, the limonite is primarily geothite with some hematite (red internal reflections). Rock samples weathered for 20 weeks showed weaker development of limonite. Limonite was present as rims on fragments and in fractures. Pyrite in the interior of rock fragments was unweathered.

TABLE 6-2
ACID-BASE ACCOUNTING RESULTS FROM BEFORE AND AFTER HUMIDITY CELL TESTS AND COMPARISON OF SULPHATE PRODUCTION

WASTE ROCK GROUP	HUMIDITY CELL NUMBER	POWDER pH		TOTAL SULPHUR (%)		NEUTRALIZATION POTENTIAL (kg CaCO3/t)		CUMULATIVE SULPHUR LOST (%)		NP/MPA (4)	
		PRE-TEST	POST-TEST	PRE-TEST	POST-TEST	PRE-TEST	POST-TEST	CALCULATED (1)	OBSERVED(2)	PRE-TEST	POST-TEST
20 WEEKS											
Haida Mudstone	3-19	8.4	8.2	0.872	0.710	49.40	49.32	0.16	0.033	1.81	2.22
Skonun Sediments	3-23	5.1	4.5	3.84	3.11	-1.89	-0.87	0.73	1.23	-	-
	3-14	7.7	7.6	2.61	2.30	13.40	6.12	0.31	0.11	0.16	0.09
	3-5	4.7	4.2	0.839	0.531	0.50	0.27	0.31	0.384	0.02	0.02
Rhyolite	3-33	5.0	3.7	3.22	2.97	2.39	-0.27	0.25	0.57	0.02	-
Breccia	3-26	4.3	3.9	2.14	1.13	0.01	-1.55	1.01	0.79	<0.01	-
Argillically Altered Skonun Sediments	3-13	6.5	-	4.00	5.01	3.99	0.89	-1.01	1.88	0.03	0.01
140 WEEKS											
Haida Mudstone	3-20	7.7	4.3	1.15	0.521	7	-2	0.63	-	0.19	-
	3-22	8.1	6.9	1.21	0.902	86	86	0.31	-	2.27	3.05
Skonun Sediments	2-4	3.7	5.5	1.66	0.224	-1	-1	1.44	-	-	-
Breccia	3-11	7.7	5.0	2.53	0.532	6	0	2.00	-	0.08	-
Argillically Altered Skonun Sediments	2-3	2.6	4.5	2.59	0.645	-21	-1	1.95	-	-	-

Notes:

1. This value is calculated as (pre-test total sulphur) - (post-test total sulphur).
2. This value is calculated from sulphur concentrations in humidity cell leachates.
3. "-" indicates data are not available to calculate the value.
4. NP/MPA is not calculated for NP<0.

6.5 DISCUSSION

6.5.1 Stages of Oxidation and Leaching

For the most part, the humidity cell results concurred with observations previously documented for other projects (Ferguson and Morin 1991). Stages of oxidation and leaching were observed in the cells as follows:

- **Stage 1 - Neutral Leachate.** In this stage, sulphide oxidation was relatively slow as neutralizing minerals consumed acid at the same rate it was produced, maintaining pH neutral conditions. Sulphate concentrations were initially elevated and pH initially depressed as acidic weathering products accumulated during sample storage were leached out over the first weeks. Alternatively, this may have represented the rapid oxidation of very fine sulphide mineral particles. The duration of this pH-neutral leachate stage probably depended on a number of factors such as amount, availability and type of neutralizing minerals, degree of weathering during storage, and reactivity of sulphide minerals. The results suggested that if NP was low it would be depleted disportionately rapidly. For example, in Category 2 cells (delayed acid producers), NP depletion was at least half as slow as in Category 1 cells (immediate acid producers). It is likely that a quantity of NP (less than 2.5 kg $CaCO_3$/t) in Skonun Formation rocks did not represent reactive carbonate minerals but clay and mica alteration products (primarily kaolinite and illite). Higher NP's determined for some Skonun Formation rocks and Haida Mudstone more likely represented carbonate minerals, such as calcite, as observed in petrographic studies. This showed that a portion of the NP does not readily neutralize acid.

  In this stage, leaching of heavy metals was slow due to the formation of weakly soluble hydroxides and carbonates.

- **Stage 2 - Acidic Leachate and Sulphate Production Rapidly Increasing.** Once readily available neutralizing minerals were consumed, pH dropped rapidly allowing bacterial populations to increase, and sulphate production increased. This stage generally lasted 5 to 10 weeks in the Cinola humidity cells. Accelerated metal leaching was correlated with the onset of acidic conditions and sulphate concentrations in the leachate.

- **Stage 3 - Acidic Leachate and Sulphate Production Decreasing.** Once fully acidic conditions developed and bacterial populations reached the optimal conditions for growth, sulphate production decreased as the availability of pyrite decreased. Sulphate production steadily declined as sulphide mineral grains shrank and were replaced by goethite. Leachate pH also slowly increased at the same time as acidic components in the leachate were diluted.

A theoretical fourth stage is possible during which leachate chemistry was no longer significantly controlled by sulphide oxidation. During this stage, leachate chemistry would have been buffered by dissolution of remaining rock components. Since iron hydroxides would probably be abundant, pH values would remain near 3. As the iron hydroxides mature due to dehydration and crystallization, their solubility would decrease and their control on pH diminishes. The fourth stage would therefore be transitional to a condition in which the rock mass became relatively inert and leachate pH rose close to the pH of the deionized water. Any dissolved components would therefore reflect dissolution of residual silicate minerals.

6.5.2 Sulphate Release Rates

City Resources (1988, Volume V) calculated sulphate release rates on the basis of mass (in mg SO_4/100 g/week) and surface area (in mg SO_4/m^2/week) for the first 20 weeks of experiments. The mass calculation was used to correct for differences in the mass of material placed in the cells. The surface area approach was investigated to allow for differences in particle size distribution. It is generally accepted that reactive surface area is an important consideration in calculating acid generation rates. Rates for Stage 1, and Stage 2 and 3, were determined separately. A detailed tabulation and evaluation of sulphate release rates under different conditions in comparison to other types of kinetic tests is presented in Section 9.3.

Sulphate release rates for cells operated on wet-dry cycles were less than for cells operated with continuous moist air by almost an order of magnitude. The difference may be attributed to formation of less soluble iron hydroxide coatings on sulphide grains during the dry cycle.

Sulphate release rates calculated based on areas varied over a smaller range than rates calculated on an mass basis. Average area-based rates for Skonun Formation in Stages 2 and 3 varied from 83 to 150 mg SO_4/m^2/week, whereas mass-based rates varied from 100 to 2600 mg SO_4/kg/week. This supports the use of the area-based sulphate release rates since the effect of different particle sizes is reduced.

Average Stage 1 (see Section 6.5.1) rates are lower than average Stage 2 and 3 rates by roughly an order of magnitude. This result was expected since oxidation is abiological at this stage. Haida Mudstone yielded lower average Stage 1 rates than Skonun Formation rocks (4.2 and 11 mg SO_4/m^2/week, respectively).

Average Stage 2 and 3 rates of 87 mg SO_4/m^2/week were measured for both unaltered and argillically-altered Skonun Formation rock. Breccia and rhyolite samples yielded the highest rates at 120 and 150 mg SO_4/m^2/week.

7.0 LONG TERM WEATHERING TRENDS WASTE ROCK PAD STUDY

Four 20 to 30 tonne waste rock pads were constructed in February 1987 at the Cinola Project Site with the specific objective of determining acid generation and metal leaching rates under site conditions. One pad was constructed from rock removed from the exploration adit in 1982. The study was continued after City Resources ceased mine feasibility studies because of the low maintenance costs and because this was one of the few sites with such a study. The pads presented an opportunity to monitor acid generation trends over a long period, and review the reliability of sulphide oxidation predictions developed by City Resources after one year of monitoring. The data produced were expected to provide insight into the duration of significant acid generation and metal leaching, seasonal variation of leachate quality, and the applicability of short-term laboratory tests to characterizing long-term natural processes.

7.1 TEST MATERIAL CHARACTERISTICS

All pads were constructed from Skonun Sediments. Pad 1 contained five-year weathered silicified Skonun Sediments. Pad 2 contained freshly-blasted silicified Skonun Sediments. Pad 3 contained argillically-altered Skonun Sediments. Pad 4 contained brecciated Skonun Sediments. The pads are approximately 8 m x 8 m and 1.2 m high (Figure 4-3), except for Pad 1 which is less than 1 m high.

Acid-base accounts for pad rock determined in February 1987 are summarized in Table 7-1. ABA predicted that rock in all four pads would be acid-generating. Neutralization potentials were extremely low and probably did not represent carbonates but slowly reactive kaolonite and illite hydrothermal alteration products. The negative neutralization potential of material on Pad 3 indicated that this rock contained soluble minerals which generate low pH water when dissolved.

The inert quartz sand used to line the bottom of the pads contained negligible sulphur (0.003%) and had a neutralization potential of 3.6 kg $CaCO_3$/t. This neutralization potential is considered insignificant and reflects small quantities of minerals, such as micas, included in the sand.

Particle size analysis was used to estimate the exposed surface area of all particles on a weight basis. Pads 1, 3, and 4 had exposed areas ranging from 1.81 to 2.00 m^2/kg of rock (Table 7-1). The exposed area of Pad 2 was significantly lower at 1.07 m^2/kg, perhaps because this rock is competent (resists breaking) due to silicification and was not previously weathered. Multiplication of total sulphur concentrations and exposed particle area yields a factor (in m^2-%S/kg) which gives an indication of the exposure of sulphur on grain surfaces (Table 7-1). Pad 3 combined greatest exposed area and sulphur content and therefore had almost double the amount of exposed sulphur compared with unweathered rock in Pads 2 and 4. Waste rock in Pad 2 had a greater total sulphur content than rock in Pad 4, but was coarser. Pads 2 and 4 therefore had comparable sulphur exposure factors and would therefore

TABLE 7-1
WASTE ROCK PAD ACID-BASE ACCOUNTING

PARAMETER	BOTTOM SAND	PAD 1 Five-year Weathered Silicified Skonun Sediments	PAD 2 Silicified Skonun Sediments	PAD 3 Argillically-Altered Skonun Sediments	PAD 4 Brecciated Skonun Sediments
Quantity of Waste Rock (t)	10	20	30	30	30
Total S (%)	0.003	1.95	2.96	3.06	1.75
Maximum Potential Acidity (kg CaCO3/t)	0.1	60.9	92.5	95.6	54.7
Neutralization Potential (kg CaCO3/t)	3.6	2.2	3.1	-6.4	0.7
Powder pH	7.8	5.3	7.2	3.5	7.1
NP - MPA (1, 2)	3.5	-58.7	-89.4	-102.0	-54.0
NP/MPA (1,2)	38.40	0.04	0.03	-	0.01
Grain Surface Area (m2/kg) (3)	No data	1.81	1.07	2.00	1.92
Area x Total S (m2 - S%/kg) (3)	No data	3.5	3.2	6.1	3.4

Notes:

1. MPA - Maximum Potential Acidity
2. NP - Neutralization Potential
3. A particle size distribution was not determined for the bottom sand.

be expected to yield similar sulphate production rates if only the sulphide grains on particle surface were oxidizing. Although Pad 1 yielded a similar sulphur exposure factor to Pads 2 and 4, this rock had been weathered for five years prior to being placed in the pads. Results from this pad were therefore expected to differ from the others.

7.2 DESCRIPTION OF LEACHATE RESULTS

All leachate results are provided on a diskette in the report pocket.

7.2.1 Indicator Parameters and Major Ions

pH

In the first year of monitoring, leachate pH (Figure 7-1) dropped rapidly from initial levels near 7 to less than 3 for pads 2 and 4 (freshly blasted rock) and less than 5 for Pad 1 (five-year weathered rock) reflecting the almost complete absence of acid-neutralizing minerals. Pad 3 leachate pH began at less than 3.0. In the first year, leachate pH from Pads 2, 3 and 4 decreased to 1.5 (September 1987) increased sharply through the fall and peaked at near 3 in late December. A similar, though less pronounced trend, was observed for Pad 1. Leachate pH for all pads then dropped again in mid-1988, immediately increased, and appeared to be decreasing again in the fall of 1988 before monitoring was terminated. During the period of renewed monitoring, pH of leachate was the same or slightly higher that the levels measured in 1987 and 1988. Leachate pH reached a low point in June 1991, and then increased through the summer and fall. Decreasing pH values were again observed in early 1992. In summary, pH-trends showed seasonal effects, that is, pH tended to decrease in the late summer and increase during the winter. Based on 1991 and 1992 data, it is also appeared that, for the highly acidic pads, pH increased.

Sulphate

Conductivity correlated strongly with the sulphate content of the various leachate solutions from all four pads, indicating that sulphate was the dominant ion in solution.

Annual fluctuations in sulphate levels (Figure 7-2) were noted with concentration increases through the spring/summer and reaching a sharp peak in the early autumn. They then decreased rapidly reaching lowest concentrations in late December. This condition persisted through the winter until concentrations increased again in the Spring.

General changes in sulphate concentration can be explained by accumulation of acid weathering products in the drier summer months, rapid flushing with increased precipitation in the fall and dilution of acid leachate through the wet winter months.

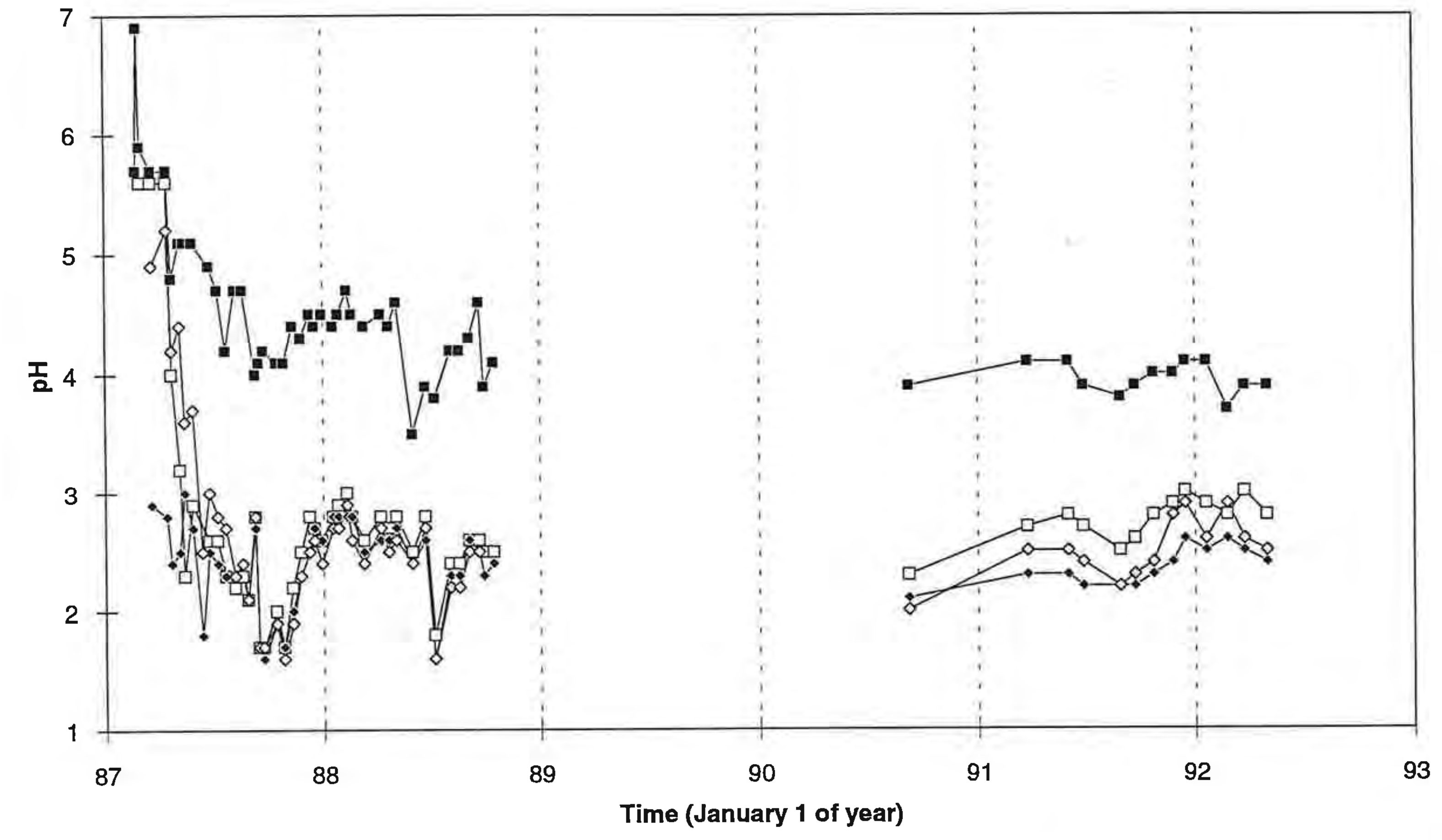

Figure 7-1
WASTE ROCK PADS
pH LEVELS IN LEACHATE

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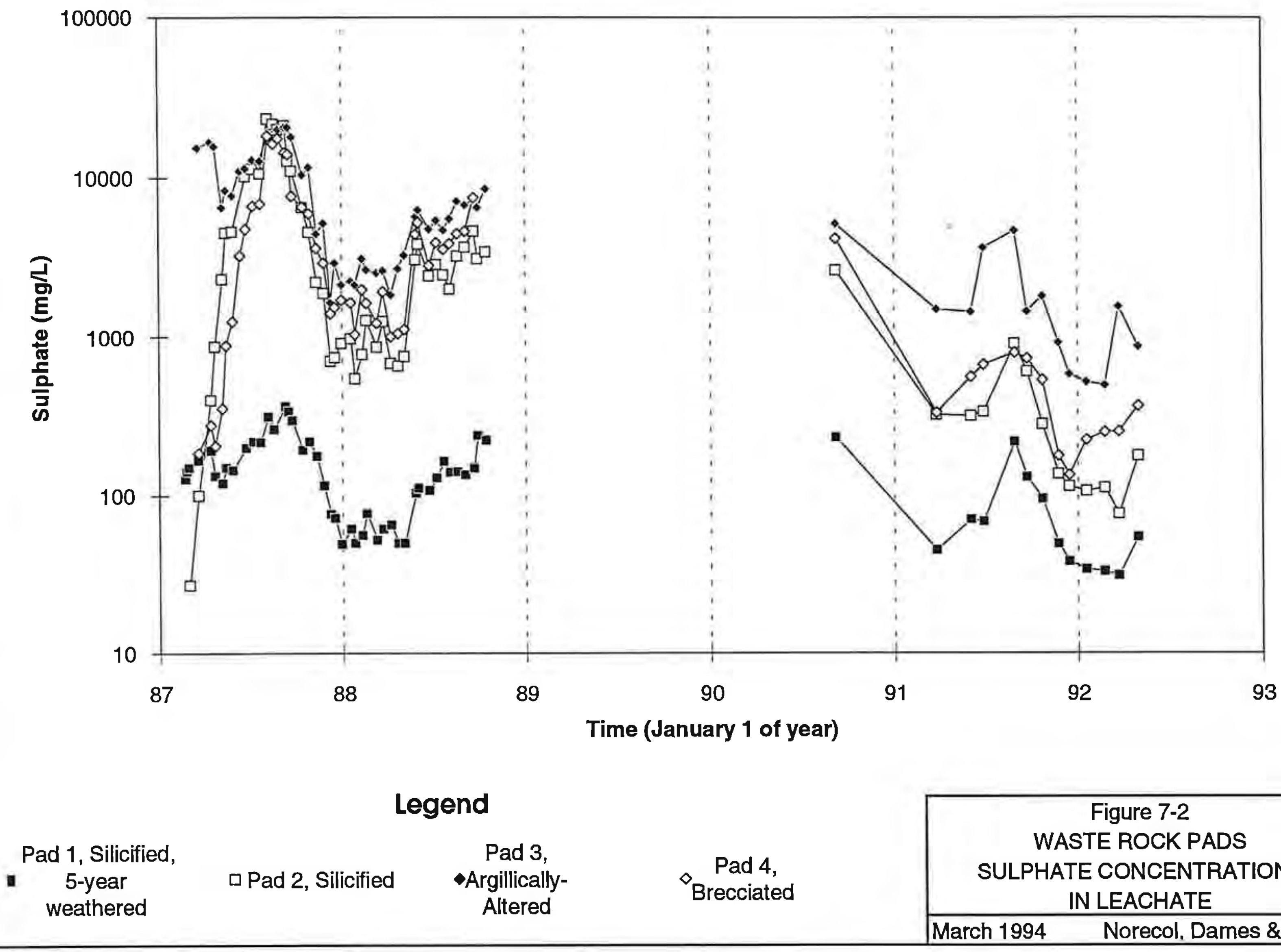

Figure 7-2
WASTE ROCK PADS
SULPHATE CONCENTRATIONS
IN LEACHATE

March 1994 Norecol, Dames & Moore

Sulphate losses were greatest in Pad 3, similar in Pads 2 and 4 and lowest in Pad 1. Sulphate concentrations in leachates from all four pads have decreased since the tests were begun. Comparison of sulphate concentrations in the late fall and winter of 1988, 1991 and 1992 indicates that sulphate concentrations dropped to their lowest recorded levels in 1992.

Total Acidity

Total acidity measures the total concentration of species in solution capable of consuming dissolved alkalinity. These species include H^+, HSO_4^-, Al^{3+} and Fe^{3+}. Acidity is determined by titrating the pad leachate with an alkaline solution of known strength. The titration is continued until the pH of the leachate reaches 8.4. Acidity required to be neutralized to reach pH 4.5 was also determined but is not reported here.

As would be expected, the acidity of pad leachate was very strongly positively correlated with sulphate concentrations. For example, acidity increased during spring and summer, peaked in early fall and then dropped rapidly to low levels in winter (Figure 7-3). Like sulphate, acidity levels decreased over the five years of testing.

Calcium

Calcium was the only consistently measured parameter which indicated the rate of leaching of acid-consuming minerals. Other possible indicators of acid consumption (magnesium, aluminium, potassium and sodium) were added to the list of metals determined in the leachates, but insufficient data are available to recognize trends.

Seasonal changes in leachate calcium concentrations in leachates (Figure 7-4) paralleled the trends in parameters related to acid generation (sulphate, acidity). Release of calcium was greatest in September, though the peaks were not as well-defined as similar peaks for sulphate and acidity, particularly for Pad 3.

7.2.2 Minor and Trace Components

Dissolved concentrations of arsenic and several heavy metals (iron, copper, zinc) were determined throughout the monitoring program. Changes in iron concentrations were strongly correlated with sulphate for the three pads constructed of freshly blasted rock (Pads 2, 3 and 4) (Figure 7-5). After initially increasing rapidly from close to the detection limit concentration of 0.1 mg/L, iron concentrations in these pads followed the same distinctive seasonal cycle observed for other parameters. Iron concentrations in leachate from Pad 1 were much lower and at times not detectable. During the period of recent monitoring, iron concentrations were very erratic.

Copper concentrations in leachate (Figure 7-6) showed a strong correlation with iron, acidity and sulphate for Pads 2, 3 and 4, and, on average, steadily decreased with time. In comparison, copper concentrations in leachate from Pad 1 steadily increased with time and showed well-defined seasonal trends in 1991, comparable to the other pads. Copper

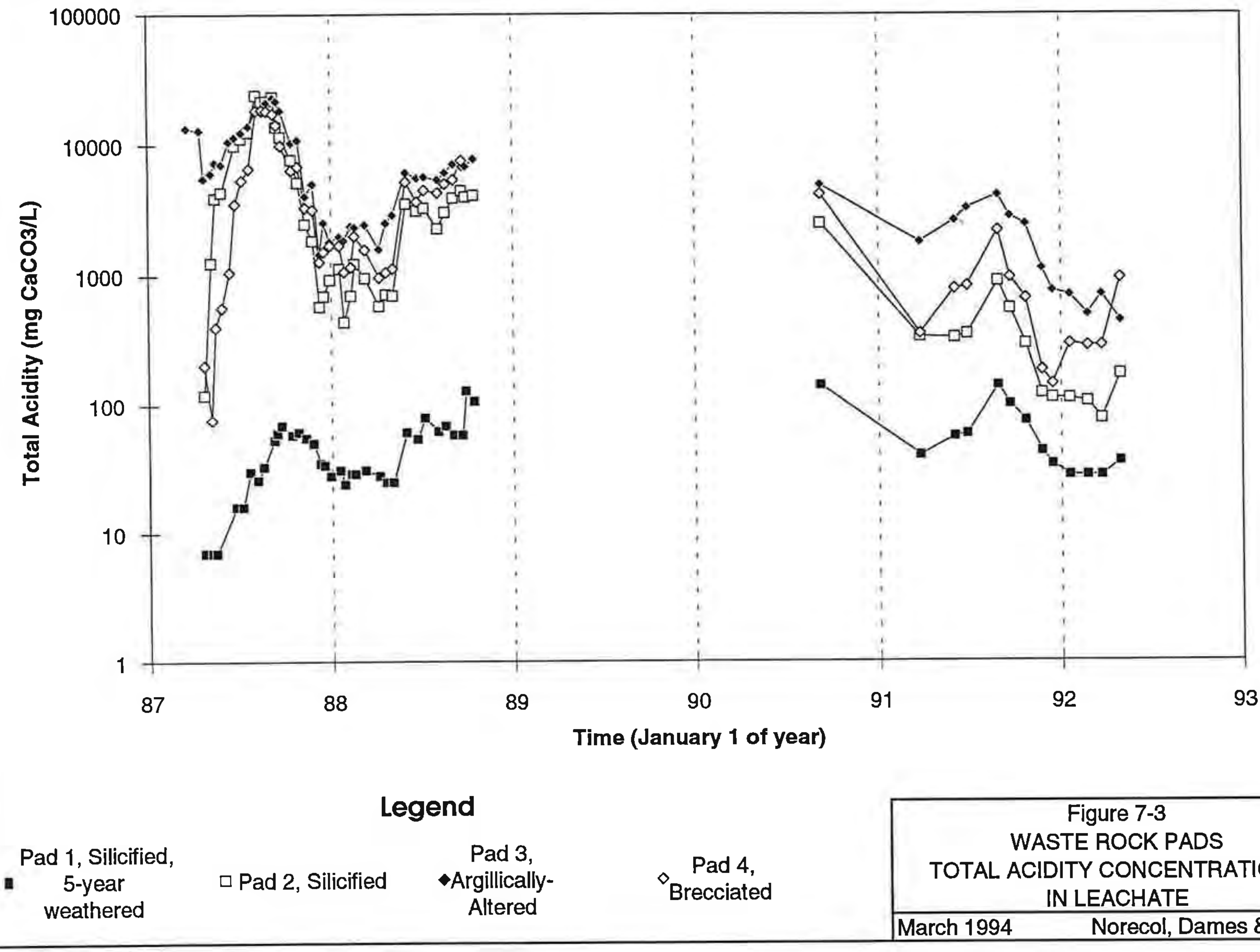

Figure 7-3
WASTE ROCK PADS
TOTAL ACIDITY CONCENTRATIONS
IN LEACHATE

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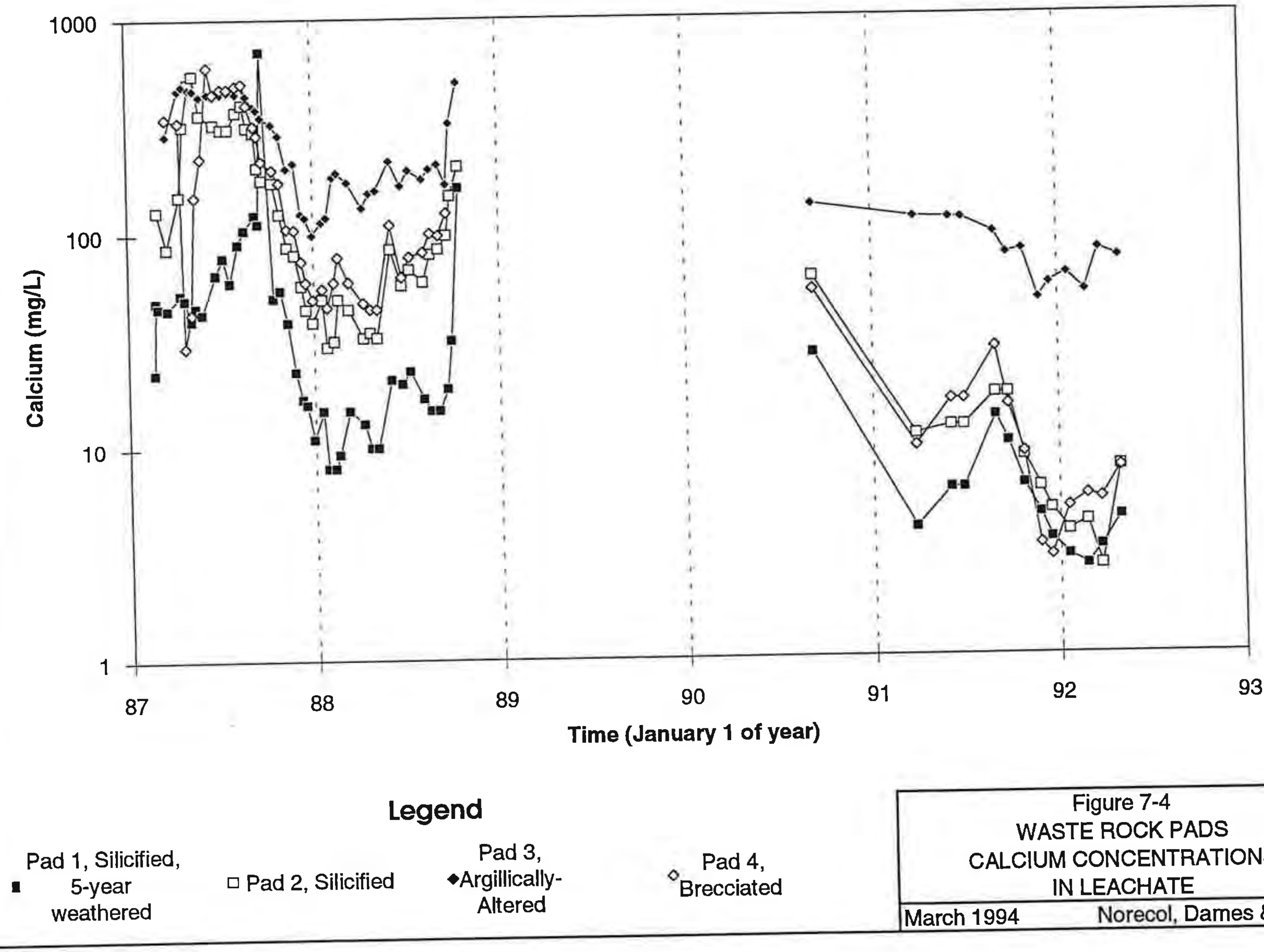

Figure 7-4
WASTE ROCK PADS
CALCIUM CONCENTRATIONS
IN LEACHATE

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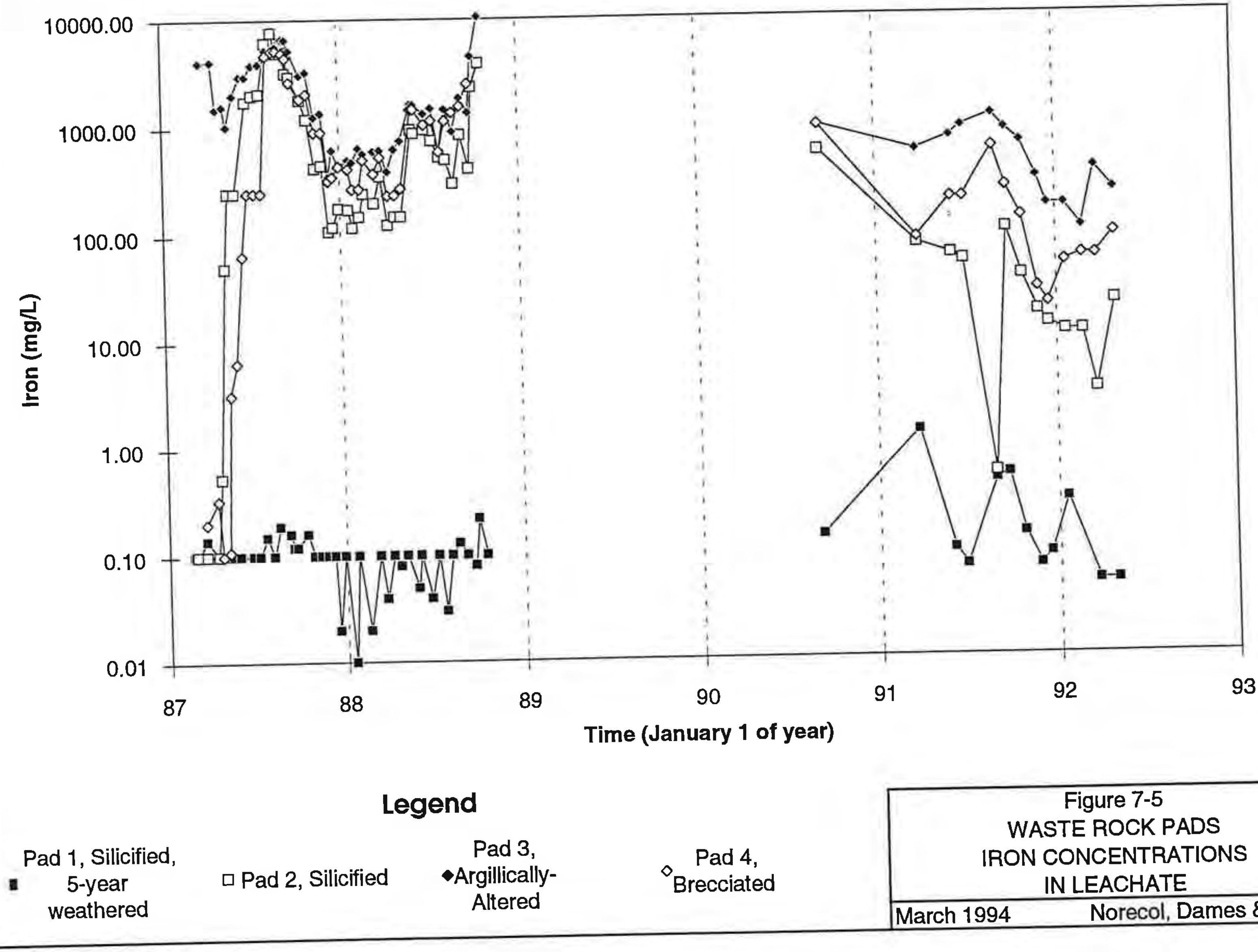

Figure 7-5
WASTE ROCK PADS
IRON CONCENTRATIONS
IN LEACHATE

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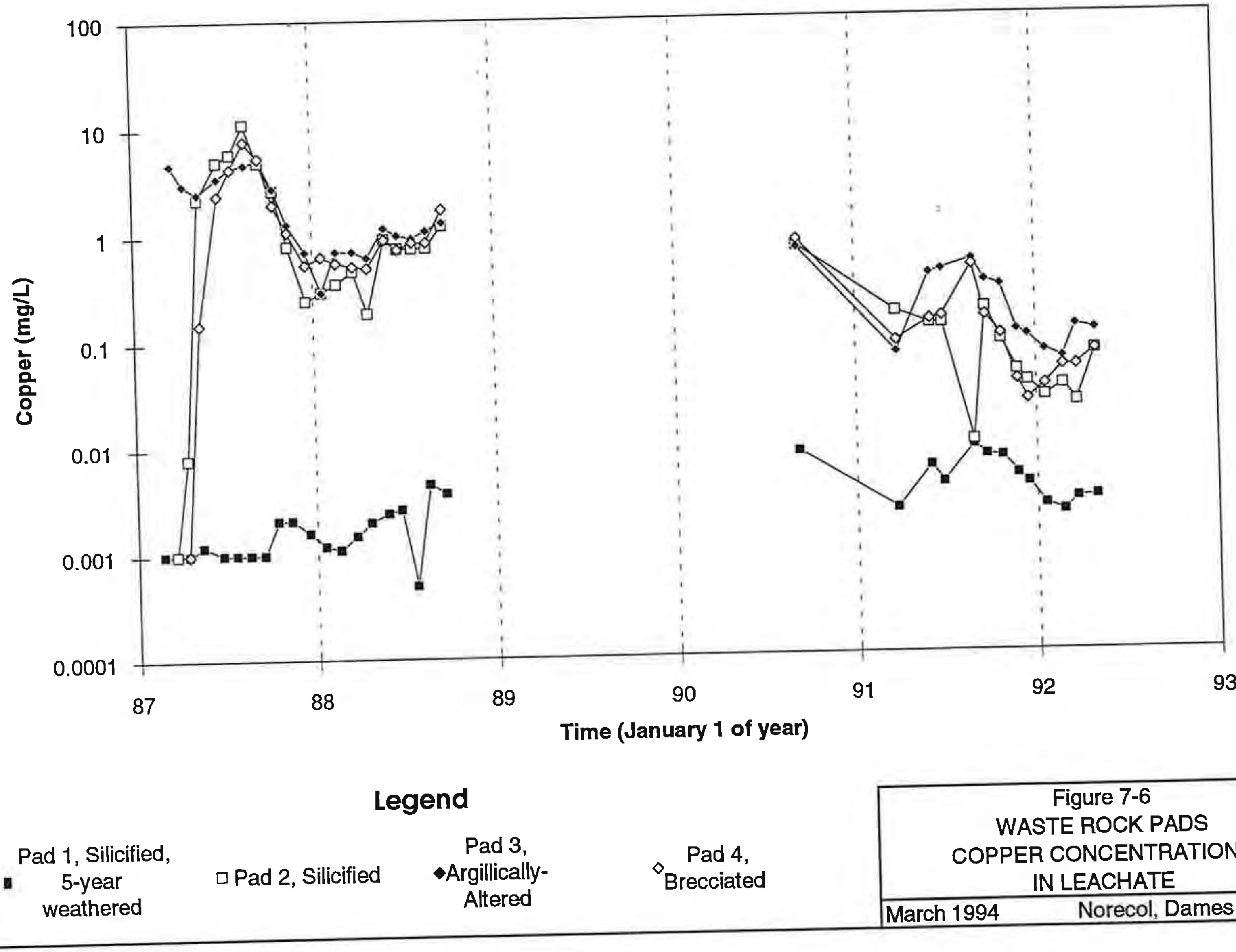

Figure 7-6
WASTE ROCK PADS
COPPER CONCENTRATIONS
IN LEACHATE

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concentrations for pads 2, 3 and 4 did not show the same magnitude differences as observed for sulphate.

Zinc concentrations were slightly greater than copper, and less variable, although the seasonal variations were still apparent (Figure 7-7). Zinc concentrations tended to decrease more rapidly than copper for Pads 2, 3 and 4; however, zinc concentrations in leachate from Pad 1 remained near 0.1 mg/L.

In 1987 and 1988, arsenic concentrations followed a similar seasonal trend as the heavy metals; Pads 2, 3, and 4 showed very similar trends and concentrations (Figure 7-8). From 1990 to 1991, Pads 2, 3 and 4 arsenic concentrations continued to be well correlated, although there were clear differences in the level of arsenic (Pad 3 greater than Pad 4, which was greater than Pad 2) and the overall levels decreased for all three pads. Arsenic in Pad 1 leachate was close to the detection limit, except for seasonal spikes in September of each year.

7.3 RESIDUE CHARACTERISTICS - PAD 2

Pad 2 waste rock residues were selected for sampling and analyses due to the similarity with the leach column materials. The sampling and profile descriptions were conducted on June 9, 1993. The 115 cm deep profile was excavated on one corner of the pad (Figure 7-9).

7.3.1 Macroscopic Characteristics

Waste rock exposed in the profile was primarily grey and structureless. The only features observed were a series of dark brown cemented sub-horizontal lenses typically 5 to 13 cm thick (Figure 7-9) and light yellow brown 5 cm mottles were present within the predominantly grey layers. The profile description is summarized in Table 7-2.

Sulphide mineral grains were not observed in the rock, nor was carbonate detected by a fizz reaction with 10% hydrochloric acid.

7.3.2 Microscopic Features

The majority of waste rock particles contained the common silicate minerals that dominate the Cinola deposit host rocks. These particles had not been obviously altered or corroded by acidic pore water. A few small euhedral pyrite particles were observed within silicate grains (Figure 7-10). Pyrite particles at grain margins had been partly or completely replaced in-situ by geothite. In one instance, intricate intergrowths of pyrite and geothite were observed (Figure 7-11) indicating that the goethite had formed by direct replacement. Goethite pseudomorphs after pyrite were also observed.

Rock fragments from the brown cemented layers were smaller that those in other parts of the profile. The cement was limonite formed by deposition of iron transported from nearby sulphide oxidation sites.

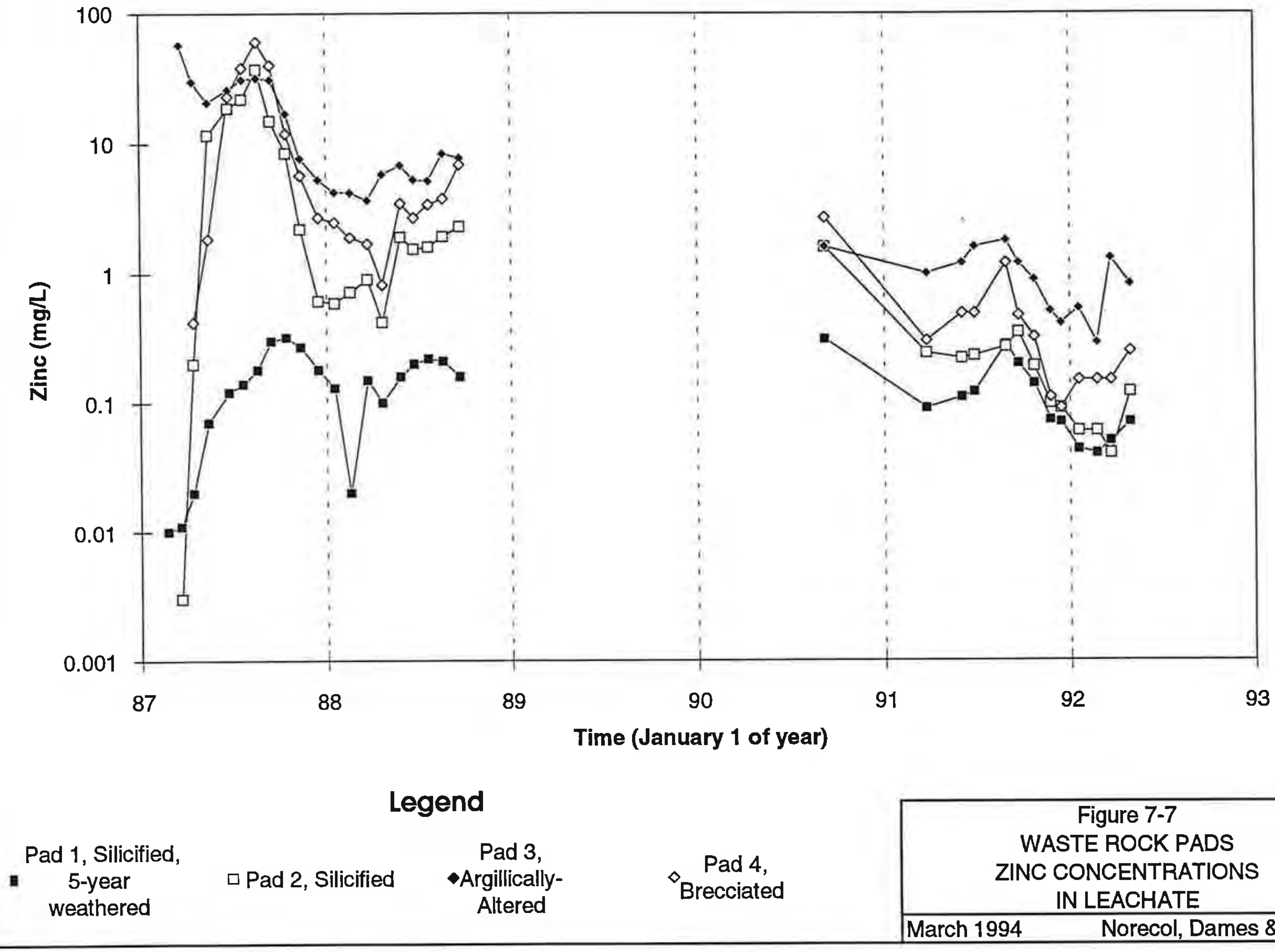

Figure 7-7
WASTE ROCK PADS
ZINC CONCENTRATIONS
IN LEACHATE

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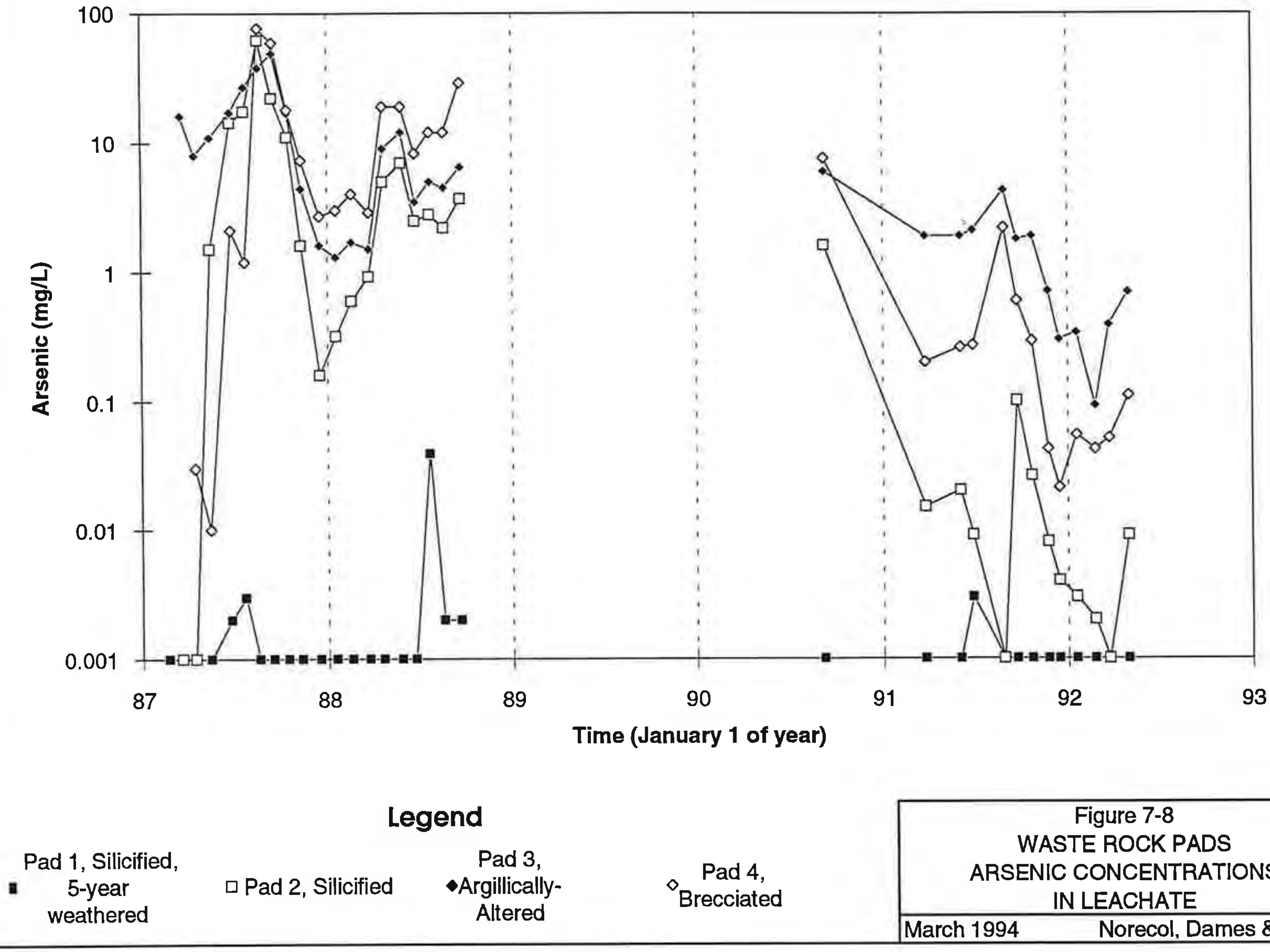

Figure 7-8
WASTE ROCK PADS
ARSENIC CONCENTRATIONS
IN LEACHATE

March 1994 Norecol, Dames & Moore

Figure 7-9 Cross-section of Pad 2 in June 1993. Note discontinuous orange layering (indicated). Spade is about 1.6 m long.

TABLE 7-2
PAD 2 PROFILE AND RESIDUE ACID-BASE ACCOUNTING

SAMPLE NUMBER	DEPTH	DESCRIPTION	RESIDUE pH	POWDER pH	TOTAL SULPHUR (%)	SULPHIDE SULPHUR (%)	MPA	NP
							(kg CaCO3/t)	
1.	0 - 5 cm	10 YR 4/3 m (dark brown). Surface covering, varied from 2 to 7 cm deep, deepest in dry areas under stones.	2.27	-	-	-	-	-
2.	5 - 35 cm	5 Y 5/2 m (grey); plus small discrete areas 5 cm in diameter, 2.5 Y 6/4 (light yellow brown) covering 5% of the total.	2.00	4.6	0.43	0.33	10.3	-6.3
3.	30 - 35 cm	7.5 YR 4/4 (dark brown) to 10 YR 6/6 (brown yellow). Roughly horizontal lense, inclined at approximately 5 degrees; up to 7 cm deep; intermittent, covers 25% of the 30 to 35 cm depth; strongly cemented fine matrix including gravel and small stones.	2.58	4.0	0.37	0.21	6.6	-11.1
4.	35 - 55 cm	10 YR 6/1 (grey); plus 5% 2.5 Y 6/4 (light yellow brown).	2.45	-	-	-	-	-
5.	45 - 52 cm	7.5 YR 4/4 (dark brown) to 10 YR 6/6 (brown yellow). Like sample #3, strongly cemented and intermittent but smaller, covering 10% of the 45 to 52 cm depth and less planar.	1.97	-	-	-	-	-
6.	55 - 75 cm	2.5 Y 6/2 (light olive brown).	1.98	-	-	-	-	-
7.	75 - 115 cm	10 YR 6/1 (grey); plus local 5 Y 7/4 (pale yellow) staining along surface of stones.	1.94	5.3	0.66	0.60	18.8	2.5
8.	62 - 75 cm	As per sample #5, except smaller, covering 5% of the 62 to 75 cm depth.	1.99	-	-	-	-	-

NOTES:
1. Sampled on June 9, 1993 during heavy rain.
2. ABA determined on pulverized rock finer than 1 cm.
3. "-" indicates samples were collected but not analyzed for all parameters.

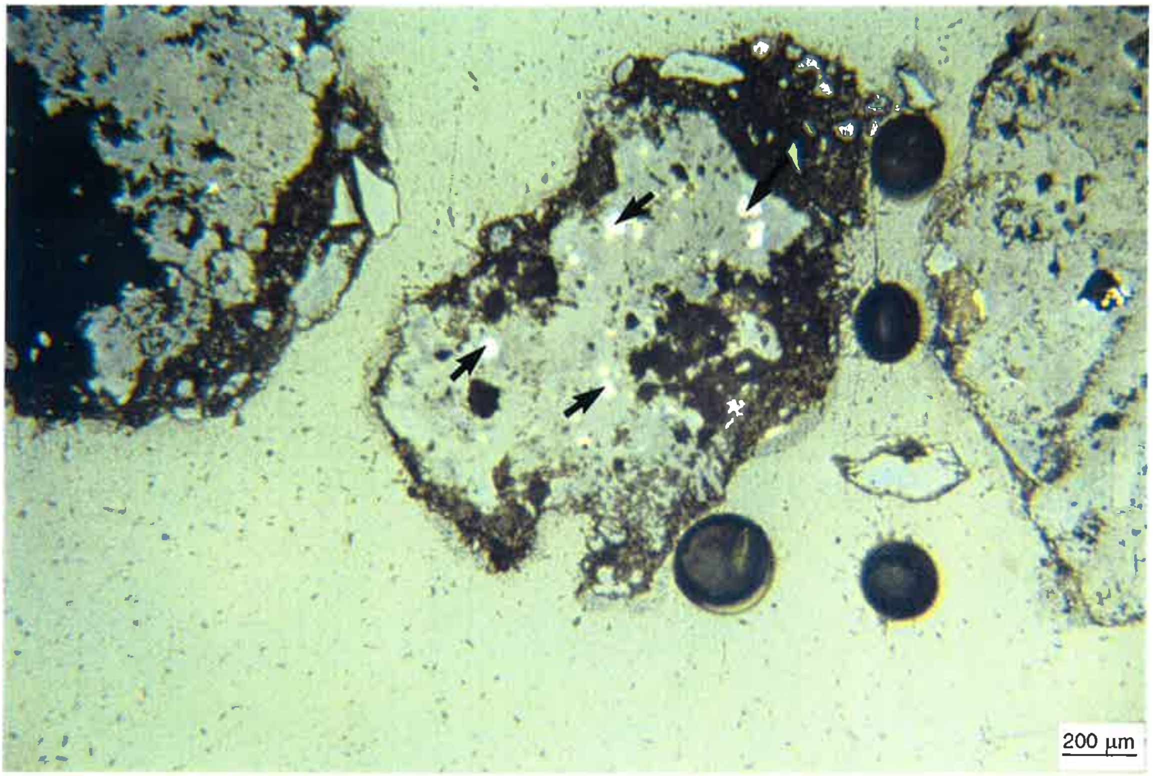

Figure 7-10 Pad 2. Silicified Skonun sediments with pyrite grains (indicated). Reflected light. The black circles are bubbles in the epoxy mount.

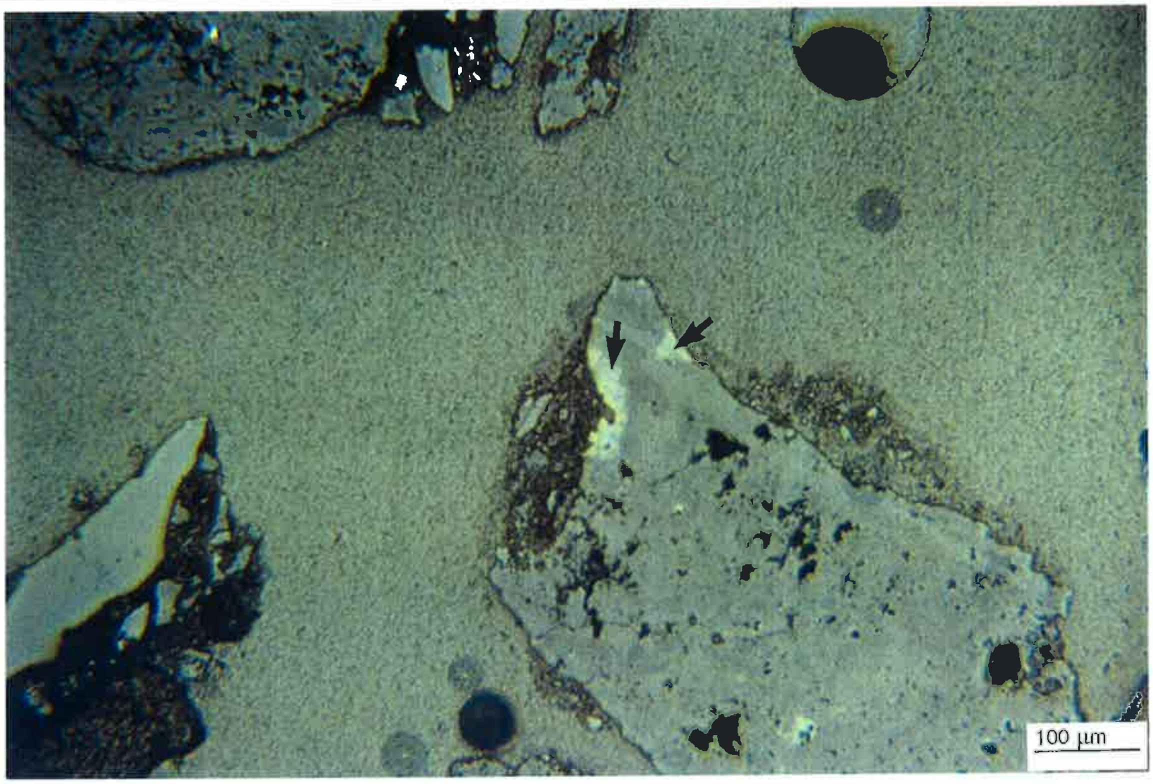

Figure 7-11a Silicified Skonun sediments showing intergrowth of pyrite (pale yellow) and goethite (light grey) at particle edge (indicated). Reflected light.

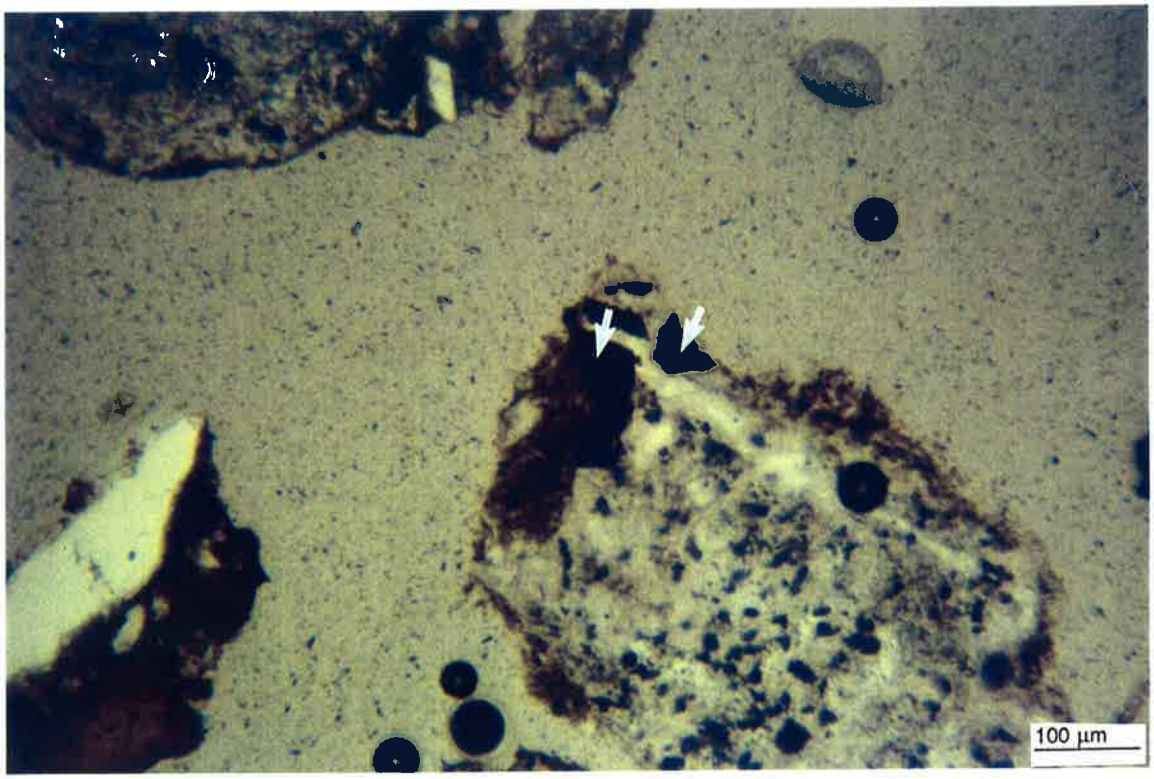

Figure 7-11b Same particle in plane polarized light.

7.3.3 Chemical Characteristics

Residue pH's and Acid-Base Accounting

Residue pH's were extremely acidic and indicate that sulphide mineral oxidation products are stored within the pile. These low values are supported by strongly negative neutralization potentials which resulted from release of acidity when water was added.

Residue pH's of the rock showed an irregular decrease with depth (Table 7-2). The reason for this decrease is not readily apparent. The samples were not tested in order of depth. Therefore, the decrease may have reflected deposition of acidic salts near the base of the pile, or alternatively could represent accumulation of fines at the base due to downward movement by percolating leachates. No correlation of residue pH and appearance of the rock was noted.

Acid-base accounts for three residue samples are shown in Table 7-2. The determinations were performed on the pulverized portion of rock finer than 1 cm to improve the statistics of sampling. When compared to initial (pre-test) material characteristics, it is apparent that total sulphur concentrations have decreased by 78 to 88% during the course of the study (compare Tables 7-1 and 7-2). Concentrations of sulphide sulphur indicate that between 10 and 38% of the sulphur remains as potentially reactive pyrite.

Sequential Metal Extractions

Sequential leach results for two samples analyzed are shown in Table 7-3. The four leachants used were selected to extract specific mineral groups (Percival *et al.*, 1990). The 10% hydrochloric acid (pH 2 to 3) was expected to dissolve secondary sulphates (such as gypsum, alunite, jarosite). Ammonium oxalate was used to extract amorphous aluminum and iron hydroxides. Nitric acid-bromine was used for sulphide extraction, and a nitric-perchloric acid digestion was used as a total digestion for resistant silicates. The order of extraction increases in strength, dissolving minerals not removed by the weaker extractions. The results shown in Table 7-3 have been corrected to show metal levels extracted by the indicated leachant less metal extracted by the weaker leachants. The "Proportion of Total" was calculated by dividing the concentration for a particular extraction by the total amount of that metal. These amounts total 100% by definition.

The results suggest that iron, copper and zinc were present in forms dissolved by hydrochloric acid and nitric acid-bromine. The dominant form was apparently soluble minerals such as gypsum and alunite. The balance was indicated to occur as iron, zinc and copper sulphide minerals.

The results do not correspond with petrographic observations. Pad 2 residues clearly contained iron-bearing silicate minerals which should only have been dissolved by the strongest acid mixture (nitric-perchloric). Instead, it appears either that the nitric acid-bromine solution was able to dissolve these minerals or that the nitric-perchloric extraction

TABLE 7-3
RESULTS OF SEQUENTIAL METAL EXTRACTIONS FROM PAD 2 RESIDUES

	Concentrations (ppm)				Proportion of Total (%)			
Samples	Hydrochloric Acid	Ammonium Oxalate	Nitric Acid - Bromine	Nitric Acid - Perchloric Acid	Hydrochloric Acid	Ammonium Oxalate	Nitric Acid - Bromine	Nitric Acid - Perchloric Acid
Copper								
Pad 2, #2	5	0	3	0	63	0	38	0
Pad 2, #3	10	0	3	0	77	0	23	0
Zinc								
Pad 2, #2	9	0	5	0	64	0	36	0
Pad 2, #3	27	0	5	0	84	0	16	0
Iron								
Pad 2, #2	720	0	540	0	57	0	43	0
Pad 2, #3	2400	0	1700	0	59	0	41	0

Notes:

1. Similar tests were not performed on waste rock prior to weathering.

was not strong enough to dissolve silicates. The lack of any detectable amorphous iron hydroxides is also surprising as these were expected based on the orange coatings observed in the pad residues. A possible explanation is that the hydroxides had crystallized. This would reduce their solubility in ammonium oxalate.

As the oxalate and perchloric-nitric extractions do not appear to have functioned as expected, results for the other two extractions should be treated with caution. The weaker HCl extraction presumably removed readily soluble secondary minerals, whereas the stronger nitric-bromine digestion appears to have dissolved unweathered primary silicate and sulphide minerals.

The cemented layer (sample #3) contained higher concentrations of all three metals. The iron concentration was more than three times that of the grey, less cemented layer. As the cement was primarily iron hydroxides, the high iron concentration in the nitric acid-bromine leachate stronger extraction was anomalous. If the pile were truly homogeneous, total iron concentrations throughout the pile should be relatively uniform. The observed distribution of iron, therefore, may simply have reflected layering within the pile created during construction. The discontinuous orange stained layers (Figure 7-9) might have represented layers containing higher concentrations of iron sulphides and silicates. Further analysis of other residue samples would be needed to evaluate this hypothesis.

Both zinc and copper were more concentrated in secondary minerals and phases. The relatively low concentrations of these metals in primary crystalline minerals indicated that these metals have been leached from sulphides and silicates.

7.4 DATA ANALYSIS AND DISCUSSION

The following sections provide interpretations of the data with respect to leachate chemistry, seasonal loadings and consumption of sulphides and alkalinity. The chapter concludes with a discussion of the application of the test pad results to the prediction of conditions in full-scale waste rock dumps.

7.4.1 Leachate Chemistry

Leachates from the Cinola waste rock pads were typical of ARD. The drainage was characterized by high concentrations of sulphate, acidity, and heavy metals, and low pH. Pad 1 leachates were dissimilar from Pads 2, 3 and 4, as shown by higher pH and lower metal concentrations. This is partly attributable to the previous weathering (5 years) of this rock, however, even after five years of weathering, leachate pH's for the other pads had not increased to the same levels. The reason for the difference is not clear, although Pad 1 contains less material and is shorter than the other pads. Leachates generated are possibly more dilute due to a shorter contact time with the rock, although the difference in mass and height is not sufficient to generate the observed order of magnitude difference in hydrogen ion concentrations.

Saturation indices determined by City Resources (1988, Volume V) using the equilibrium model MINTEQ (Peterson *et al.*, 1986) indicated that the drainage was saturated with respect to gypsum during the summer months of 1987 (City Resources, Volume V, 1988). When saturation occurred, the concentrations of calcium and sulphate in the leachate solutions were chemically limited. The trend in the molar concentration product of calcium and sulphate ($[Ca^{2+}][SO_4^{2-}]$) showed that gypsum saturation was mostly likely to occur in the summer months (Figure 7-12) when the product was greatest, and very unlikely during the winter. Over the five years of the experiment, the product generally decreased. Therefore, sulphate in flushed regions of the piles was probably not being stored extensively as gypsum.

7.4.2 Seasonal Loading of Acidity, Sulphate and Metals

As described in the preceding sections, drainage chemistry showed well-defined seasonal changes. Seasonal trends in loadings are important since these will determine the mass of contaminants reaching the receiving environment, the demand for natural alkalinity, and the effect of dilution by precipitation on pH and the concentrations of oxidation and leaching products. Loadings in the pad drainage were estimated using the formula:

$$\text{Loading (mg/week)} = \text{Concentration of Component (mg/L)} \times \text{Volume of drainage (L/week)}. \qquad (7\text{-}1)$$

The volume of drainage was estimated using the predicted precipitation (section 2.1.2) and the catchment area of each pad (approximately 16 m^2). To allow a comparison of results from different pads on a week-by-week basis, the loading was divided by the mass of rock in the pad (Table 7-1) and the time (in weeks) since the last measurement. This value was expressed as mg component/week/kg of rock. All four pads showed the same general seasonal trends for sulphate (Figure 7-13) with peak loadings observed in late summer and early fall. High loadings were also commonly observed for a brief period in late winter and early spring although the winter peak was smaller than the summer peak.

The sulphate loading peak in late summer corresponded to increased precipitation in the fall but preceded the actual peak monthly precipitation in December. This was probably because the first fall storms removed most accumulated oxidation products. As precipitation increased towards late fall (November), sulphate concentrations were rapidly diluted and fell to very low levels in winter.

The smaller sulphate loading peak observed in the springs of 1987 and 1988 corresponded to periods of high monthly precipitation in April 1987 and March 1988, following relatively dry late winter conditions. Sulphate concentrations in leachate also increased slightly at that time.

Loading peaks resulted from increased flux of water flushing regions not flushed during drier conditions. As increasing volumes of water entered the piles, flow paths within the piles probably widened, or new flow paths were initiated to accommodate the flow. Oxidation products stored in these areas were seasonally dissolved and flushed from the piles. Since new areas of the piles were being flushed, more neutralizing minerals should have been

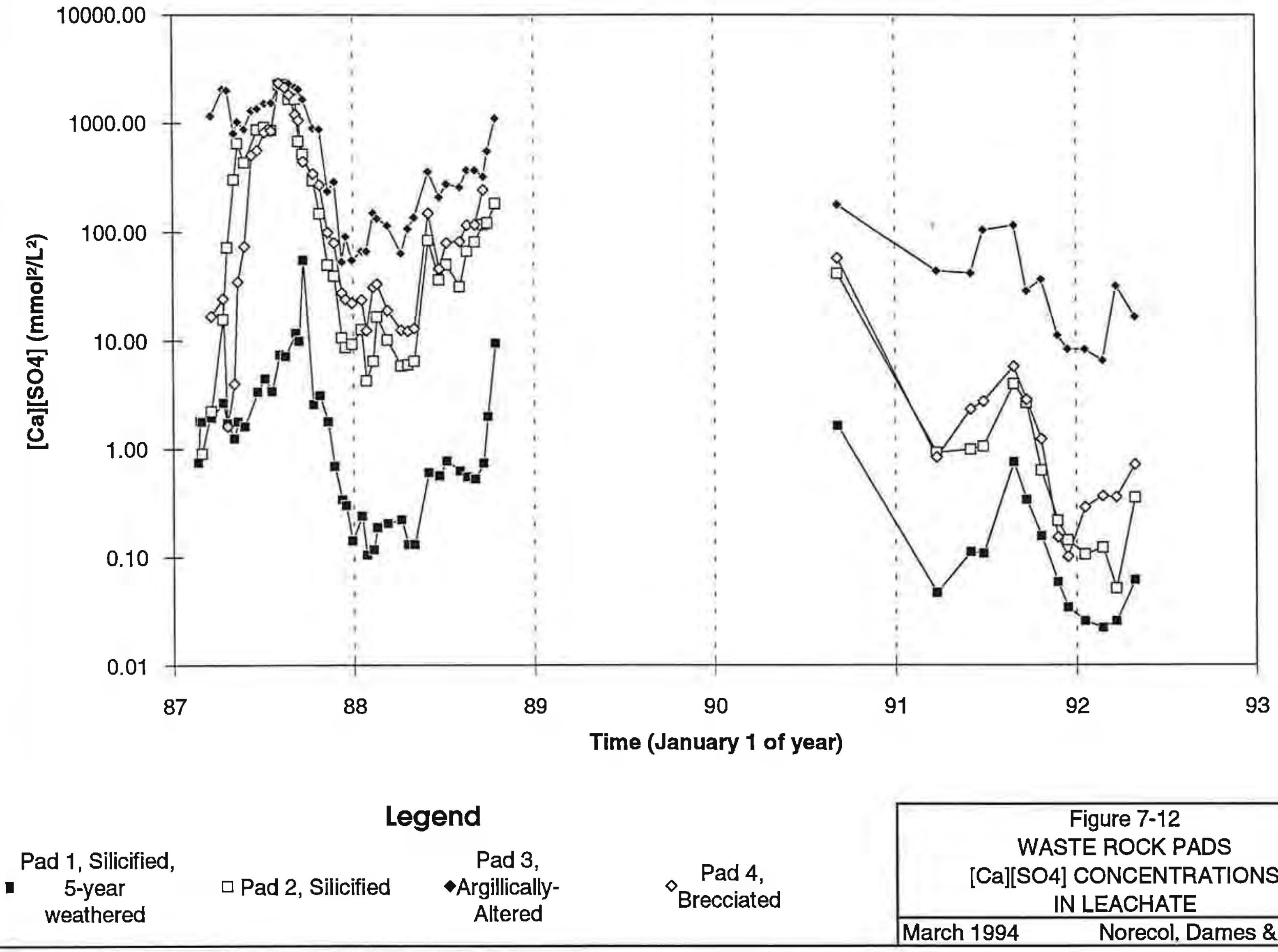

Figure 7-12
WASTE ROCK PADS
[Ca][SO4] CONCENTRATIONS
IN LEACHATE

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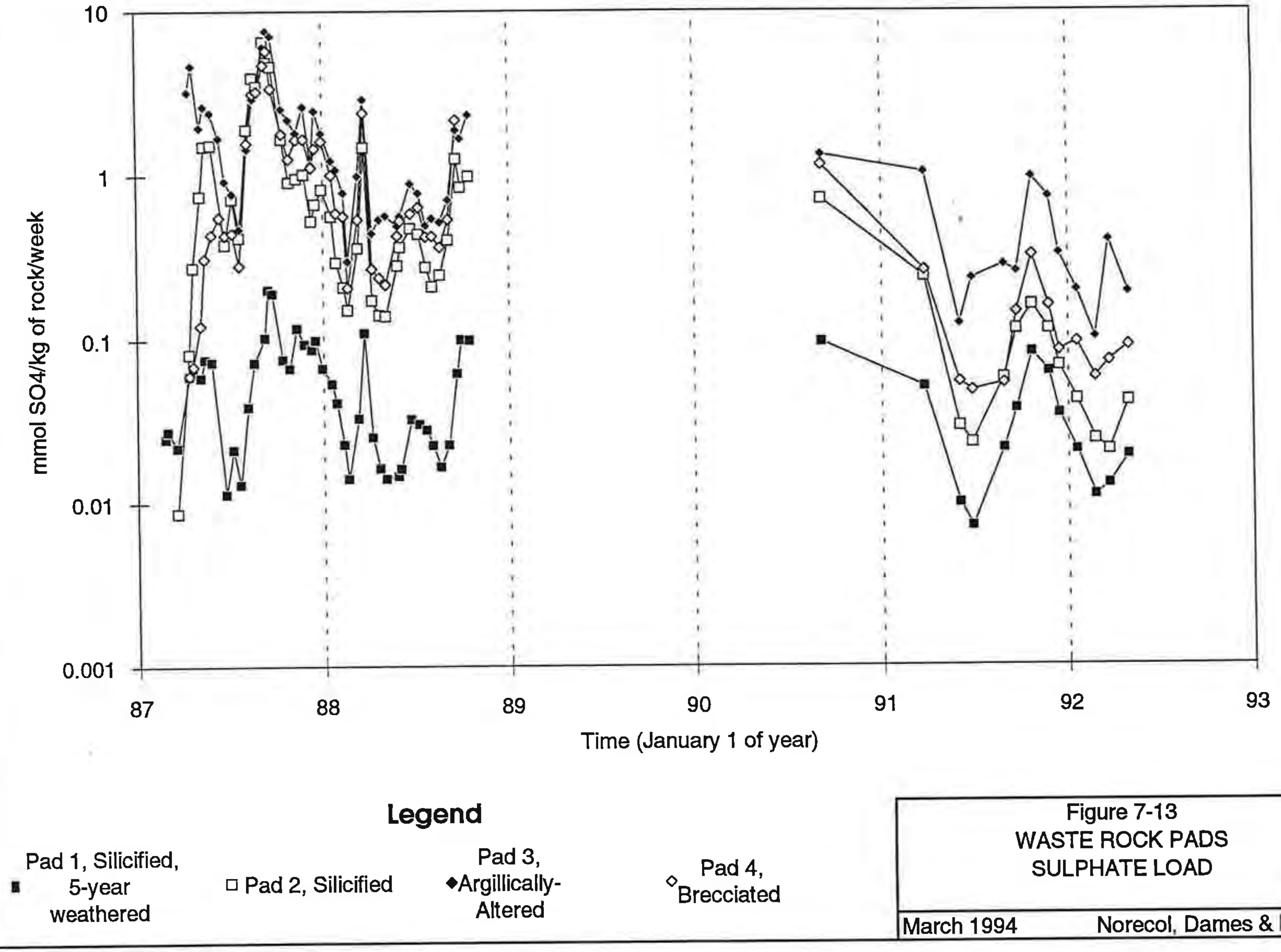

Figure 7-13
WASTE ROCK PADS
SULPHATE LOAD

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available. However, results showed that the pH fell, acidity increased and the ratio of sulphate to calcium ($[SO_4^{2-}]/[Ca^{2+}]$) increased. Possible reasons include reduced contact time with neutralizing minerals due to the increased flow rates within the piles or blinding of seasonally flushed neutralizing mineral surfaces was greater than in more frequently flushed areas due to crystallization of amorphous iron hydroxide precipitates during drier periods.

Under the climatic conditions at Cinola, the highest loads of sulphate, metals and acidity would be released in September, approximately one month before the increase in flows in the Yakoun River in response to fall rains. Potential for environmental impact from contaminated runoff would therefore probably be greatest in September.

7.4.3 Availability and Consumption of Sulphides

Estimation of Sulphate Release Rates

Consumption of sulphide minerals in flushed regions of the rock piles would ideally be estimated by totalling all sulphate released from the pads over the full monitoring period. As the pads were not monitored from September 1988 to September 1990, data for this period had to be estimated through interpolation, based on data prior to and following the missing period, and accounting for major sources of variation.

The variation in sulphate release consisted of two components: (1) seasonal fluctuations resulting from the accumulation and flushing of weathering products due to climatic changes; and (2) long term decay of sulphate release due to depletion of sulphide minerals. Although both trends were qualitatively apparent, seasonal climatic variations were erratic. A logical approach would be to determine sulphate production rates over complete annual cycles using a moving average; however, less than three complete annual cycles have been obtained making this approach statistically unreliable. Therefore, less exact methods were used to a estimate sulphate production rates.

For this study, an estimate of the amount of sulphate consumed during the five year test period was made by summing sulphate released over the three years of active monitoring and calculating average weekly release rates for each pad. This release rate was then scaled up to the five-year monitoring period by multiplying by the total number of weeks. This estimate was probably biased by the relatively high release rates observed in September 1987, which corresponded to maximum sulphide oxidation rates.

Sulphate release rates are summarized in Table 7-4. The more-weathered Skonun sediments in Pad 1 had the lowest average sulphate release (87 g SO_4/week). At this rate, only 2% of all sulphur in the pad was released during the five years of weathering. In comparison, on average, the three pads originally composed of fresh material (2, 3 and 4) weathered at a much higher rates. However, by the end of the study sulphate release rates had decreased to levels comparable to Pad 1. Pad 3 weathered most rapidly (3.3 kg SO_4/week), and 32% of sulphur was oxidized. Weathering rates for Pads 2 and 4 were similar (1.5 kg SO_4/week and 1.7 kg SO_4/week, respectively) with 16% and 29% of sulphur oxidized, respectively.

TABLE 7-4
SULPHATE DEPLETION RATES FOR WASTE ROCK PADS

PAD	ROCK TYPE	MASS OF WASTE ROCK	TOTAL SULPHUR (%)		RATE OF SULPHATE LOSS BASED ON DRAINAGE CHEMISTRY				OBSERVED RELEASED (1,2)
		(tonnes)	PRE-TEST	POST-TEST (2)	mg/kg/week	g/week	mg/m2/week	% of total	% of total
1	Five-Year Weathered Silicified Skonun Sediments	20	1.95	-	0.0044	87	0.0024	2	-
2	Silicified Skonun Sediments	30	2.96	0.49	0.051	1500	0.048	16	83
3	Argillically-altered Skonun Sediments.	30	3.06	-	0.11	3300	0.055	32	-
4	Brecciated Skonun Sediments.	30	1.75	-	0.056	1700	0.029	29	-

Notes:
1. Observed released value is based on pre- and post-test total sulphur.
2. "-" indicates analysis not completed because investigation limited to Pad 2. Observed released value cannot be calculated.

Rates reported on a surface area basis were determined by dividing by the Particle Surface Area for the corresponding pads given in Table 7-1. The higher sulphate release rate for Pad 3 corresponded with the higher sulphur concentration and greater surface area of Pad 3 material (section 2.4.1). Although Pad 2 rock had a higher initial sulphur content than Pad 4, Pad 2 rock was relatively coarse and the products of surface area and sulphur concentration were similar for these two pads, hence the similar sulphate release rates.

The depletion of sulphur measured in the analysis of Pad 2 residues (given in Table 7-2) is much greater than that predicted from sulphate release rates (Table 7-3). Since sulphur concentrations in residues were relatively consistent through the Pad 2 section, it appears that sulphate release underestimates consumption of sulphur. Several explanations can be suggested to explain the discrepancy, including:

- lateral heterogeneity within the pad;
- incorrect initial determination of total sulphur concentrations;
- inappropriate procedure for interpolation of sulphate release between City Resources and MEND/BC AMD Task Force projects;
- very high sulphate loss during extreme precipitation periods when the drainage was not sampled;
- retention of sulphate in the unanalyzed areas of the pads;
- dilution of leachates in barrels.

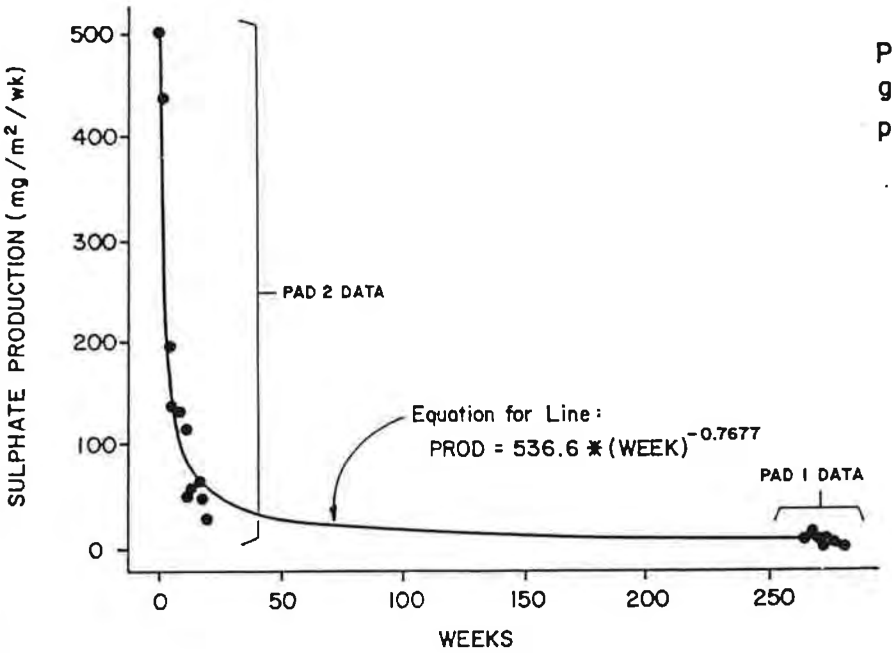
The two most significant unknowns are the magnitude of sulphate loss during extreme precipitation events, and possible retention of sulphate in the pads.

Decay Model

City Resources (1988, Volume V) predicted sulphate production rates (in mg SO_4/m^2/week):

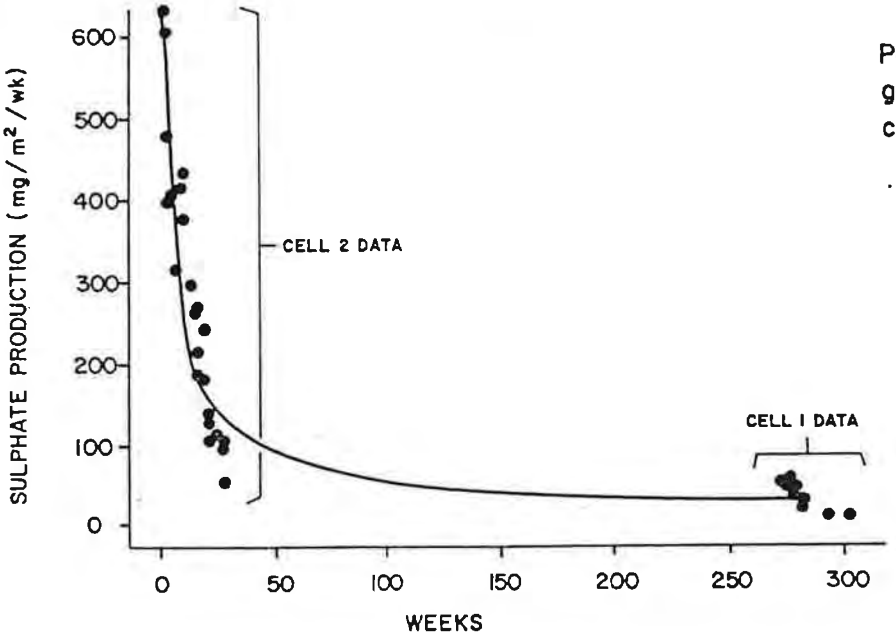
$$\text{Sulphate Production} = d(SO_4)/dt = -536.6t^{-0.7677} \qquad (7\text{-}2)$$

for Pad 2, based on sulphate release rates for Pads 1 and 2, where t is time in weeks. The trend used to determine this rate equation is shown in Figure 7-14. Pad 1 (5-year weathered rock) release rates were used on the assumption that the rock in the two pads were similar and that Pad 2 release rates would eventually decrease to rates measured for Pad 1. This assumption is not supported by data generated for this study which shows that Pad 2 was releasing sulphate more rapidly after five years than Pad 1 at the start of the experiment. Day and Cowdrey (1988) solved the differential rate equation (1) to yield a total sulphate produced (from t=0 to t=t) in mg/m^2:



Potential long-term rates of acid generation based on waste-rock pads I and 2.

- PAD I CONTAINS ROCK THAT HAS BEEN EXPOSED TO WEATHERING FOR 5 YEARS LONGER THAN PAD 2



NOTE · Spurious value of 781 at week 7 not plotted.

Potential long-term rates of acid generation based on humidity cell series II, cells I and 2.

- CELL I CONTAINS ROCK THAT HAS BEEN EXPOSED TO WEATHERING FOR 5 YEARS LONGER THAN CELL 2.

Extracted from City Resources (1988, Volume V)

Figure 7-14
CITY RESOURCES CURVES USED TO PREDICT LONG TERM SULPHATE PRODUCTION RATES

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$$\int_0^{Total} d(SO_4) = \int_0^{t} -536.6t^{-0.7677}\,dt \qquad (7\text{-}3)$$

$$\text{total } SO_4 = 2310t^{0.2323} \qquad (7\text{-}4);$$

assuming the particle surface area of the waste rock remains constant. After 270 weeks, equation (7-2) predicts that Pad 2 would be releasing sulphate at a rate of 7.296 mg SO_4/m^2/week, or 234 g SO_4/week. Measured rates at this time varied from 60 to 480 mg SO_4/week. The average sulphate release rate over the period was predicted to be 1000 g SO_4/week (equation (7-4)). This is less than the estimated average of 1500 g SO_4/week (Table 7-4). Consequently, Pad 2 appeared to have weathered about 50% faster then predicted. The difference reflects shortcomings in the model developed in 1988. Firstly, the model assumed that decay of sulphate production rates towards the end of 1988 was due to sulphide grain effects (for example, shrinking core) rather than a seasonal leaching effect, as has now been recognized. Secondly, Pad 2 is weathering faster than Pad 1, perhaps due to differences in mineralogy and handling.

These results illustrate the difficulties involved in predicting sulphate release rates from natural rock piles over a relatively short monitoring period. At least four or five seasons of monitoring are necessary to reliably address seasonal variations.

7.4.4 Comparison of Release Rates for Other Parameters

Release rates for other drainage parameters measured during monitoring in 1991 and 1992 are shown in Figure 7-15. The comparison is limited to this period since the majority of parameters were not determined consistently in the earlier monitoring period. Rates are presented as molar quantities re-calculated on a mass basis to allow direct comparison of different parameters and different pads.

Sulphate and iron were the most common dissolved components in leachate from Pads 2 to 4. Release rates for iron are much lower for Pad 1 primarily because its pH's were greater than that required to prevent precipitation of iron hydroxide. As a result, sulphate and aluminum were the main dissolved components in Pad 1 leachate. Aluminum hydroxide is relatively soluble below pH 4.5 and therefore aluminum concentrations are elevated in the leachates. After aluminum, the next most common cations were calcium, magnesium and sodium. Potassium concentrations were less than the detection limit of 0.05 mg/L. In contrast, sodium was detectable (>0.1 mg/L). These results are consistent with acidic leaching of silicates containing primarily iron, calcium, aluminum and magnesium. Silicate minerals observed in the Cinola waste rock and potentially leachable are plagioclase (Al, Ca, ±Na), chlorite (Mg, Fe, Al), kaolinite (Al), and hornblende (Ca, Mg, Al, Fe, ±Na). Corrosion and other evidence of the leaching of silicates, was not readily apparent in thin sections. However, the quantities of the major elements leached were less than 1% of the amount of these metals in the rock, and therefore, evidence of leaching would not be apparent.

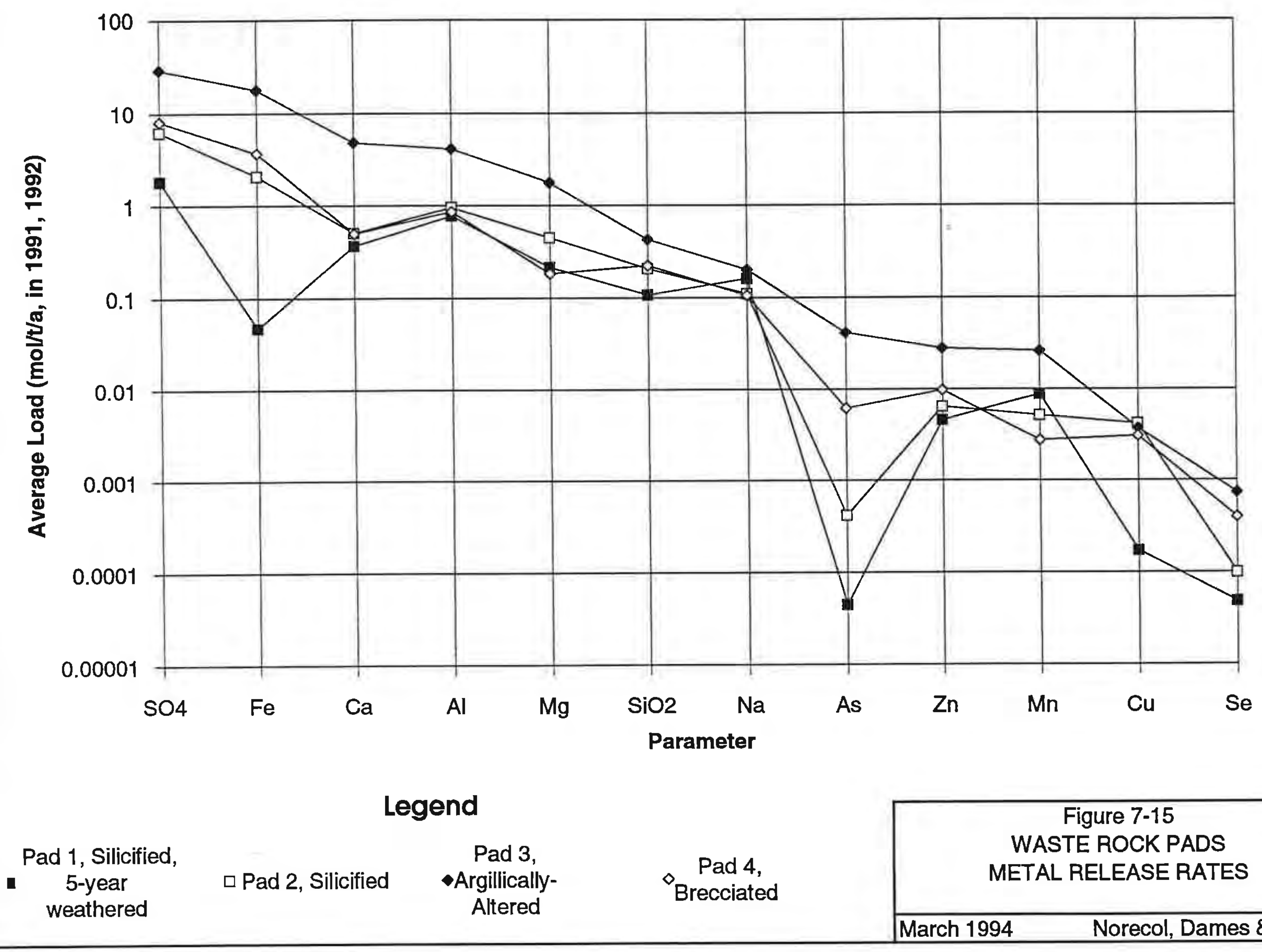

Figure 7-15
WASTE ROCK PADS
METAL RELEASE RATES

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Zinc and manganese were the most highly leached heavy metals (after iron). Both zinc and arsenic release rates appear correlated with sulphate. Arsenic release is least in Pad 1, presumably due to pH constraints. Similarly, copper release is lowest for Pad 1. Based on typical metals concentrations for this type of rock, about 30% of copper has been leached, whereas only 3% of zinc has been leached.

7.4.5 Application of Results to Processes in Full-Size Waste Rock Dumps

To assess the applicability of results from the waste rock pads to full size waste rock dumps, it is necessary to determine whether any significant processes occurring in full size dumps are affected by the change of scale. Table 7-5 lists possible differences between small scale test waste rock piles and full-scale piles, presented in terms of the features and processes reviewed by Morin (1991). It is readily apparent that the ability to determine the applicability of small scale tests to large scale dumps is limited by the lack of quantitative knowledge of the significance of the various processes controlling the chemistry of water emerging from either large or small-scale dumps.

Table 7-5 indicates fundamental differences between small test pads and full-scale dumps. The change in scale results in differences in the water to solid ratio, which decreases as size of dump of same shape increases, and the process of gas transport (from wind to thermal advection). These factors are likely to produce significant non-random differences in water quality. Other factors, such as physical and chemical distribution of particles, water flow patterns, and migration of solids, are likely to introduce greater variability in the quality of water from full-scale waste rock dumps. These factors result more from a change in complexity than the change in scale, as it would be possible to produce a small scale pile with complex internal chemical and physical features.

The change in water to solid ratio may affect processes at the grain scale. As the volume of water in contact with mineral particles increases, micro-environments near particles become more dilute and weathering products may be more readily removed. Although processes at grain surfaces have been modelled (12 examples are documented by Morin, 1991), it is unclear how the rate of water flushing affects conditions at grain boundaries. This question is also relevant to the interpretation of results for humidity cells in which flushing of mineral surfaces is frequent and thorough.

The process of gas diffusion can be in part a result of the development of temperature gradients in full-size piles. Although temperature gradients may develop in test piles due to exothermic weathering reactions, the heat is likely to be dissipated by water flow and wind advection. Test piles are more likely to duplicate the near surface conditions of full-size piles where oxygen concentrations and temperatures are comparable to ambient conditions. At greater depth within full-size piles, temperatures may be much greater than ambient conditions, and oxygen concentrations may be lower due to depletion by oxidation reactions. Conditions in full scale dumps are therefore likely to be significantly different from test piles.

TABLE 7-5
COMPARISON OF PROCESSES IN TEST AND FULL-SCALE ROCK PILES

FEATURE/ PROCESS	TEST PILES	FULL-SCALE PILES
Physical Distribution of Particles	Relatively homogeneous, lack of layering unless planned. Probably low fines content due to removal of rock from exploration adit.	Extremely heterogeneous due to dumping techniques, variation in rock type and mining techniques. Layering and compacted layers probable. Relatively more fines than test piles due to mine blasting techniques.
Chemical Composition of Particles	Relatively homogeneous if planned. Readily defined by sampling.	Probably complex due to changes in rock type during mining. Difficult to characterize due to physical heterogeneity.
Water Movement	In small piles, relatively high proportion of rock particles contacted due to short distance from surface to base. Higher water:solid ratio. Retention time relatively low. Probable lack of water table(s).	Flow is complex due to internal variations in permeability. Flow is probably concentrated in a number of small channels resulting in relatively low proportion of particle contacted by water. Water table(s) are possible both perched and at the dump base.
Effect of Climactic Processes	Snow melt and major rainfall events result in more rapid flow and expansion of flow paths into seasonally dry areas. Flushing of weathering products occurs. During dry periods, weathering products accumulate.	Snow melt and major rainfall events result in more rapid flow and expansion of flow paths into seasonally dry areas. Flushing of weathering products occurs. During dry periods, weathering products accumulate.
Migration of Solids	Large scale failure unlikely. Small scale transport of solids probable due to downward movement of water.	Large scale failure possible. Small scale transport of solids probable due to downward movement of water.
Gas Transport	Wind advection is possibly dominant process of gas transport into and out of the pile. Significant oxygen depletion within pile unlikely.	Thermal advection accepted as dominant process due to formation of temperature gradients within pile. Oxygen concentration gradients likely.
Internal Reactions	Reactions comparable but less variable within pile due to lesser temperature and oxygen variation. Greater water flow and flushing of weathering products possibly important.	Extremely complex within various parts of the dump due to varying oxygen, temperature and water flow conditions.
Overall Water Chemistry	Less likely to be limited by saturation due to higher water flow. Metal concentrations potentially lower due to dilution and development of less acidic conditions, or higher due to lesser saturation control.	Expect water chemistry to be controlled by saturation.

NOTES:

1. Features of full-scale waste rock dumps from review by Morin (1991).
2. Relative terms compare test and full-scale piles.

Notwithstanding the above differences, some results from the Cinola waste rock piles can be applied to understanding processes in waste rock dumps:

- Seasonal water quality fluctuations in a mild moist maritime climate. It is apparent that the poorest quality water is released when precipitation increases in the late summer and early fall.
- Decrease in sulphate release (correlated with sulphide oxidation) is apparent, but the rate of decrease cannot be quantified due to seasonal variations.
- Storage and leaching of heavy metals. Metals release is correlated with sulphate. Very low concentrations of metals in the waste rock can yield elevated metal concentrations in leachate.

In conclusion, further research is needed to assess changes in rock pile design on processes controlling rates of acid generation. The current ability to apply results in small test piles to full-scale test-piles is hampered by this lack of knowledge. Identification of critical parameters (for example, water:rock ratio and gas movement) for modelling of waste rock dump processes should naturally lead to the design of well-characterized small-scale experiments.

8.0 WASTE ROCK AND LIMESTONE MIXING STUDY

The waste rock management plan for the Cinola Gold project proposed mixing of limestone with waste rock in stockpiles to prevent release of acid drainage prior to backfilling the waste rock in the open pit during mine closure followed by flooding. Several concerns were raised regarding this approach, including limited limestone reactivity due to coating of limestone particles with reaction products, and premature loss of limestone due to physical flushing and chemical dissolution. Tests were therefore initiated to investigate parameters such as limestone particle size and required quantity of limestone to prevent acid generation over the proposed stockpiling period.

8.1 EXPERIMENTAL DESIGN

The tests were set up in February 1988 as leach columns to address the effectiveness of adding different quantities of mixed or layered limestone. Three columns contained varying amounts of well-mixed limestone to (1) neutralize all acidity which could potentially be generated if all sulphur were oxidized; (2) neutralize 50% of all acidity; and (3) neutralize acidity for 10 weeks at a typical rate of acid generation predicted from Skonun Sediment humidity cells. The quantity of acidity (in kg $CaCO_3$/t) was determined conventionally using the total sulphur concentration multiplied by 31.25 to predict maximum potential acidity.

Five columns were designed (descriptors used to refer to the columns are indicated):

Column 1	Control	Waste rock (Skonun Sediments) only.
Column 2	6.6% Limestone	Approximately 6.6% limestone mixed with waste rock (predicted to neutralize all acid).
Column 3	3.3% Limestone	Approximately 3.3% limestone mixed with waste rock capped with 1 cm of column 2 material (predicted to neutralize 50% of acid). The limestone enriched waste rock cap was included in order to investigate one dump design option.
Column 4	0.8% Limestone	Approximately 0.84% limestone mixed with waste rock capped with 1 cm of column 2 material (acid neutralized for 10 weeks).
Column 5	Layered	To evaluate the effects of layering, approximately 1.2% limestone was applied in five 1 cm thick layers of column 2 material interbedded with four 10-cm layers of column 4 material.

Limestone and waste rock were mixed on plastic sheets. Mixing was deliberately imperfect to mimic conditions expected in a waste rock pile. This source of variation was not evaluated as part of the study. Columns 1, 2 and 3 were operated continually for five years. Columns 4 and 5 were terminated after two years at the initiation of the MEND/BC AMD Task Force project since acid leachate had been produced.

8.2 TEST MATERIAL CHARACTERISTICS

Pre-test characterization consisted of acid-base accounting and size fraction analysis for samples of waste rock and limestone. The Skonun Sediment waste rock contained approximately 2.1% total sulphur, had a neutralization potential of 8 kg $CaCO_3$/t and a net neutralization potential of -57 kg $CaCO_3$/t.

The limestone contained some sulphur (0.22%), and based on the neutralization potential of 932 kg $CaCO_3$/t, was extremely pure. However, a separate CO_2 determination indicated a purity of only 75%. The reason for the discrepancy in values could not be determined from laboratory reports. The dominant carbonate mineral in the limestone was calcite. Dolomite was assumed to be a minor component though was not observed.

Grain size distributions for both limestone and rock are summarized in Table 8-1. The rock mixture was much coarser than the limestone to mimic particle sizes in proposed waste rock stockpiles.

Based on size fraction analysis, the surface area of particles was estimated by assuming that particles were perfectly spherical as described in Section 4.2.2. Waste rock yielded calculated surface areas of 5.4 m^2/kg. The limestone was much finer and yielded a calculated surface area of 30.9 m^2/kg. The limestone was deliberately crushed finer than the waste rock to yield a greater reactive surface area. The surface area estimates were lower than would be expected if material finer than 0.04 mm was taken into account.

Acid-base accounts for the four columns containing limestone (2 through 5) were determined using two methods. These are summarized in Table 8-2. The first method involved conventional mass-weighting. Values for each parameter were determined using the formula:

$$P_{weighted} = (P_{lst}.M_{lst} + P_{rock}.M_{rock})/(M_{lst} + M_{rock}) \quad (3)$$

where P is the parameter (eg. NP, MPA, NNP), and M_{lst} and M_{rock} are the masses of limestone and waste rock in the column. Values are listed in Table 8-1. Since the quantity of sulphur in the limestone was relatively small, the variation in MPA was small (62 to 65 kg $CaCO_3$/t). Variation in NP due to the addition of limestone accounted for the difference in NNP and NP/MPA. Only column 2 was considered potentially acid consuming according to the conventional interpretation of ABA criteria used for the data. The remaining columns have NNP<0 and NP/MPA<1, implying potential for net acid generation.

TABLE 8-1
GRAIN SIZE DISTRIBUTIONS FOR ROCK MIXTURE AND LIMESTONE IN COLUMNS

TYPE OF MATERIAL	SCREEN SIZE		WEIGHT RETAINED (g)	WEIGHT RETAINED (%)
	(mm)	(ASTM Mesh)		
ROCK MIXTURE	3.35	6	53	18.1
	2.00	9	48	16.4
	1.00	18	69	23.5
	0.600	28	43	14.7
	0.300	48	42	14.3
	0.212	65	14	4.8
	0.106	150	18	6.1
	0.053	270	6	2.0
AVERAGE SURFACE AREA	5.39 m²/kg			
LIMESTONE	0.600	28	30	40.0
	0.300	48	23	30.7
	0.212	65	5	6.7
	0.106	150	8	10.7
	0.053	270	5	6.7
	0.045	325	4	5.3
AVERAGE SURFACE AREA	30.9 m²/kg			

TABLE 8-2
ACID-BASE ACCOUNTS FOR COLUMNS

COLUMN	DESCRIPTION	NET NEUTRALIZATION POTENTIAL		NP/MPA(1)	
		By Mass(2)	By Area(2)	By Mass(2)	By Area (2)
		(kg CaCO3/t)			
1	Control	-57	-57	0.1	0.1
2	6.6% Limestone	3	212	1.1	5.3
3	3.3% Limestone	-26	97	0.6	2.7
4	0.8% Limestone	-49	-11	0.2	0.8
5	Layered	-45	7	0.3	1.1

Notes

1. NP - Neutralization Potential; MPA - Maximum Potential Acidity (kg CaCO3/t)
2. Refer to text for calculation of mass and area weighted values.

The second acid-base account was based on exposed surface area of the waste rock and limestone particles, the assumption being that only the immediate surfaces of the rock particles would be readily reactive, and therefore the limestone should have provided more neutralizing potential than predicted using the mass weighted approach. The first step was therefore to estimate the total surface area (A_{lst}) represented by limestone using the formula:

$$A_{lst} = M_{lst}.A_{s,lst} \qquad (4)$$

where $A_{s,lst}$ is the estimated limestone area expressed in m^2/kg and A_{lst} is in m^2. The total area (A_{rock}) of waste rock was estimated using a similar formula. Using the estimates, the relative percentages of limestone were greater than on a mass basis. In column 2, 29% of the particle surface area is limestone. This decreases to 16, 5 and 7% for columns 3, 4 and 5, respectively. These estimates can then be used in a different version of equation (3) to estimate area weighted values of NP, MPA and NNP:

$$P_{weighted} = (P_{lst}.A_{lst} + P_{rock}.A_{rock})/(A_{lst} + A_{rock}) \qquad (3)$$

Based on the area weighted values, only column 4 was predicted to be acid generating. Column 5 was expected to be marginally acid generating or acid consuming, and columns 2 and 3 were expected to be acid consuming.

Petrographic studies were not completed on either the limestone or the waste rock at the start of the study. However, the waste rock samples were typical of the Skonun Sediments and had the same mineralogical characteristics described in Section 2.2.2.

8.3 DESCRIPTION OF LEACHATE RESULTS

All leachate results are provided on diskette in the pocket.

8.3.1 Major Ions and Indicator Parameters

pH

The pH of leachate from all four columns receiving a limestone treatment was initially between 7 and 8 (Figure 8-1). The control column initially generated leachate with pH 5 then pH decreased to 3 for about 11 weeks. Subsequently, pH dropped to near 2. Leachate pH from this column steadily increased to greater than 3.

Column 4 (0.8% Limestone) and Column 5 (layered limestone) columns both generated acidic leachate at week 33. For both columns, leachate pH dropped very rapidly without intermediate plateaus to between 2 and 3. There was no earlier indication from pH that acidic leachate was about to be produced. These columns were terminated after two years.

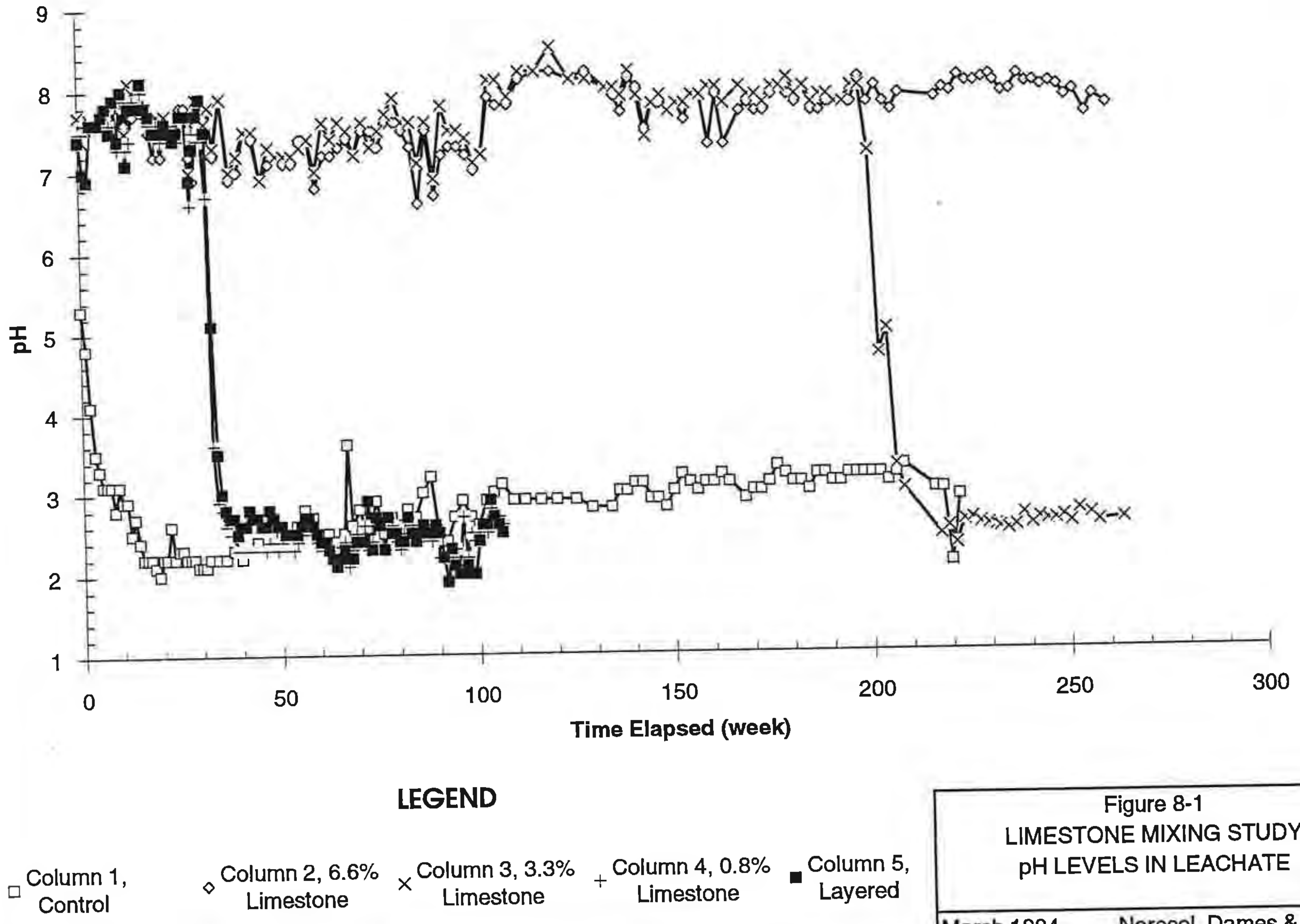

Figure 8-1
LIMESTONE MIXING STUDY
pH LEVELS IN LEACHATE

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Column 3 (3.3% Limestone) generated acidic leachate after about four years. The transition to low pH conditions was not quite as rapid as columns 4 and 5. pH stabilized at 4 to 5 over a period of about 1 week. Column 2 (6.6% Limestone) generated pH-neutral water throughout the study.

Sulphate (Figure 8-2) and Acidity (Figure 8-3)

Sulphate concentrations and total acidity measurements were strongly positively correlated. Trends in sulphate concentrations in leachate were comparable to trends for sulphate loadings because the water percolation rate remained relatively constant throughout the duration of the study, and evaporative losses appeared to vary randomly.

Sulphate concentrations in leachate from columns 1 (Control), 3 (3.3% Limestone), 4 (0.8% Limestone) and 5 (Layered) followed similar trends. Most columns showed initially decreasing sulphate concentrations. Concentrations then increased several weeks before pH dropped to between 2 and 3 (labelled "B" on Figure 8-2), and peak sulphate release (labelled "P" on Figure 8-2) occurred several weeks after pH dropped. These observations are quantified as follows:

- the time elapsed from a noticeable increase in sulphate concentrations to the production of acidic leachate increased with the proportion of limestone. For columns 4 and 5, 12 weeks elapsed. For Column 3 (3.3% Limestone), 100 weeks elapsed. Although Column 2 (6.6% Limestone) did not generate acidic leachate, the time elapsed would be expected to be greater than 180 weeks;

- the time elapsed from release of acidic leachate to peak sulphate concentrations was between 9 and 21 weeks for all columns, including the control column;

- the intensity of the sulphate concentration peak decreased with increasing limestone concentration;

- the sulphate concentration peak became less well-defined with increasing limestone concentrations; and

- on semi-logarithmic graphs, the slope of the decay curves appear to be similar, and indicate half lives (i.e. time taken to reach half the maximum sulphate concentration, labelled "H" on Figure 8-2) of 5 (Column 1, Control) to 22 weeks.

Leachate sulphate concentrations in Column 2 (6.6% Limestone) were increasing when the column was terminated. While the characteristics of the curve were similar to the other column, sulphate concentrations had not yet reached a level which might be expected prior to the onset of fully acidic conditions.

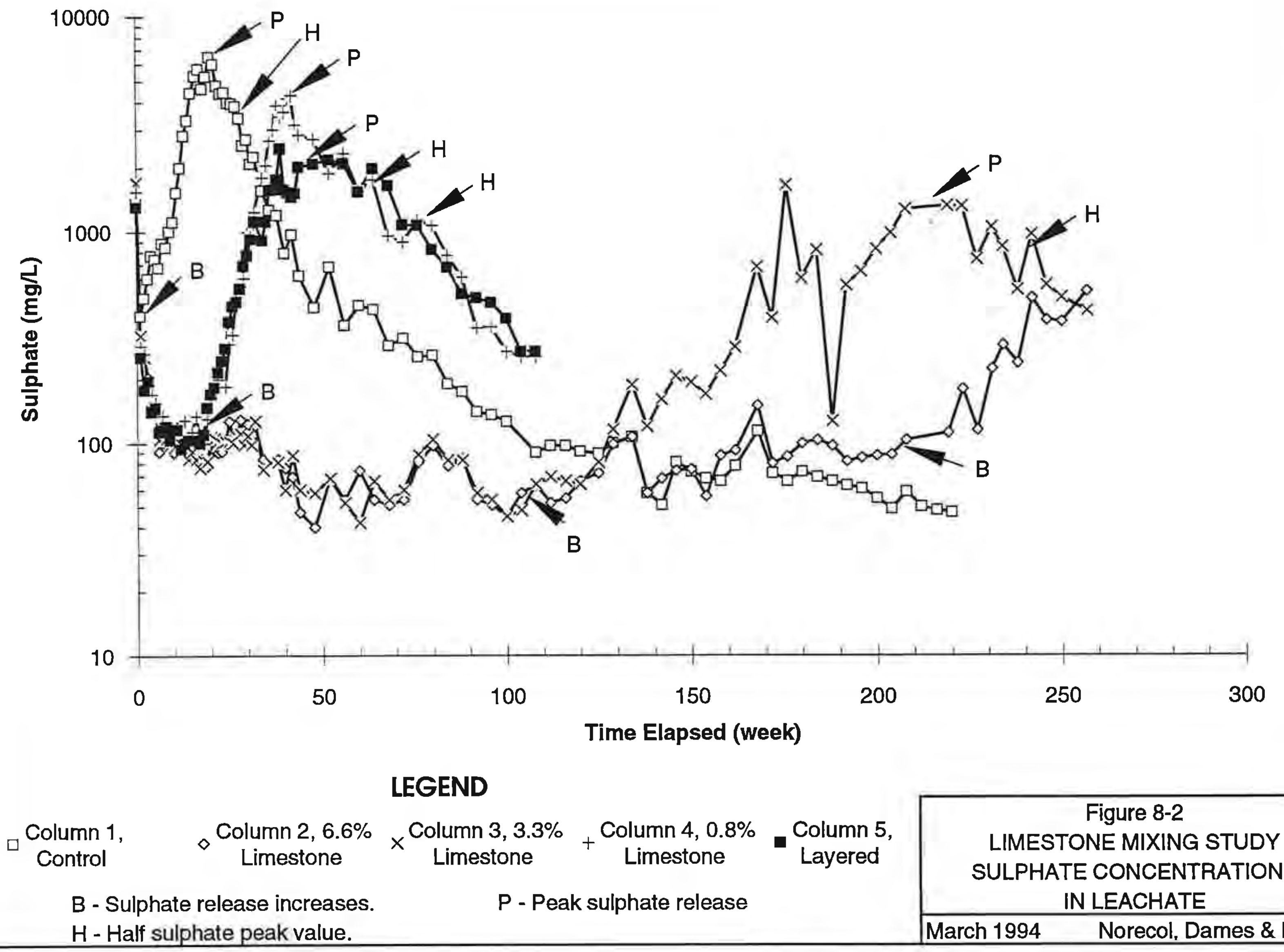

Figure 8-2
LIMESTONE MIXING STUDY
SULPHATE CONCENTRATIONS
IN LEACHATE

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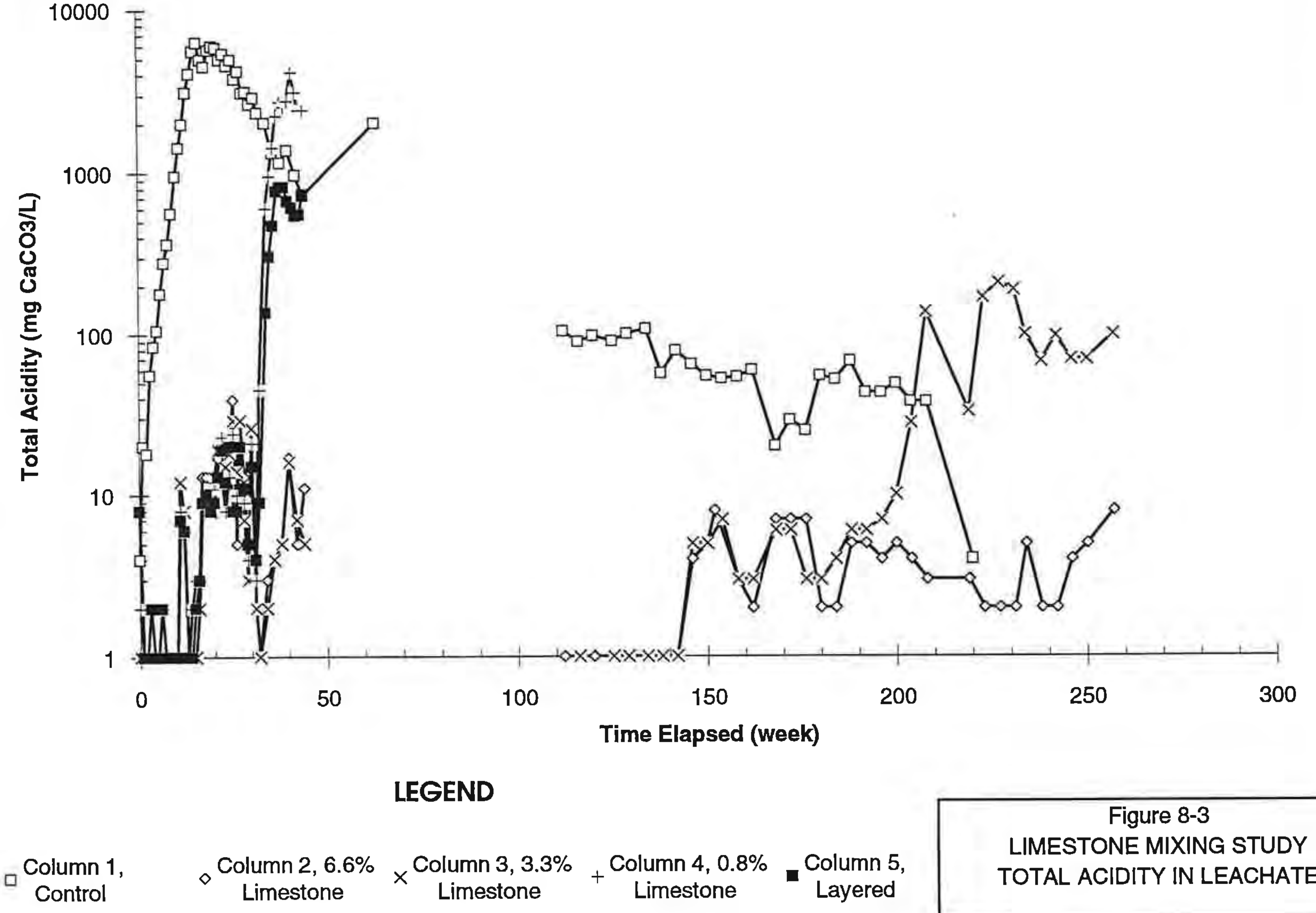

Figure 8-3
LIMESTONE MIXING STUDY
TOTAL ACIDITY IN LEACHATE

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Total Alkalinity and Calcium

Total alkalinity (Figure 8-4) represented all species in solution which were capable of consuming acid, for example, HCO_3^-, CO_3^{2-}, OH^-. It may also have included species such as $Al(OH)_2^+$. For pH-neutral solutions produced by contact with limestone, the main source of alkalinity was bicarbonate (HCO_3^-). Therefore, total alkalinity roughly correlated with trends in bicarbonate concentrations. If the pH of the solution was less than 4.5, alkalinity was not measured. Leachate alkalinity and calcium concentrations were strongly correlated indicating that both were primarily controlled by the dissolution of calcium carbonate, therefore these parameters are considered together. Calcium concentrations (Figure 8-5) were useful for monitoring leaching of acid consuming minerals because determinations were made regardless of pH.

Initially, all columns containing limestone yielded elevated alkalinity. As the study proceeded, alkalinity dropped to between 60 and 80 mg $CaCO_3$/L, and varied erratically. At the same time, calcium concentrations were between 50 and 90 mg/L. Measurement of alkalinity was discontinued after 50 weeks, but re-initiated as part of the MEND/BC AMD Task Force project. During the period of missing alkalinity data, pH conditions in leachates did not change significantly.

Alkalinity in leachate from Column 3 (3.3% Limestone) began to increase about 20 weeks after sulphate concentrations increased, and peaked at 110 mg $CaCO_3$/L just before pH dropped. During this period, calcium concentrations also increased and peaked at about the same time sulphate peaked. Once pH decreased, alkalinity also decreased very rapidly and was not, by definition, measured once pH decreased to less than 4.5.

Alkalinity in leachate from Column 2 (6.6% Limestone) began increasing about 30 weeks after sulphate concentrations began increasing. Likewise calcium also began increasing.

8.3.2 Heavy Metals and Other Trace Components

Dissolved iron was the most significant heavy metal in the column leachates, although it was determined infrequently (Figure 8-6). Sulphate and iron concentrations show similar trends although iron varies over a wider range. At very low pH (less than 2.9), iron and sulphate concentrations are very similar. At neutral pH, iron concentrations in Columns 2 (6.6% Limestone) and 3 (3.3% Limestone) were commonly less than the detection limit of 0.03 mg/L used in the last three years of the project. As soon as Column 3 leachate pH decreased to less than 3, iron concentrations increased by three orders of magnitude.

Zinc concentrations were determined on a more regular basis than iron and showed similar trends to sulphate. Zinc concentrations began increasing as sulphate increased weeks or months before pH decreased (Figure 8-7). Peak zinc concentrations tended to precede peak sulphate concentrations by a few weeks. Arsenic (Figure 8-8) and copper (Figure 8-9) concentrations showed similar trends to zinc. However, the peak arsenic concentration tended to be lower as the limestone concentration increased. Zinc and copper concentration peaks were comparable regardless of the limestone concentration.

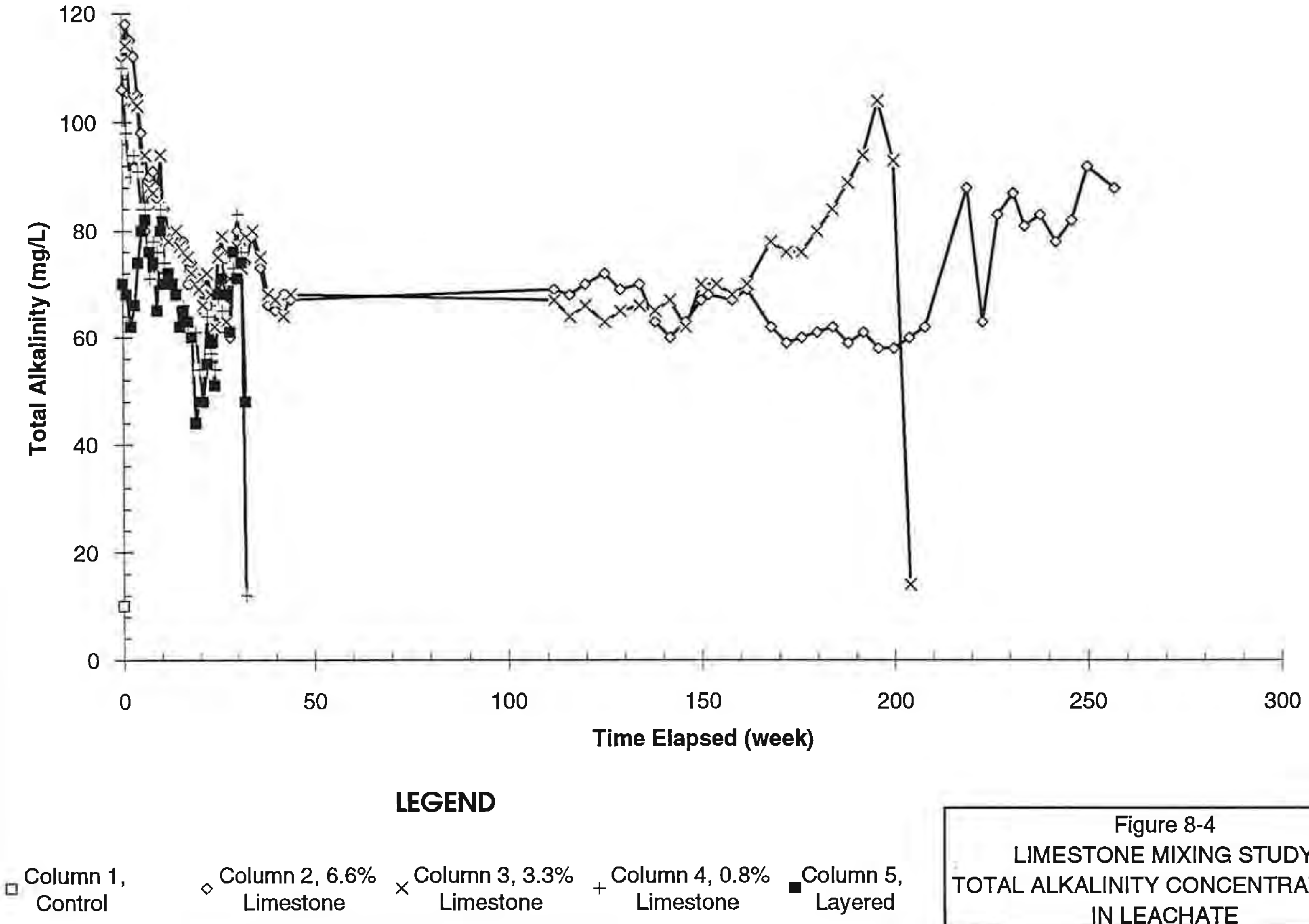

Figure 8-4
LIMESTONE MIXING STUDY
TOTAL ALKALINITY CONCENTRATIONS
IN LEACHATE

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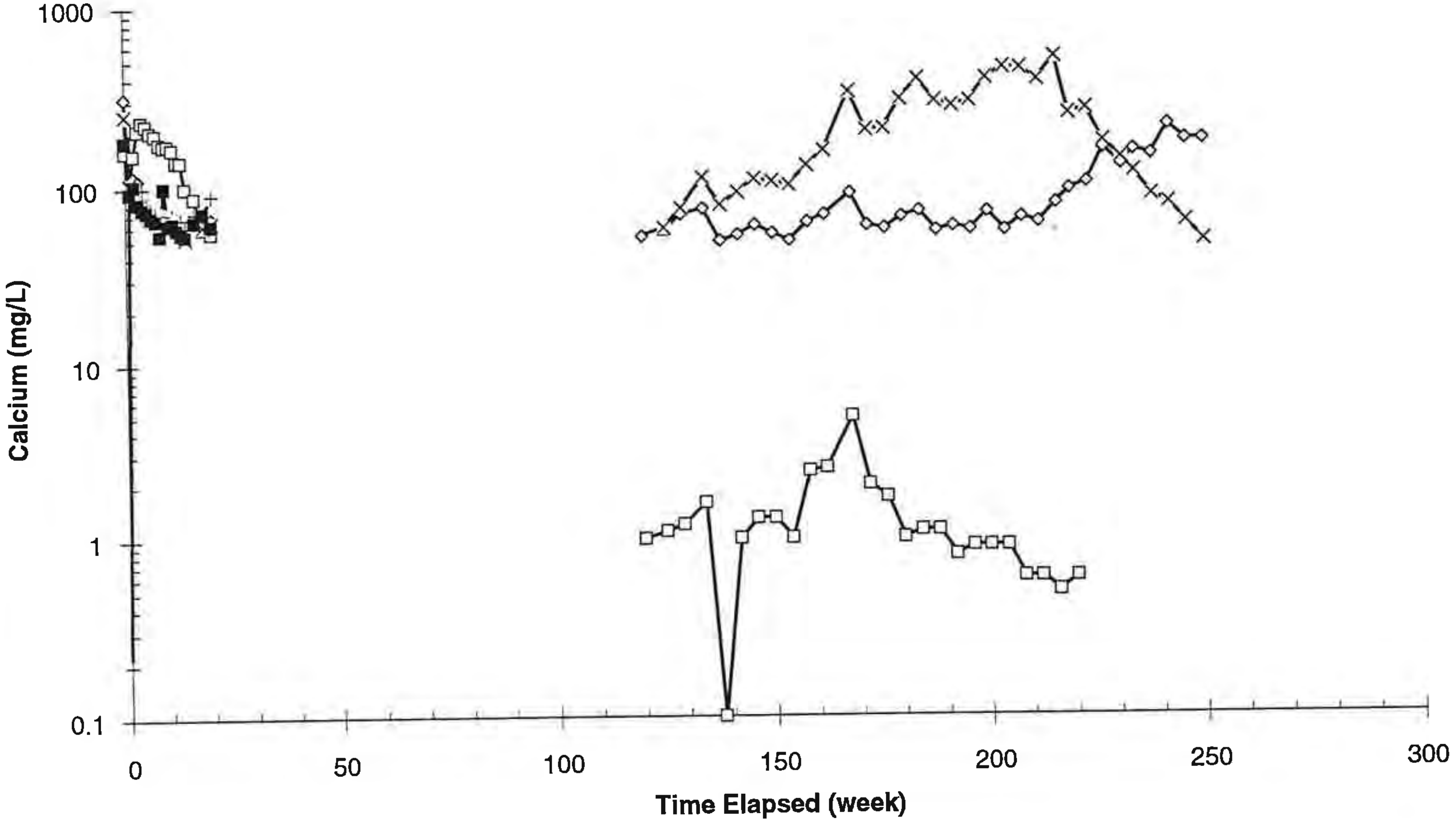

Figure 8-5
LIMESTONE MIXING STUDY
CALCIUM CONCENTRATIONS
IN LEACHATE

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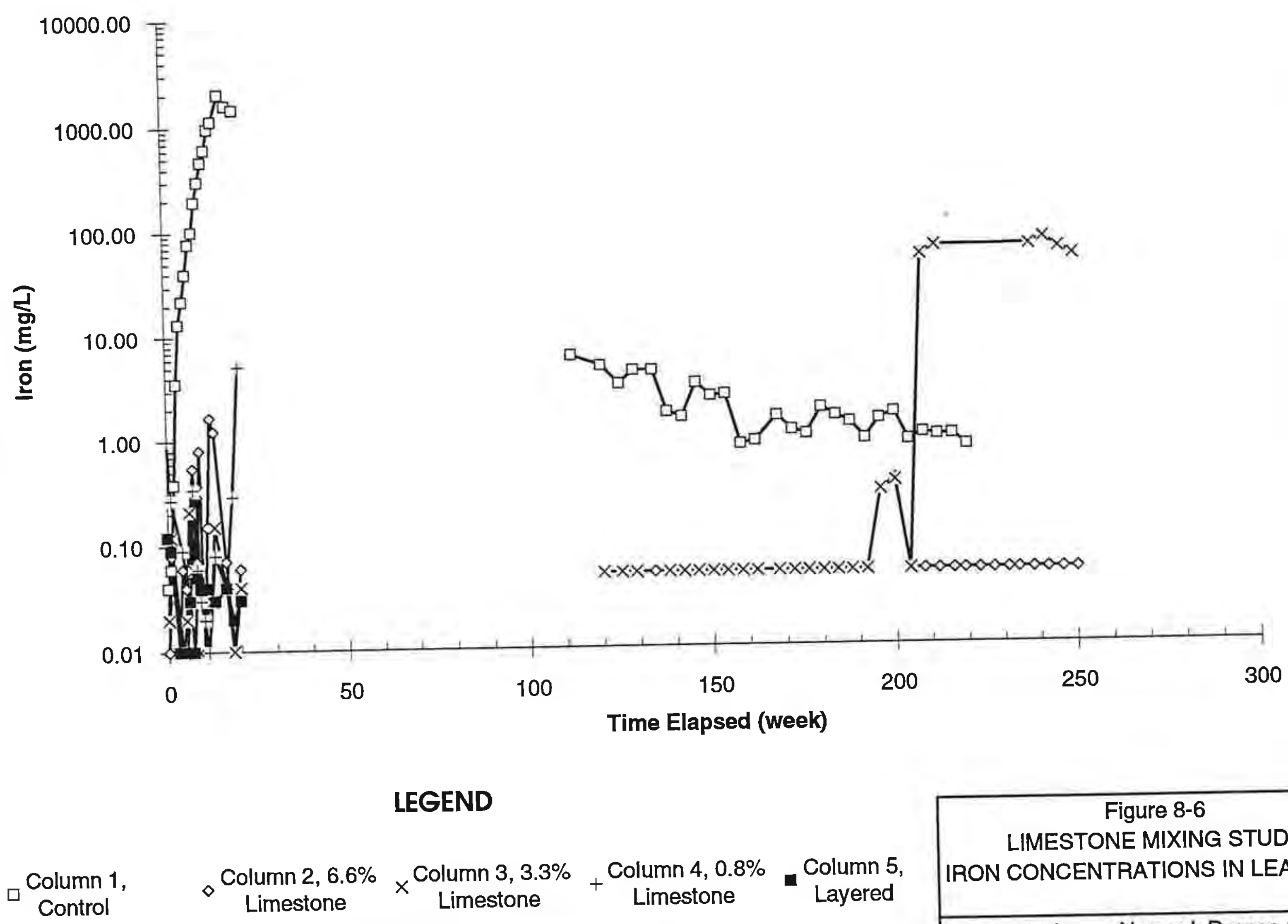

Figure 8-6
LIMESTONE MIXING STUDY
IRON CONCENTRATIONS IN LEACHATE

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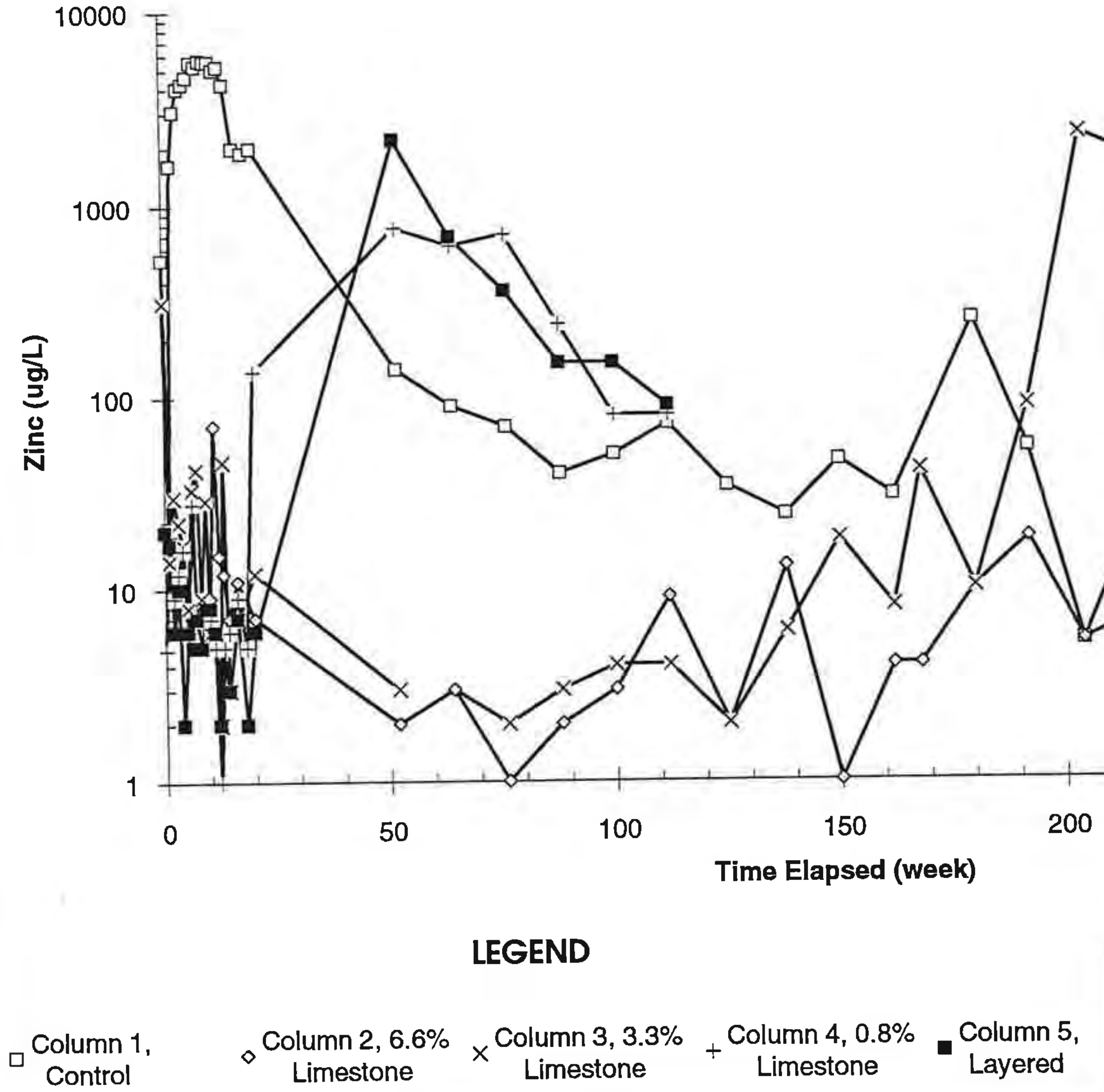

Figure 8-7
LIMESTONE MIXING STUDY
ZINC CONCENTRATIONS
IN LEACHATE

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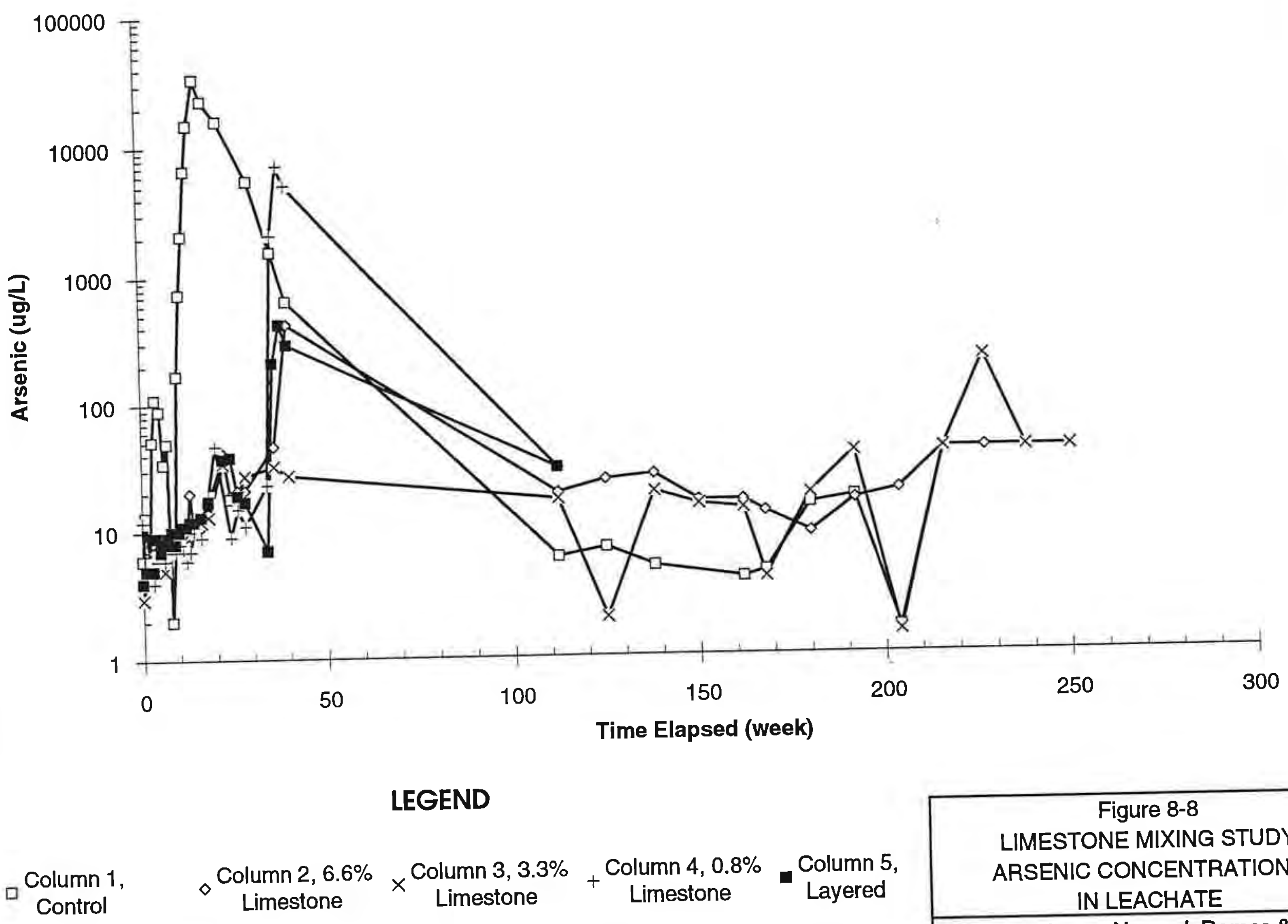

Figure 8-8
LIMESTONE MIXING STUDY
ARSENIC CONCENTRATIONS
IN LEACHATE

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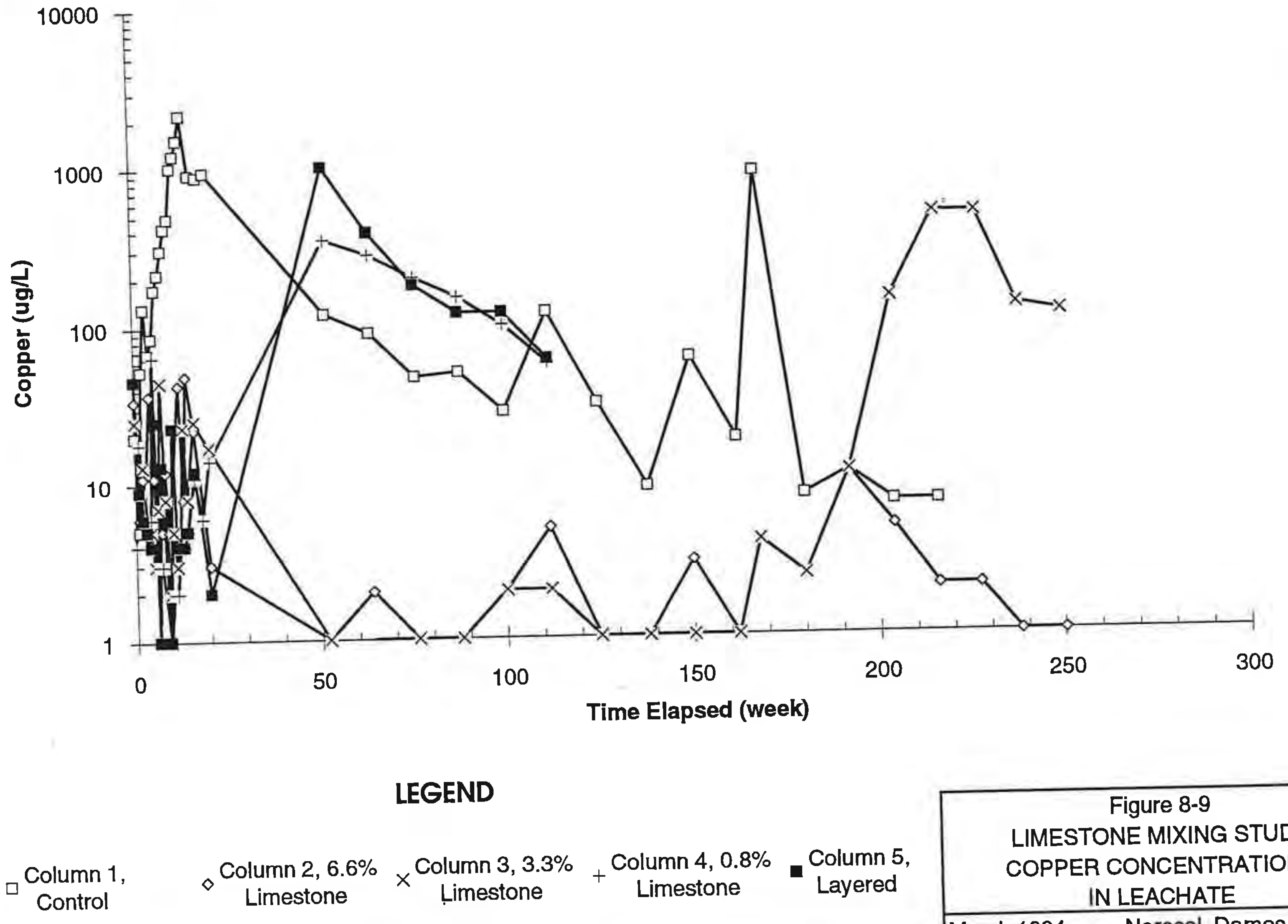

Figure 8-9
LIMESTONE MIXING STUDY
COPPER CONCENTRATIONS
IN LEACHATE

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8.4 TEST RESIDUE CHARACTERISTICS

Characterization of test material residues consisted of the following procedures:

1. Column dismantling and examination of residues.
2. Petrographic descriptions of residues.
3. Size fraction analysis, acid-base accounting and sequential leach on residues.

Results from these procedures are described in the following sections.

Column Dismantling and Examination of Residues

Columns 4 (0.8% Limestone) and 5 (Layered) were dismantled before the MEND/BC AMD Task Force project was initiated. The residues were not examined during dismantling but were stored for subsequent analysis.

Column 1 (Control) was found to be strongly oxidized and slightly cemented throughout (Figure 8-10). The top portion of the column was cemented. The material had an overall yellow coloration with small orange mottles, presumably representing oxidation of sulphide-bearing grains. The material did not react visibly with 10% hydrochloric acid indicating that calcium carbonate was generally absent. No evidence of flow path formation was observed indicating that water had moved uniformly throughout the column.

Column 2 (6.6% Limestone) showed vertical zonation (Figure 8-11). The top third of the column was orange and cemented. This material reacted slightly with 10% hydrochloric acid indicating that small amounts of limestone remained. The lower two thirds were grey with very few orange grain-sized mottles. This material reacted rapidly with HCl indicating the presence of readily-available limestone. At the transition, large orange mottles composing about 50% of the mass were observed. Residue pH's of rock removed from these zones were determined without crushing the rock. The well-oxidized zone yielded residue pH's of 2.8 to 4.5. In the transition zone, this increased to 5.5. Finally, the much less-oxidized rock yielded residue pH's of 7.8 to 8.5 consistent with the presence of limestone. Residue pH's increased uniformally with increasing depth in the column. These values were indicative of acidic rapidly oxidizing conditions in the upper part of the column and neutral to alkaline less oxidized conditions in the lower part of the column.

Since Column 3 (3.3% Limestone) was constructed of clear plastic, the residues could be examined prior to dismantling. The majority of the material resembled the upper portion of Column 2 (6.6% Limestone). However, a distinctive vertical zone of grey less-oxidized material was observed along one side (Figure 8-12). When the residues were removed, the grey material was found to react strongly with hydrochloric acid indicating the presence of unreacted limestone.

Figure 8-10a Column 1 residue (top of column is at right).

Figure 8-10b Close up of column 1 rock.

Figure 8-12a Column 3 residue (top of column is at right).

Figure 8-12b

Side view of Column 3. Note less oxidized rock (grey).

Petrographic Descriptions

Petrographic descriptions were completed for polished thin sections of the residues (Appendix C). The following features were noted for sulphide grains:

- in residues from non-acidic columns, abundant fresh pyrite and marcasite grains were observed within rock particles. These grains showed some in situ replacement along grain boundaries by limonite (Figure 8-13);
- in residues from acidic columns, alteration of pyrite grains varied from negligible to complete. In situ replacement of sulphide grains by limonite was commonly observed. Replacement had taken place along grain edges and along internal fractures and crystal boundaries;
- corrosion of sulphide grains or boxwork textures were not observed;
- limonite formed by precipitation of iron from solution was less common than in situ replacement and generally occurred as a very thin coating on grain edges resulting in a general yellow appearance (Figure 8-14);
- limestone particles in non-acidic and acidic columns appeared relatively unaltered and did not have significant limonite rinds (Figure 8-14);
- very little limestone was observed in the acidic residues from Columns 3 (3.3 Limestone), 4 (0.8% Limestone), and 5 (Layered) and the upper acidic part of Column 2 (6.6% Limestone);
- any limestone particles in acidic columns had irregular grain edges suggesting corrosion; and
- corrosion of silicate grains was not observed.

In summary, pseudomorphic (one-for-one replacement) of iron sulphide grains by limonite (primarily goethite, FeOOH) appeared to be common. Blinding of limestone grains by transported limonitic coatings did not appear to have occurred.

Particle Size Analyses

The procedure used to determine size distributions for waste rock and limestone prior to the tests was repeated on all column residues. Surface areas were estimated to evaluate tendency for generation or removal of fines. No significant differences were observed between pre- and post-test materials. This observation probably reflects the inaccuracy of the method rather than the absence of change.

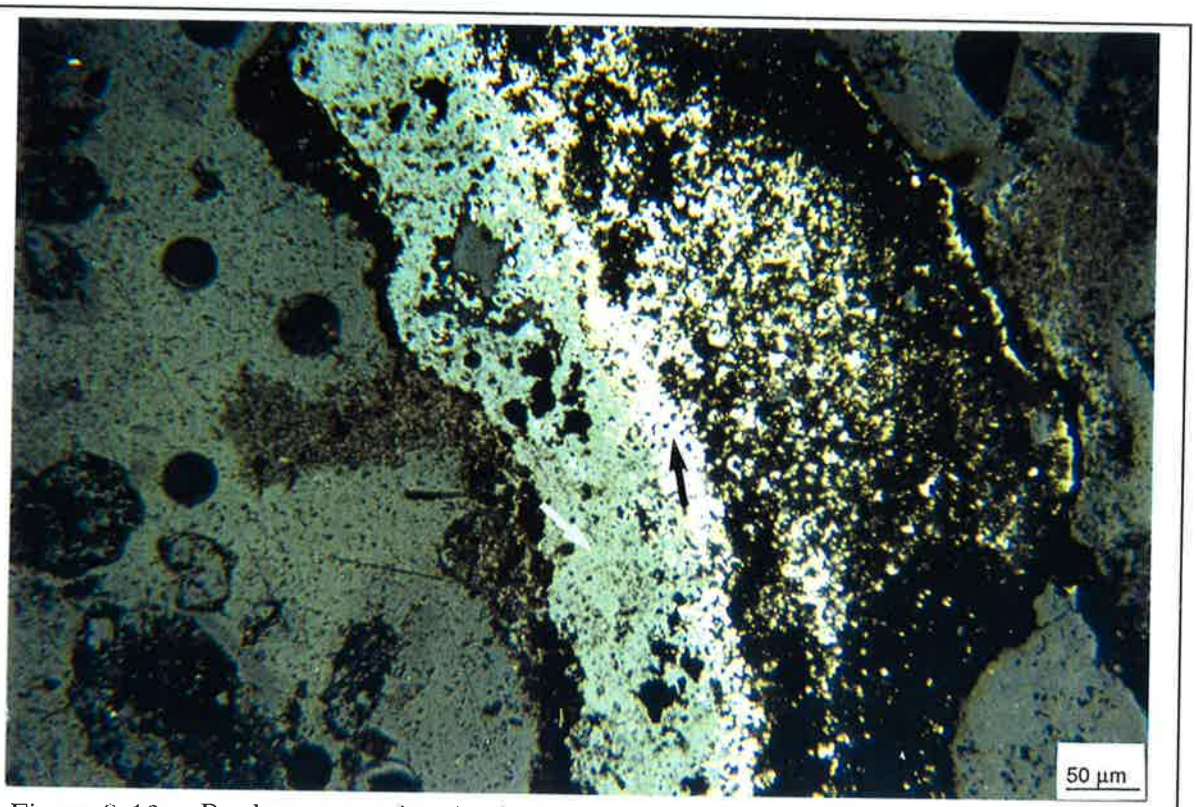

Figure 8-13a Replacement of pyrite (pale yellow, black arrow) by goethite (light grey, white arrow). Goethite is about 0.1 mm across. Column 2, less oxidized material in reflected light.

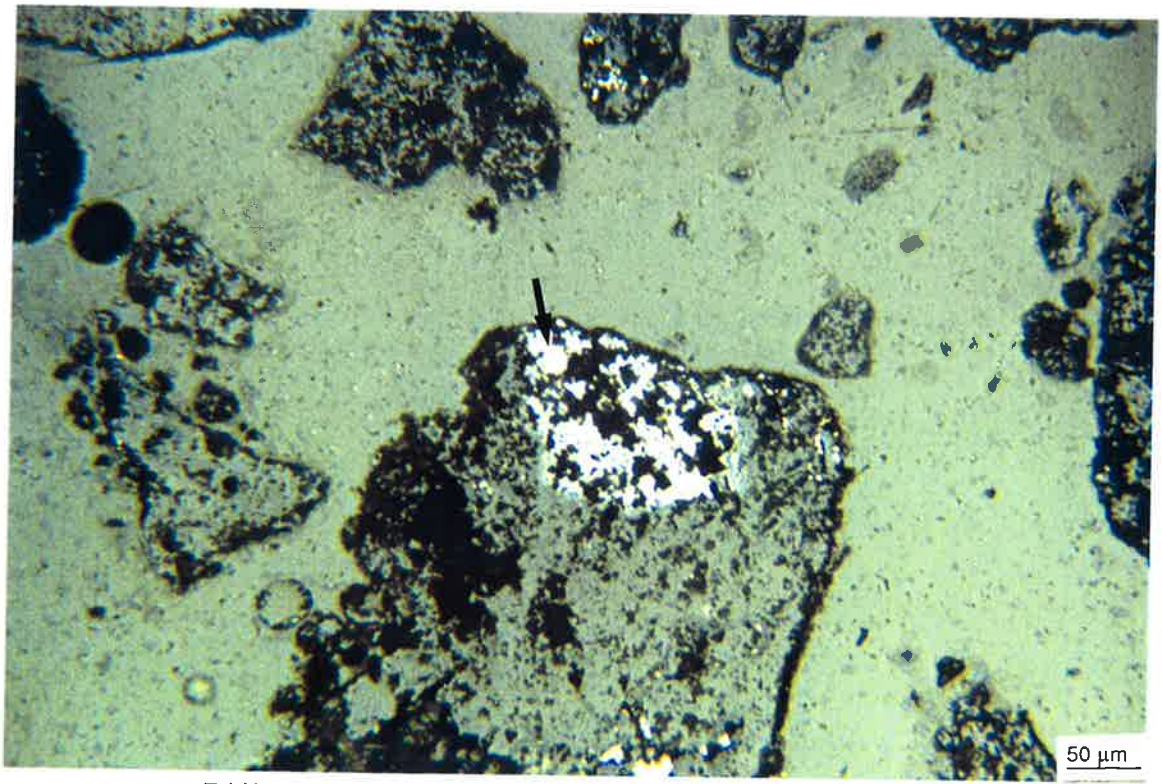

Figure 8-13b Different grain in Column 2, less oxidized material in reflected light. Mostly pyrite (black arrow).

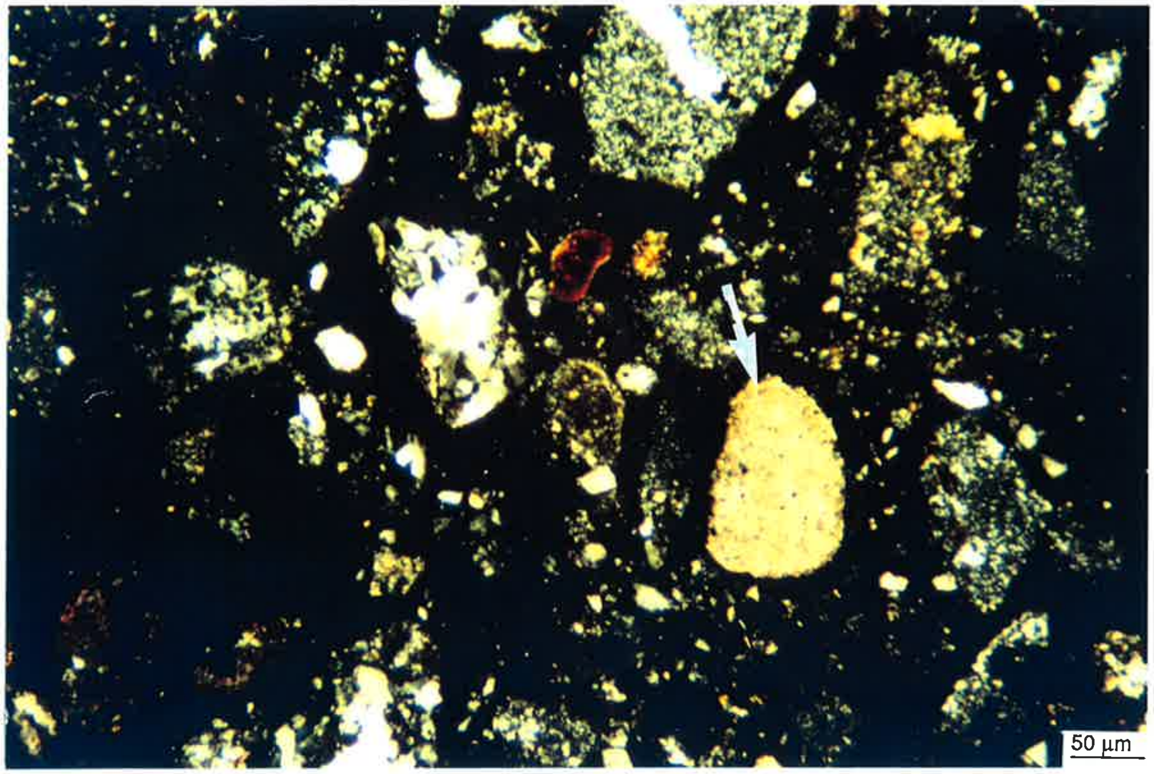

Figure 8-14a Typical column material. Yellowish oval grain right of centre is limestone (indicated). Field of view is about 1 mm. Cross-polarized light.

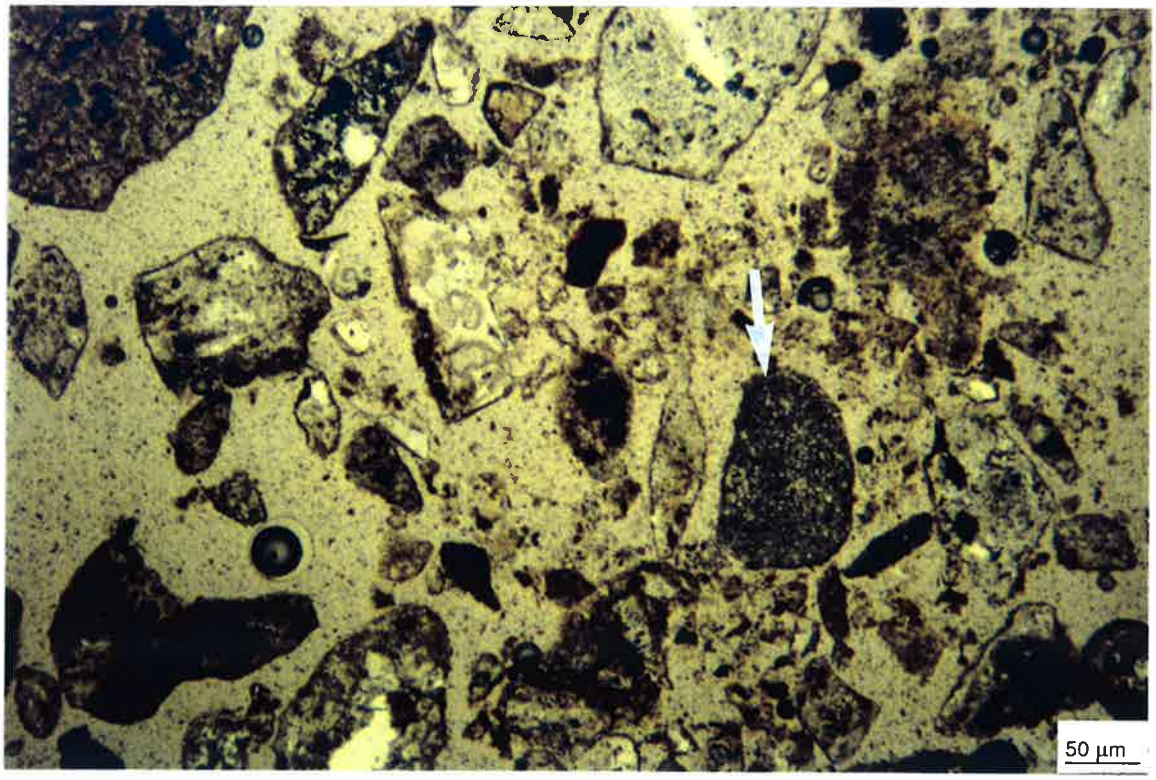

Figure 8-14b Same view as 8-14a. Plane-polarized light.

Acid-Base Accounting

Pre- and post-test acid-base accounting results (on a mass-weighted basis) are summarized in Table 8-3. For Columns 1 (Control) and 3 (3.3% Limestone), acid-base accounts were determined for material collected from the top and middle parts of the columns. For Column 2 (6.6% Limestone), well-oxidized and less oxidized materials were sampled and tested separately. For Columns 4 (0.8% Limestone) and 5 (Layered), the bulk material was sampled and tested. Two sub-samples of each type of material were tested to determine sampling and analytical variability. Reproducibility of duplicate analyses was excellent and confirmed that differences in chemistry between column zones and experiments were significant.

Columns 4 (0.8% Limestone) and 5 (Layered) yielded very similar results for total sulphur and sulphate. Total sulphur concentrations decreased by about 1.3% over the two years of weathering. All reactive neutralizing material was consumed, as shown by negative neutralization potentials. Column 1 (Control) yielded slightly lower sulphur concentrations after five years of leaching and similarly had no detectable NP. Column 3 (3.3% Limestone) yielded slightly greater sulphur concentrations and had no NP. Lower concentrations were determined in the middle samples. This may represent sampling of different proportions of oxidized and less oxidized material. Large scale mottling was observed in the column.

Material from the top part of Column 2 (6.6% Limestone) contained higher concentrations of sulphur than any of the other well-oxidized material, and had a small amount of NP. The deeper less oxidized material contained about 0.3% less sulphur than at the start of the study. NP decreased by 12 kg $CaCO_3$/t from 69 to 57 kg $CaCO_3$/t. The small NP measured in the upper material may have represented inclusion of mottles of less oxidized material. Carbon dioxide determinations indicated a lower neutralization potential (37 compared to 57 kg $CaCO_3$/t) than the conventional acid titration method. Pre-test acid-base accounting indicated a similar discrepancy between neutralization potential and CO_2 determination. The difference suggests that the limestone may contain minerals other than calcite which are contributing to neutralization potential, or that either the NP or CO_2 determinations are consistently erroneous. Pre- and post-test values were determined by the same laboratories which may indicate a systematic laboratory error in either determination.

Sequential Leach on Residues

The sequential leach results from the column residues (Table 8-4) demonstrated similar difficulties with the extraction procedures discussed in Section 7.3.3.

The distribution of iron appeared to reflect the state of weathering in the residues. The four strongly oxidized materials (Columns 1, 3, 4, 5) contained more than 55% iron as secondary minerals (probably ferric hydroxides), and proportion results were relatively consistent. The top part of Column 2 (6.6% Limestone) was also acidic but the proportion of iron in secondary minerals was less than 50%. In time, this material might have been expected to be similar to the other four columns.

TABLE 8-3
ACID-BASE ACCOUNTING
RESULTS FOR COLUMN MATERIALS AND RESIDUES

COLUMN			POSITION IN COLUMN	Total Sulphur	Sulphate Sulphur	Sulphide Sulphur(1)	MPA (2)	NP (2)	NNP (2)	NP/MPA (3)	Residue or Powder pH (4)
				(%)	(%)	(%)	(kg CaCO3/t)				
1	Control	Pre-Test	Bulk	2.1	-	-	66	8	-58	0.12	6.9
		Post-Test	Top, bulk	0.54	0.09	0.45	14	-2	-16	-	3.3
				0.52	0.09	0.43	13	-2	-15	-	-
		Post-Test	Middle, bulk	0.53	0.1	0.43	13	-2	-15	-	3.6
				0.57	0.1	0.47	15	-2	-17	-	-
2	6.6% Limestone	Pre-Test	Bulk	1.98	-	-	62	69	7	1.11	-
		Post-Test	Oxidized, bulk	1.11	0.05	1.06	33	2	-31	0.06	5.3
				1.13	0.05	1.08	34	3	-31	0.09	-
		Post-Test	Non-oxidized, bulk	1.72	<0.01	1.71	53	57	4	1.08	7.8
				1.71	<0.01	1.7	53	56	3	1.06	-
		Post-Test	0 to 5 cm	-	-	-	-	-	-	-	2.8
			Oxidized	-	-	-	-	-	-	-	4.5
			Mostly oxidized	-	-	-	-	-	-	-	5.5
			Mostly non-oxidized	-	-	-	-	-	-	-	7.8
			Non-oxidized	-	-	-	-	-	-	-	8.5
3	3.3% Limestone	Pre-Test	Bulk	2.05	-	-	64	38	-26	0.59	-
		Post-Test	Top, bulk	0.83	0.05	0.78	24	0	-24	0.00	4.8
				0.86	0.05	0.81	25	0	-25	0.00	-
		Post-Test	Middle, bulk	0.77	0.11	0.66	21	-2	-23	-	4.1
				0.77	0.11	0.66	21	-2	-23	-	-
4	0.8% Limestone	Pre-Test	Bulk	2.08	-	-	65	16	-49	0.25	-
		Post-Test	Bulk	0.63	0.11	0.52	16	-2	-18	-	4.1
				0.67	0.11	0.66	21	-2	-23	-	-
5	Layered	Pre-Test	Bulk	2.08	-	-	65	19	-46	0.29	-
		Post-Test	Bulk	0.68	0.12	0.56	18	-2	-20	-	4.3
				0.68	0.12	0.56	18	-2	-20	-	-

NOTES:

1. Sulphide sulphur is calculated from total sulphur - sulphate sulphur.
2. MPA - Maxiumum Potential Acidity; NP - Neutralization Potential; NNP - Net Neutralization Potential.
3. NP/MPA is only determined if NP>0.
4. Colum 1 pre-test value determined on pulverized sample. Remainder on small uncrushed samples.
5. "-" sample collected but not tested for indicated parameter.

TABLE 8-4
SUMMARY OF SEQUENTIAL METAL EXTRACTIONS ON COLUMN RESIDUES

Column	Description	Position in Column	Concentrations (ppm)				Proportion of Total (%)			
			Hydro-chloric Acid	Ammonium Oxalate	Nitric Acid - Bromine	Nitric Acid - Perchloric Acid	Hydro-chloric Acid	Ammonium Oxalate	Nitric Acid - Bromine	Nitric Acid - Perchloric Acid
COPPER										
1	Control	Bulk	4	0	0	0	100	0	0	0
2	6.6% Limestone	Middle	5	0	8	0	38	0	62	0
2	6.6% Limestone	Top	8	0	3	0	73	0	27	0
3	3.3% Limestone	Bulk	6	0	3	0	67	0	33	0
4	0.8% Limestone	Bulk	4	0	1	0	80	0	20	0
5	Layered	Bulk	2	0	3	0	40	0	60	0
ZINC										
1	Control	Bulk	9	0	0	0	100	0	0	0
2	6.6% Limestone	Middle	38	0	4	0	90	0	10	0
2	6.6% Limestone	Top	24	0	3	0	89	0	11	0
3	3.3% Limestone	Bulk	16	0	1	0	94	0	6	0
4	0.8% Limestone	Bulk	11	0	0	1	92	0	0	8
5	Layered	Bulk	12	0	1	0	92	0	8	0
IRON										
1	Control	Bulk	600	0	430	0	58	0	42	0
2	6.6% Limestone	Middle	410	0	1690	0	20	0	80	0
2	6.6% Limestone	Top	1070	0	1140	60	47	0	50	3
3	3.3% Limestone	Bulk	1200	0	950	0	56	0	44	0
4	0.8% Limestone	Bulk	770	0	500	0	61	0	39	0
5	Layered	Bulk	890	0	550	0	62	0	38	0

Notes:

1. Similar tests were not performed on samples prior to weathering.

The weakly oxidized residue from the middle part of column 2 contained the lowest proportion of iron as secondary minerals. This was consistent with the observed oxidation state.

Although both zinc and copper occur as sulphides (sphalerite, chalcopyrite) in Cinola ore-grade material, these minerals have not been observed in the waste rock. As concentrations of zinc and copper are very low (background for these rock types), the metals may be occurring as minor components of sulphide minerals (pyrite) and silicates (zinc in feldspars; copper in biotite).

In the residues, zinc was clearly partitioned to a greater degree in the secondary phase fraction than copper. Most zinc appeared to be present as secondary phases. Both copper and zinc were probably incorporated into the structures of precipitated iron hydroxides. Several reasons for the difference in behaviour between copper and zinc can be suggested. Chalcopyrite is more resistant to bacterial oxidation than sphalerite. If, however, these metals are occurring as silicates, a difference in reactivity of silicate phases would also explain the difference.

8.5 INTERPRETATION OF RESULTS

8.5.1 Leachate Chemistry

Column leachate chemistry followed a series of stages. Initially, sulphate concentrations were elevated as weathering products accumulated during sample storage were flushed from the columns. During stable pH neutral conditions, the dominant ions in solution were calcium and sulphate. The molar ratio of sulphate to calcium under these conditions was between 0.5 and 1 (Figure 8-15) which was consistent with general chemical theory for acid generation and neutralization. The usual reaction used to express overall acid generation under conditions pH>3 is:

$$FeS_2 + 15/4O_2 + 5/2H_2O \text{ --> } 2SO_4^{2-} + Fe(OH)_3 + 4H^+;$$

Under acidic conditions (pH less than 5.0), the acidity will be neutralized by $CaCO_3$, thus:

$$CaCO_3 + 2H^+ \text{ --> } Ca^{2+} + H_2CO_3^{o}$$

and under neutral to alkaline (pH 7 to 9) conditions:

$$CaCO_3 + H^+ \text{ --> } Ca^{2+} + HCO_3^-$$

Under acidic conditions, the molar ratio of sulphate to calcium would be equal or greater than 1, whereas under less acidic conditions the ratio would be less than 1. Several months prior to generation of acidic leachate, this ratio steadily increased and gradually approached 1. Once acidic leachate was produced, the ratio passed 1.

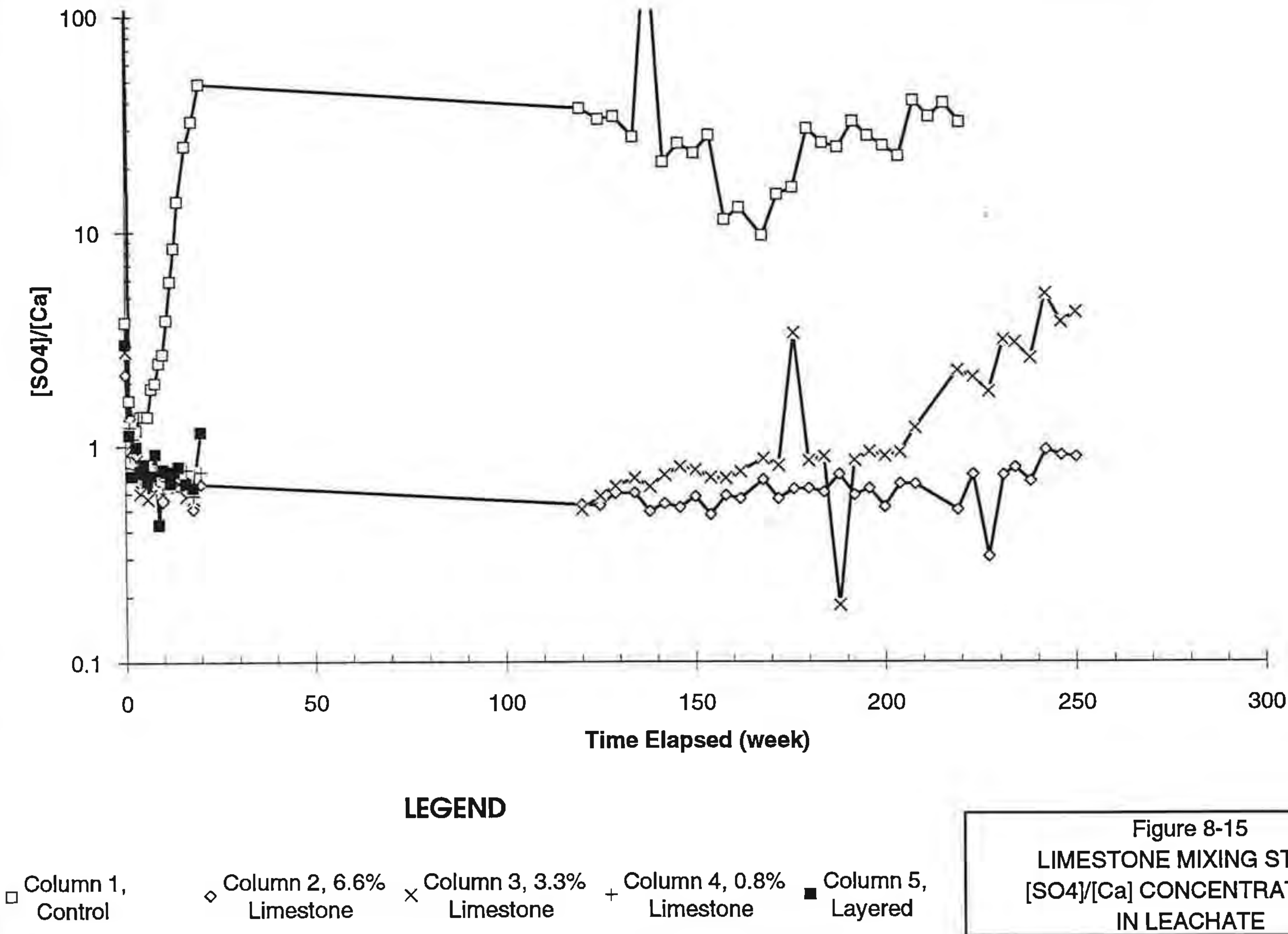

Figure 8-15
LIMESTONE MIXING STUDY
[SO4]/[Ca] CONCENTRATIONS
IN LEACHATE

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Column leachates were previously evaluated for saturation with respect to gypsum in the Cinola Stage II report (City Resources 1988, Volume V). Modelling of aqueous species using MINTEQ (Peterson *et al.*, 1986) indicated that the solutions were generally not saturated with respect to gypsum.

The dominant anion in acid leachates was sulphate with the cationic balance being made up by aluminum, iron and calcium. At the lowest pH's (less than 2.9) observed during peak sulphate production, the ratio of molar concentrations of sulphate and iron was less than 2. Since the molar ratio of sulphur to iron in pyrite is 2, leachate chemistry implied sulphate was being stored in the columns, or that other iron minerals were being dissolved by the acidic leachate. As MINTEQ calculations by City Resources showed that sulphate concentrations were not being limited by saturation, it appears that previously precipitated iron hydroxide was being leached to release iron. As sulphate production decreased and pH rose to greater than 3.0, limonite apparently became stable and sulphate to iron concentration ratios increased to greater than 2.0.

8.5.2 Consumption of Iron Sulphide

The mass of sulphate released can be estimated from the sulphate concentration in the leachate and the volume of water recovered from the column:

$$\text{Mass of Sulphate (mg)} = SO_4^{2-} \text{ concentration (mg/L) x Volume (L)} \qquad (8\text{-}1)$$

Sulphate was not determined every week, but the volume of water recovered was measured continuously. Therefore, the total amount of sulphate released could be estimated. As indicated in Section 8.5.1, gypsum saturation did not appear to have limited the concentration of sulphate in the leachates, except perhaps when sulphate concentrations were greatest. Since gypsum was not likely to be storing significant amounts of sulphate in the column, the total sulphate released by the columns is probably a reasonable approximation of the total sulphate produced by oxidation of sulphides. This assumes that all material was leached and that focusing of flow along a few discrete pathways did not occur.

The total equivalent amount of sulphate in the column can be estimated from the total sulphur determined for the acid-base account. The proportion of sulphur consumed during the course of the experiment can then be estimated:

$$\text{Sulphur consumed (\%)} = \text{(Sulphate Released/Sulphate Available) x 100.} \qquad (8\text{-}2)$$

Post-test acid-base accounting provided an alternative method to calculate the amount of sulphate released (Table 8-3).

Total sulphate released was greatest for the control test (column 1). Sulphate released was 62% of the estimated sulphate which could be produced by oxidizing all sulphur in the column. The three columns which subsequently generated acid released between 49 and 61% of the total sulphur content. Most sulphate was released during the sulphate concentration peak which followed the release of acidic leachate. Column 2, which had not generated acidic leachate when terminated, released only 11% of contained sulphur. Sulphate load was also used to estimate the expected sulphur concentration in the residue. Actual sulphur concentrations in residues (Table 8-3) were between 0.2 to 0.4% less than predicted by sulphate load. As the bias was always positive and relatively constant, it appeared the difference may have resulted from an incorrect measurement of the weight of material in the column, the volume of leachate produced, the analytical sulphate concentration or the original acid-base account.

8.5.3 Consumption of Limestone

Acid-base accounting results for residues from columns generating acidic leachate (1,3,4,5) indicated that no significant neutralization potential remained in the residues. Since calcium concentrations in leachates were not measured continuously, it was not possible to obtain an accurate indication of limestone consumption. Results from Column 3 (3.3% limestone) were most amenable to interpolation across the gap in monitoring results. Using the same calculation method as for sulphate, it was estimated that 75% of calcium had been removed (assuming that all neutralization potential occurs as calcite). The discrepancy between the predicted loss of limestone and measured residue neutralization potential (Table 8-3) could be due to the presence of dolomitic limestone, or the previously described difference between limestone purity determined by acid-base accounting and CO_2. If the CO_2 value is assumed to be correct, the observed release of calcium accounted for all limestone in the column. Slower release of calcium following the onset of acidic conditions may have reflected removal of small residual amounts of limestone and leaching of silicates, as noted for the waste rock pads.

Petrographic observations supported the conclusion that almost all limestone was dissolved and thus was available for buffering of acidic leachate. Very few limestone fragments were observed in the residues from acidic columns. In the oxidized part of Column 2 (6.6% Limestone), remaining limestone particles were corroded and did not have a thick coating of precipitated limonite.

The lack of limonite rinds on limestone fragments was consistent with the low iron concentrations in leachate prior to generation of acid, and the observed in situ one-for-one replacement of pyrite by limonite (goethite). During pH neutral conditions, iron probably remained at the oxidation site as goethite and was not transported to limestone grains. In this study, the limestone and acid generating rock were relatively well mixed. Under less well-mixed conditions where local areas of acidity develop, one might expect iron to move away from the oxidation site, precipitating in areas of higher pH and perhaps cementing limestone grains. This hypothesis suggests that the availability of calcareous material would probably decrease as the mixture becomes more heterogeneous and may explain the observation that the limestone applied in layers did not appear to be completely available to neutralize acid. Coating and cementation of limestone particles by limonite was likely to occur once the material became acidic.

8.5.4 Determination of Theoretical Quantity of Limestone Required to Neutralize All Acidity

Four of the columns were predicted to be acid generating based on mass-weighted acid-base accounts, and all four columns produced acidic leachate during the course of the study. Column 2 (6.6% limestone) did not yield acidic leachate during five years of weathering; however, the upper part of the column was clearly acidic (as shown by low residue pH and negligible neutralization potential), and sulphate and metal concentrations were observed to be increasing at the time the study was terminated. This column fits the relationship:

$$t_{\text{SO4 increase begins}} = 2.9\text{NP} - 25 \tag{8-3}$$

where t is time in weeks and NP is neutralization potential in kg $CaCO_3$/t. Although based on only five points (see Figure 8-16(a)), the correlation coefficient (r=0.991) is statistically significant with a confidence level of better than 95%.

It is expected that Column 2 (6.6% Limestone) would have eventually produced acidic leachate. The time required to produce acidic leachate for this column can be estimated from results from the other columns (Figure 8-16b) which clearly define the relationship. As the time taken for Column 1 (Control) leachate to become fully acidic is not well defined, since the column generated acidic very rapidly, the following relationship was determined instead:

$$t_{\text{max SO4}} = 11.2e^{0.079\text{NP}}. \tag{8-4}$$

This relationship was derived because all four sulphate peaks are well defined but the transition to low pH conditions is not well-defined for Column 1 (control).

For Column 2 (6.6% Limestone), the peak sulphate concentration was predicted to occur after 2600 weeks (50 years). The visual progress of the acid generation front suggested a much shorter time frame. If the rate of migration was constant, acid release would have been expected after about 15 years. The sulphate peak would have been at a much lower concentration than for the other columns and would have been poorly defined.

The amount of limestone required to neutralize acid for an infinite time period cannot be estimated from the above relationships since neither converge to a limiting value. However, the molar ratio of sulphate to calcium during the pre-acid leachate phase indicated the release of calcium in proportion to sulphate. The ratio was typically 0.5 to 0.6. If a ratio of 0.5 is also applicable to the mine site conditions, the actual NP required to prevent acid release is double the amount in column 2 or 138 kg $CaCO_3$/t.

Surface area weighted acid-base accounts predicted that Columns 2 (6.6% Limestone) and 3 (3.3% Limestone) would not generate acid due to the greater exposed area of limestone in these columns. Since these columns generated acid, the additional surface area provided by crushing the limestone was not beneficial in increasing the availability of limestone. This was confirmed by petrographic examination which showed that all limestone was consumed,

Column	Description	NP kg CaCO3/t	Sulphate Release Increasing week	Leachate pH<7 week	Sulphate Peak week	Half Sulphate Peak week	Sulphate Released % of Total
1	Control	8	1	1	20	25	62
2	6.6% Limestone	69	170	-	-	-	11
3	3.3% Limestone	38	100	200	219	241	50
4	0.8% Limestone	16	19	31	40	58	61
5	Layered	19	19	31	54	72	49

Note: Refer to annotations on Figure 8-2

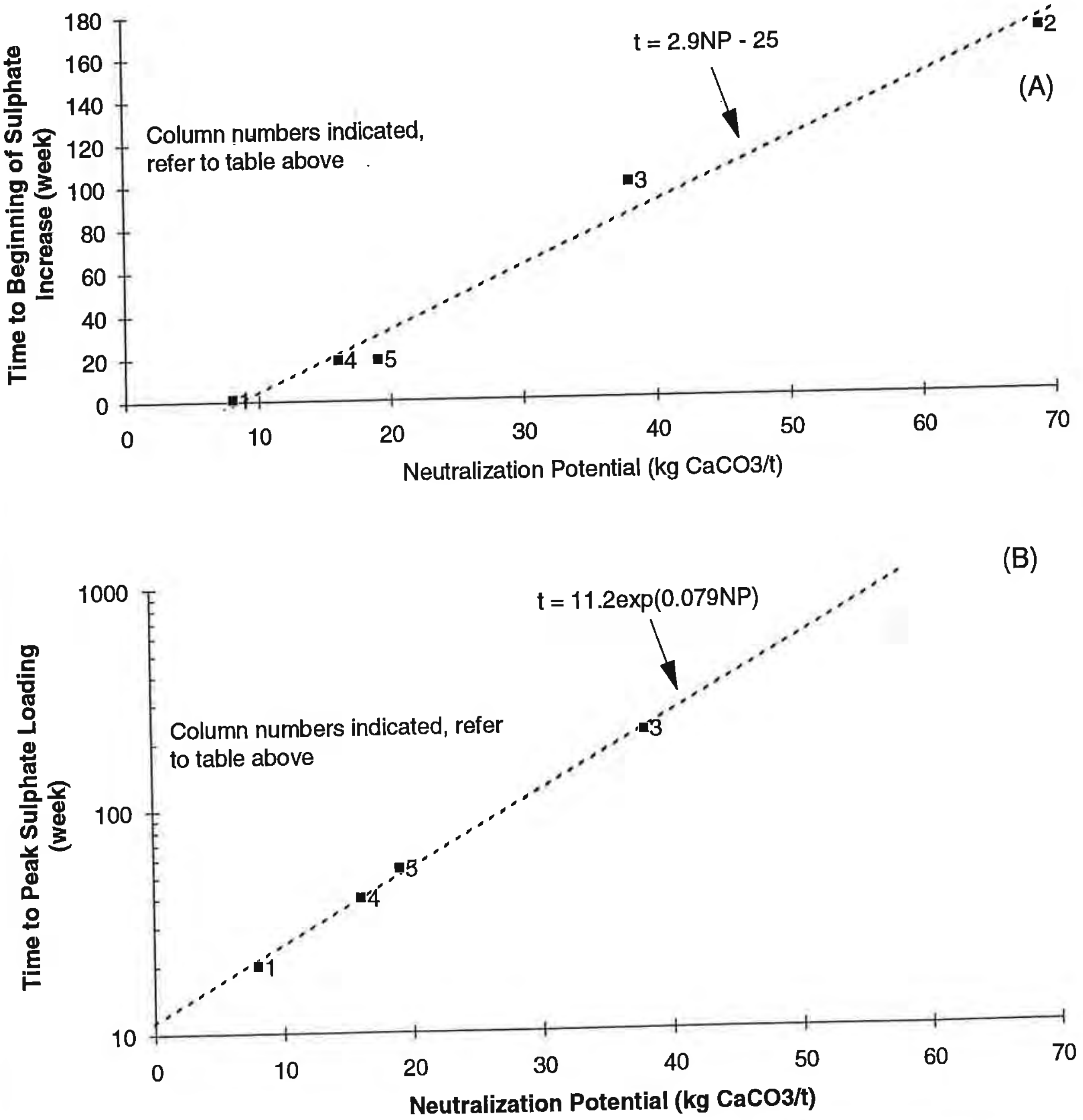

Figure 8-16
LIMESTONE MIXING STUDY
NEUTRALIZATION POTENTIAL
VERSUS TIME

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and that significant coating of limestone particles did not occur as a result of precipitation of iron hydroxide.

8.5.5 Effect of Crushing Limestone

Limestone was crushed for this study to increase the availability of limestone. Since parallel tests using coarser limestone were not operated, it is not possible to predict the full effect of reduced particle size. As indicated in Section 8.5.4, all limestone was apparently available to neutralize acid, and there was no evidence that the larger limestone particles were not available for acid buffering. Nonetheless, crushing of limestone is expected to be beneficial for several reasons:

- greater surface area provides greater reactivity, possibly resulting in a longer lead time to initial release of sulphate and metals;
- a more uniform distribution of limestone allows alkaline porewater conditions to develop throughout the waste rock;
- a greater potential for acidic streams to contact limestone, ie. fewer flow paths avoiding limestone fragments;
- lower potential for loss of neutralization potential should localized coating by iron hydroxides occur.

Some possible disadvantages of crushing limestone include greater loss of neutralization potential due to dissolution by rain water, and possible physical transport of fragments through the pile. The former concern is relatively insignificant since the concentration of calcium in equilibrium with calcite under atmospheric conditions ($P_{CO2} = 10^{-3.5}$ atm) is approximately 20 mg/L (Drever 1982).

8.5.6 Effect of Layering of Acid Consuming Materials

The concentration of limestone in Column 5 (layered) was intermediate between the lowest and intermediate limestone concentrations in Columns 3 (3.3% limestone) and 4 (0.8% limestone), respectively. However, in Column 5, the limestone was deliberately concentrated in thin layers containing Column 2 (6.6% Limestone) materials interlayed between thick layers of a mixture comparable to Column 4. This column generated acidic leachate at exactly the some time as Column 4. These results indicate that the thin layers of higher neutralization potential mixture provided negligible net benefit.

This result can be explained by noting that once acidic conditions developed in the lower concentration limestone layers, acid was produced very rapidly and probably overwhelmed the limestone in the more concentrated layers. Where higher concentrations of limestone were more homogeneously mixed with the acid generating rock, non-acidic conditions could be maintained for much longer due to suppression of isolated acid producing zones.

8.5.7 Mitigation of Metal Release by Limestone Addition

Comparison of heavy metal and sulphate concentrations indicated that:

- sulphate and heavy metal concentrations were well-correlated;
- when sulphate release increased prior to release of acidic leachate, concentrations of heavy metals and arsenic also increased;
- peak concentrations of arsenic decreased as limestone content increased.

These observations show that under fully alkaline conditions (pH greater than 7.0) where sulphate production is fairly uniform, metal and arsenic concentrations will remain low and stable. Once sulphate production begins increasing, metal release also increases. Zinc was the first to appear followed by arsenic and copper. This is consistent with the known pH stability of these metals. Zinc tends to be more soluble at high pH values and therefore is released most readily from the columns. Copper is less soluble at high pH values in the presence of carbonate alkalinity and thus tended to be retained in the columns until fully acidic conditions (pH less than 3) developed.

In terms of mitigation of release of zinc (and related metals such as cadmium) and arsenic, limestone addition delayed release approximately according to equation 8-3. However, if these metals are not a concern, heavy metal release is delayed according to equation 8-4.

The observed decrease in arsenic peaks as limestone concentration increased may be a result of decreased solubility due to the formation of calcium arsenate.

8.5.8 Cost of Limestone Addition

The proposed source of limestone for the project was Texada Island. The limestone would have been transported by barge along the British Columbia coast and then transferred to trucks for delivery to the project site. In 1993, the cost of bulk limestone in the volumes required for the project was \$5/tonne. Transportation costs were estimated at \$8/tonne, for a total delivery cost of \$13/tonne. Some handling of the limestone would have been required at the site, although costs would probably be in the order of \$1/tonne. At an addition rate of 6.6% limestone, the cost to treat one tonne of waste rock would be \$1.90. Based on this study, general costs would be \$0.88/%S/t of waste rock (assuming an addition rate of 62.5 kg/t/%S), of which \$0.34/%S/t is the cost of limestone.

9.0 COMPARISON OF TESTS

The purpose of this chapter is to present comparisons of results obtained from the various tests. These comparisons are presented under the following headings:

- overall prediction of the generation of acidic leachate;
- overall long term trends and lag time to net acid generation;
- sulphate release rates;
- alkalinity release rates; and
- heavy metal leaching.

The chapter concludes with a discussion of application of the tests to various scenarios.

9.1 PREDICTION OF NET ACID GENERATION

Table 9-1 allows comparison of acid-base accounts with the detection of acidic leachate. The majority of tests confirmed ABA predictions when operated long enough to confirm the presence of acidic leachate. The least potentially acid generating material (based on ABA) to positively generate acid was column LC-3 with NP/MPA of 0.59 and NNP of -26 kg $CaCO_3$/t. LC-2 with a NP/MPA of 1.1 was expected to generate acid based on acidic conditions in the upper part of the column and increasing sulphate, although acidic leachate was not detected at the base of the column. Two humidity cells (3-29 and 3-31) were expected to generate acid and did not because the 20 week period of the test was insufficient to dissolve the minerals which enhance NP. One cell (3-29) had NP of 9 kg $CaCO_3$/t.

9.2 LONG TERM TRENDS

9.2.1 General Conclusions

Qualitatively, all tests yielded similar long term trends in most parameters. Trends in concentrations of sulphate were strongly correlated with parameters such as conductivity, acidity and the heavy metals (see Figures 6-5, 7-2 to 7-8, and 8-2 to 8-9). This was expected since leaching of sulphate was a result of sulphide oxidation which generates acidity and increased leaching. In laboratory tests, once acidic conditions occurred, sulphate concentrations increased rapidly to a peak and then decayed over the remainder of the test. None of the laboratory tests varied from this trend. The waste rock pads inevitably departed from this trend due to the seasonal effect of accumulation of acidic weathering products during the summer, and leaching of these products by rain in the fall.

TABLE 9-1
SUMMARY OF TEST RESULTS

								Acid-base Accounting				Kinetic Tests	
								kg CaCO3/t				Outcome	
THIS STUDY	TEST (1)	TYPE	#	ROCK TYPE (1)	COMMENTS	POWDER pH	TOTAL S (%)	MPA (2)	NP (2)	NNP (2)	NP/MPA (3)	Acid (4) (Y/N)	Time (5) (weeks)
	HC	Wet-Dry	1-01	Skonun Sediments	WRP-1, Two of same cell	5.3	1.95	60.9	2.16	-58.8	0.04	Y	0
	HC	Wet-Dry	1-02	Skonun Sediments	WRP-2, Two of same cell	7.2	2.96	92.5	3.05	-89.5	0.03	Y	0
	HC	Wet-Dry	1-03	Skonun Sediments	WRP-4, Two of same cell	7.1	1.75	54.7	0.69	-54.0	0.01	Y	0
	HC	Wet	2-01	Skonun Sediments	WRP-1	5.3	1.95	60.9	2.16	-58.8	0.04	Y	0
	HC	Wet	2-02	Skonun Sediments	WRP-2	7.2	2.96	92.5	3.05	-89.5	0.03	Y	0
X	HC	Wet	2-03	Argillically Altered Skonun	WRP-3	3.5	3.06	95.6	-6.37	-102.0	-	Y	0
X	HC	Wet	2-04	Skonun Sediments	WRP-4	7.1	1.75	54.7	0.69	-54.0	0.01	Y	0
	HC	Wet	3-06	Haida Mudstone		8.2	1.30	40.6	29.7	-10.9	0.73	N	-
	HC	Wet	3-17	Haida Mudstone		8.2	1.38	43.1	151	107.9	3.50	N	-
	HC	Wet	3-19	Haida Mudstone		8.4	0.87	27.2	49.4	22.2	1.82	N	-
X	HC	Wet	3-20	Haida Mudstone		7.7	1.15	35.9	7.12	-28.8	0.20	Y	30
X	HC	Wet	3-22	Haida Mudstone		8.1	1.21	37.8	86.4	48.6	2.28	N	-
	HC	Wet	3-31	Haida Mudstone		7.6	1.71	53.4	35.1	-18.3	0.66	N	-
	HC	Wet	3-04	Skonun Sediments		5.4	3.01	94.1	1.32	-92.7	0.01	Y	0
	HC	Wet	3-07	Skonun Sediments		4.9	1.98	61.9	2.47	-59.4	0.04	Y	0
	HC	Wet	3-16	Skonun Sediments		4.6	3.12	97.5	0.30	-97.2	0.00	Y	0
	HC	Wet	3-21	Skonun Sediments		4.1	2.46	76.9	-0.45	-77.3	-	Y	0
	HC	Wet	3-23	Skonun Sediments		5.1	3.84	120	-1.89	-121.9	-	Y	0
	HC	Wet	3-32	Skonun Sediments		4.1	3.08	96.3	3.04	-93.2	0.03	Y	0
	HC	Wet	3-01	Skonun Sediments		6.3	0.96	30	1.00	-29.0	0.03	Y	0
	HC	Wet	3-05	Skonun Sediments		4.7	0.84	26.3	0.50	-25.8	0.02	Y	0
	HC	Wet	3-08	Skonun Sediments		4.7	2.34	73.1	1.25	-71.9	0.02	Y	0
	HC	Wet	3-10	Skonun Sediments		4.8	2.16	67.5	0.95	-66.6	0.01	Y	0
	HC	Wet	3-12	Skonun Sediments		4.9	1.90	59.4	0.57	-58.8	0.01	Y	0
	HC	Wet	3-27	Skonun Sediments		5.7	2.35	73.4	1.30	-72.1	0.02	Y	0
X	HC	Wet	3-11	Skonun Sediments		7.7	2.53	79.1	6.23	-72.8	0.08	Y	25
	HC	Wet	3-14	Skonun Sediments		7.7	2.61	81.6	13.4	-68.2	0.16	Y	0
	HC	Wet	3-15	Skonun Sediments		6.4	2.20	68.8	1.74	-67.0	0.03	Y	0
	HC	Wet	3-18	Skonun Sediments		5.0	1.47	45.9	0.95	-45.0	0.02	Y	0
	HC	Wet	3-28	Skonun Sediments		6.5	2.55	79.7	2.54	-77.1	0.03	Y	0
	HC	Wet	3-29	Skonun Sediments		7.6	2.23	69.7	9.33	-60.4	0.13	N	-
	HC	Wet	3-30	Skonun Sediments		5.0	1.63	50.9	0.25	-50.7	0.00	Y	0
	HC	Wet	3-33	Rhyolite		5.0	3.22	101	2.39	-98.2	0.02	Y	0
	HC	Wet	3-09	Breccia		4.4	1.51	47.2	0.22	-47.0	0.00	Y	0
	HC	Wet	3-26	Breccia		4.3	2.14	66.9	0.01	-66.9	0.00	Y	0
	HC	Wet	3-34	Breccia		6.9	3.00	93.8	1.51	-92.2	0.02	Y	5
	HC	Wet	3-02	Argillically Altered Skonun		4.9	4.10	128	1.32	-126.8	0.01	Y	0
	HC	Wet	3-03	Argillically Altered Skonun		3.8	6.08	190	0.01	-190.0	0.00	Y	0
	HC	Wet	3-13	Argillically Altered Skonun		6.5	4.00	125	3.99	-121.0	0.03	Y	0
	HC	Wet	3-24	Argillically Altered Skonun		6.6	4.05	127	6.58	-120.0	0.05	Y	3
	HC	Wet	3-25	Argillically Altered Skonun		7.2	4.83	151	7.15	-143.8	0.05	Y	0
X	WRP		1	Skonun Sediments		5.3	1.95	60.9	2.16	-58.8	0.04	Y	7
X	WRP		2	Skonun Sediments		7.2	2.96	92.5	3.05	-89.5	0.03	Y	7
X	WRP		3	Argillically Altered Skonun		3.5	3.06	95.6	-6.37	-102.0	-	Y	0
X	WRP		4	Skonun Sediments		7.1	1.75	54.7	0.69	-54.0	0.01	Y	0
	LCaq	Sub-aq.	1	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12	Y	7
	LCaq	Sub-aq.	2	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12	Y	0
	LCaq	Sub-aq.	3	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10	Y	0
	LCaq	Sub-aq.	4	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10	Y	0
	LCaq	Sub-aq.	5	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12	N	-
	LCaq	Sub-aq.	6	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12	N	-
	LCaq	Sub-aq.	7	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10	Y	0
	LCaq	Sub-aq.	8	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10	Y	0
	LCae	Sub-aer.	9	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12	Y	0
	LCae	Sub-aer.	10	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10	Y	0
	LCae	Sub-aer.	11	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12	Y	0
	LCae	Sub-aer.	12	Breccia		6.4	1.60	50.0	5.0	-45.0	0.10	Y	0
	LCae	Sub-aer.	13	Skonun Sediments		7.1	2.40	75	9.0	-66.0	0.12	N	-
X	LC	Limestone	1	Skonun Sediments		6.9	2.10	65.6	8	-57.6	0.12	Y	0
X	LC	Limestone	2	Skonun Sediments, 6.6% Lst		-	1.98	61.9	69	7.1	1.12	N	-
X	LC	Limestone	3	Skonun Sediments, 3.3% Lst		-	2.05	64.1	38	-26.1	0.59	Y	200
X	LC	Limestone	4	Skonun Sediments, 0.84% Lst		-	2.08	65	16	-49.0	0.25	Y	31
X	LC	Limestone	5	Skonun Sediments	Limestone layers	-	2.08	65	19	-46.0	0.29	Y	31

Notes:

1. HC - Humidity Cell, WRP - Waste Rock Pad, LC - Leach Column, aq - sub-aqueous, ae - sub-aerial, Lst - Limestone
2. MPA - Maximum Potential Acidity; NP - Neutralization Potential, NNP - Net Neutralization Potential
3. NP/MPA is calculated for NP>0.
4. "Y" - Acid conditon indicated by leachate pH<5, otherwise "N"
5. Time when acid leachate observed.

Leachate pH's generally showed a sharp chemical transition from near 7.0 to less than 3.0. Intermediate pH plateaus were not observed. The transition in humidity cells typically lasted at least 20 weeks, in leach columns without limestone lasted less than 20 weeks, and in columns containing limestone lasted less than 10 weeks. The transition in humidity cells was slowest because the leachates were most dilute and therefore leached alkaline minerals slowest. In columns without limestone, there was a period during which the less available but reactive acid neutralizing minerals were consumed. The extremely rapid transition to acidic conditions in the columns containing limestone reflected the presence of free limestone particles. Once the surface area of these particles was no longer able to consume the acidity generated, acid was released from the column.

9.2.2 Implications to Experimental Design

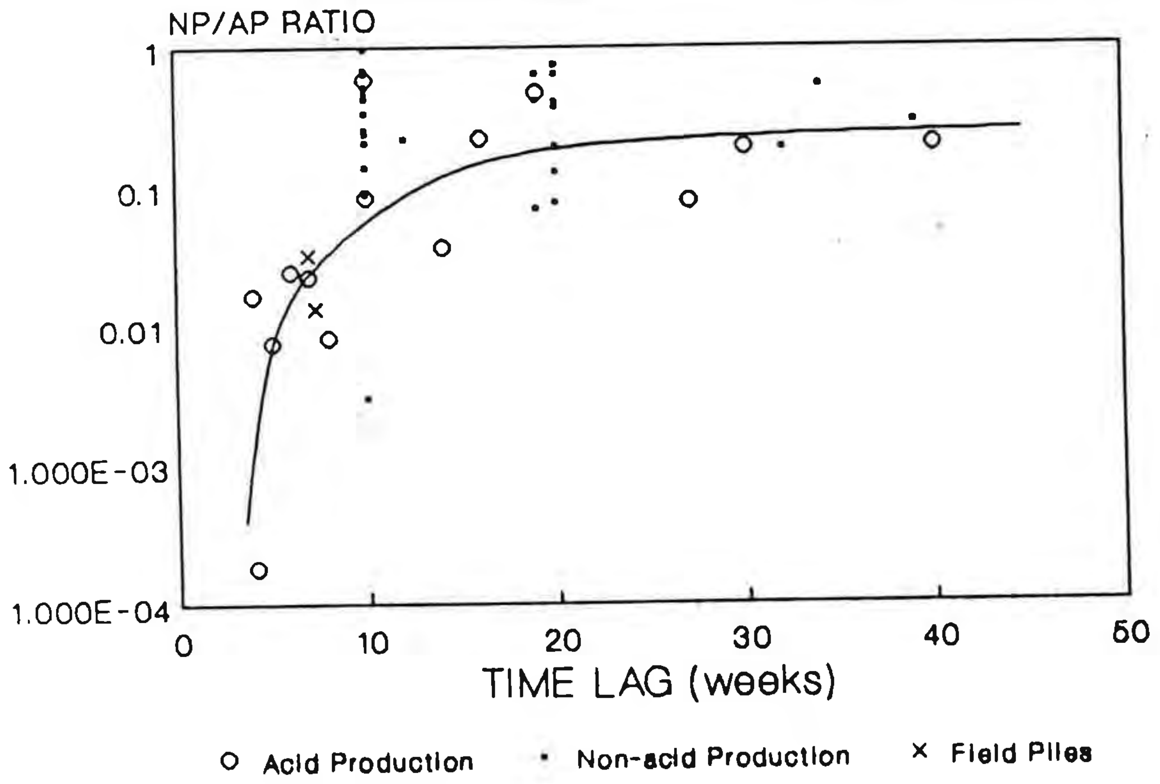
The time elapsed before acidity is generated is an important design consideration in kinetic experiments. The Cinola program, however, did not provide many opportunities to observe the delay before acidic leachate was produced because neutralization potentials were very low. Ferguson and Morin (1991) derived a relationship from 14 tests which generated acid after initially alkaline conditions:

$$\text{Time Lag (weeks)} = 55.\sqrt{(NP/MPA)} \quad (r^2=0.52) \qquad (9\text{-}1)$$

This relationship (shown in Figure 9-1) was developed partly based on the Cinola data since it was included in the database. It is unclear whether the equation included different types of tests using different procedures. It is very unlikely that the leach columns would follow the same relationship as humidity cells since the height of the column and the presence of heterogeneities (such as layers) will control the lag time. This was demonstrated by LC-2 (6.6% limestone) in which the upper part of the column was acidic after 250 weeks, but acid leachate had not appeared at the base of the column. If the column had been shorter, presumably acidic conditions might have been observed earlier. Equation 9-1 predicts a time lag of 60 weeks, but the column had not generated acid after 250 weeks.

Equation 9-1 and the relationship predicted for peak sulphate concentrations for the columns (see section 8.5.4, equation 8-4) demonstrated the difficulty with design of studies to address conditions near NP/MPA=1. The time lag increases exponentially beyond a suitable time frame to generate useful conclusions. However, the time to initial increase in sulphate concentrations may be related to NP (at constant MPA) by a non-exponential relationship (see section 8.5.4, equation 8-3). Initial increase of sulphate may be a more practical indicator for column tests provided that sulphide mineralogy is relatively simple and does not result in complex sulphate release trends.

The above analysis also implies that column length should be carefully considered when designing studies on highly alkaline materials. The columns should be long enough to allow stable flow conditions to develop. The development of stable flow conditions includes the formation of flow channels and leachate chemistry which will not change significantly due to random physical or chemical heterogeneities. Data are not available to specifically quantify



AP = MPA = Maximum Potential Acidity

Figure 9-1
RELATIONSHIP BETWEEN TIME LAG
AND NP/AP
FERGUSON AND MORIN (1991)

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these sources of variability, although Day and Harpley (1993) suggested that stable channels could develop after a vertical distance of 30 times the average particle diameter. For the Cinola leach columns, this would have been an interval of about 6 cm.

9.3 COMPARISON OF SULPHATE RELEASE RATES AND AVAILABILITY OF SULPHIDE MINERALS

In order to compare sulphate release rates two types of statistics were compiled:

- **Table 9-2** summarises average sulphate release rates for the major rock types and each different type of test under pH-neutral and acidic conditions. Rates are shown on a weight basis (mg SO_4/kg/week) and estimated area basis (mg SO_4/m^2/week). The latter values were obtained from the weight values divided by the area in m^2/kg. As indicated in Table 9-2, values shown are averages of several tests previously determined by City Resources (1988, Volume V) and in earlier chapters of this report. Release rates under acidic conditions represent averages over the duration of the test. Average rates under pH-neutral conditions tended to be relatively uniform.

- **Table 9-3** summarizes acceleration and decay slope constants (m in $week^{-1}$) for the equations of the general form:

  $$\log(\text{Sulphate}) = mt + c.$$

  where t is in weeks and c is a constant. Since the long term tests displayed acceleration and decay phases with lines of this general form, m is roughly constant and is a useful comparative tool. It is also a more appropriate means of evaluating reaction kinetics than the averages shown in Table 9-2. The latter rates provide a useful comparison for tests conducted over a relatively short period of time. Table 9-3 presents results for long term tests continued for the MEND/BC AMD Task Force Project.

A wider range of values was found for average sulphate release on a weight basis than on an area basis (Table 9-2). The respective variations in rates were 4.4 to 820 mg SO_4/kg/week, and 2.4 to 150 mg SO_4/m^2/week. This implies that the difference in rates observed between the various tests is due to differences in the degree of crushing and exposure of sulphide mineral grains. Humidity cell material is more finely ground than column and waste rock pad material.

The acceleration phase slopes are quite similar for lower neutralization potentials (0.075 to 0.085 $week^{-1}$). There was a lack of data for this phase since it is typically rapid and not clearly delineated. Column 3 (3.3% Limestone) had a much lower acceleration constant presumably due to the presence of residual limestone in the sample mixture during the acceleration phase. The decay slope constants also vary over a relatively narrow range for the laboratory tests (-0.009 to -0.019 $week^{-1}$) conducted on Skonun Sediments. The decay slope was steeper for one Haida Mudstone sample (HC3-20). The estimated rates for the four

TABLE 9-2
SUMMARY OF AVERAGE SULPHATE RELEASE RATES

ROCK TYPE (1) / TEST TYPE (2)	Skonun Sediments (pH neutral)			Skonun Sediments (pH acid)			Haida Mudstone (pH neutral)		
	Low (3)	Mean (3)	High (3)	Low (3)	Mean (3)	High (3)	Low (3)	Mean (3)	High (3)
Weight Basis (mg SO4/kg/week)									
Wet-Dry HC (4)	-	-	-	65	-	120	-	-	-
Wet 2-01 HC (4)	-	-	-	-	49	-	-	-	-
Wet 2-02 to 2-04 HC (4)	-	-	-	100	-	810	-	-	-
Wet "3-" HC (4)	-	10	-	-	820	-	-	89	-
WRP 1 (5)	-	-	-	-	4.4	-	-	-	-
WRP 2 to 4 (5)	-	-	-	51		110	-	-	-
LC (5)	-	17	-	-	170	-	-	-	-
Surface Area Basis (mg SO4/kg/week)									
Wet-Dry HC (4)	-	-	-	16	-	21	-	-	-
Wet 2-01 HC (4)	-	-	-	-	12	-	-	-	-
Wet 2-02 to 2-04 HC (4)	-	-	-	83	-	150	-	-	-
Wet "3-" HC (4)	-	11	-	-	87	-	-	4.2	-
WRP 1 (5)	-	-	-	-	2.4	-	-	-	-
WRP 2 to 4 (5)	-	-	-	29	-	55	-	-	-
LC (5)	-	3.5	-	-	35	-	-	-	-

Notes:

1. Rock type and pH conditions for rates shown.
2. HC - Humidity Cell, WRP - Waste Rock Pad, LC - Limestone/Waste Rock leach column.
3. Low - Lowest rate measured, mean - average rate, if sufficient data available or only one test, high - highest rate measured.
4. Rates shown were calculated by City Resources (Volume V, 1988).
5. Rates shown were determined for this study.
6. "-" indicates no data available.

TABLE 9-3
COMPARISON OF SELECTED LONG TERM SULPHATE ACCELERATION AND DECAY SLOPES

Test (1)	Type	Rock Type	Total S (%)	MPA (2)	NP (2)	NNP (2)	NP/MPA (3)	Acceleration(4) (1/week)	Decay(4) (1/week)	Figure (5)
				(kg CaCO3/t)						
HUMIDITY CELLS										
HC-2-03	Wet	Argillically Altered Skonun	3.06	96	-6	-102	-	-	-0.013	6-3
HC-2-04	Wet	Skonun Sediments	1.75	55	1	-54	0.01	-	-0.015	6-3
HC-3-11	Wet	Skonun Sediments	2.53	79	6	-73	0.08	0.077	-0.019	6-3
HC-3-20	Wet	Haida Mudstone	1.15	36	7	-29	0.20	0.08	-0.034 to -0.0095	6-4
WASTE ROCK PADS										
WRP-1		Skonun Sediments	1.95	61	2	-59	0.04	-	-0.0002	7-13
WRP-2		Skonun Sediments	2.96	93	3	-89	0.03	-	-0.005	7-13
WRP-3		Argillically Altered Skonun	3.06	96	-6	-102	-	-	-0.004	7-13
WRP-4		Skonun Sediments	1.75	55	1	-54	0.01	-	-0.005	7-13
LIMESTONE/WASTE ROCK LEACH COLUMNS										
LC-1		Skonun Sediments	2.10	66	8	-58	0.12	0.085	-0.014 to -0.026	8-2
LC-2		Skonun Sediments, 6.6% Limestone	1.98	62	69	7	1.12	-	-	8-2
LC-3		Skonun Sediments, 3.3% Limestone	2.05	64	38	-26	0.59	0.013	-0.009	8-2
LC-4		Skonun Sediments, 0.84% Limestone	2.08	65	16	-49	0.25	0.075	-0.017	8-2
LC-5		Skonun Sediments, Layered	2.08	65	19	-46	0.29	0.075	-0.017	8-2

Notes:

1. HC - Humidity Cell, WRP - Waste Rock Pad, LC - Limestone/Waste Rock leach column.
2. MPA - Maximum Potential Acidity; NP - Neutralization Potential; NNP = NP-MPA
3. "-" indicates not determined because NP<0
4. Slope constants (m) for equations of form: log (sulphate) = mt + c. Acceleration = increasing sulphate release, decay = decreasing sulphate release
5. Refer to Figure indicated for data used to calculate slopes.

waste rock pads are much lower. As indicated previously these estimates may be unreliable due to overprinting of seasonal variability on long term decay slopes. The significance of the flatter decay slopes observed for the field study cannot be determined. The acceleration and decay slope constants shown in Table 9-3 support the conclusions relating to particle surface area effects. Since decay slopes vary little, it appears that the kinetics of pyrite oxidation are relatively constant for the different rock types. Crushing of rock to produce different particle sizes alters the relative exposure of sulphide mineral grains resulting in different average release rates under acidic conditions.

After correction for surface area differences, several conclusions can be drawn:

- under pH-neutral leachate conditions, average sulphate release rates varied little for different rock types and tests. Rates varied from 3.5 to 11 mg SO_4/m^2/week (Table 9-2). This indicates that the presence of alkaline leachate constrains the rate of sulphide oxidation and that differences in occurrence of sulphide mineral grains. are not sufficient to cause large variations in rates.

- release rates for humidity cells operated under continuous wet conditions were significantly greater than using the conventional wet-dry cycle. The continuous moist conditions represented a more aggressive weathering condition. The drying cycle potentially causes amorphous iron hydroxides ($Fe(OH)_3$) to dehydrate and crystallize to goethite (FeOOH) or hematite (Fe_2O_3). These minerals are thermodynamically more stable than amorphous ferric hydroxide and could perhaps form stable coatings on sulphide grains and limit further oxidation.

- release rates for waste rock pads are between those for the wet-dry and continuously moist humidity cells (Table 9-2). It should be noted that the release rates for waste rock pads represent only part of the oxidation rate since some weathering products were formed but not completely flushed from the piles. This is illustrated by the relatively high sulphate concentrations in Pad 2 residues (Table 7-2). This would occur in parts of the pile between major flow paths. The proportion retained and infrequently flushed is not known, although experiments and simulations have shown that as little as 20% of the rock mass may be contacted by vertically moving flow (Morin 1991; Day and Harpley 1993); and

- the limestone and waste rock mixing tests yielded sulphate release rates comparable to the waste rock pads.

Acid-base accounts of acidic residues from the long term experiments provide an opportunity to determine the amount of sulphur which was available to oxidize and generate acid. Residue acid-base accounts are available for humidity cells (Table 6-1), Waste Rock Pad 2 (cf. Tables 7-1 and 7-2), and the waste rock and limestone columns (Table 8-2). WRP-2 yielded the most complete oxidation of sulphide minerals with only 0.06 to 0.16% remaining as sulphide sulphur. The proportion was higher for the columns (0.43 to 0.66%). Total sulphur in humidity cell residues was 0.22 to 0.52%. Results for residues, particularly

WRP-2, indicate that a very high proportion of sulphur is available for oxidation, and that less than 10% remains in a less available form. It appears, therefore, that for waste rock at Cinola, encapsulation of sulphide minerals by the silicate mineral matrix does not significantly limit the amount of sulphur available for oxidation.

9.4 AVAILABILITY OF ALKALINITY AND RELEASE RATES

In general, the Cinola program did not allow an in depth evaluation of the availability of alkalinity and release rates. Neutralization potentials were low and parameters suitable for monitoring leaching of neutralizing minerals, calcium and magnesium, were infrequently determined. Calcium and magnesium are the most useful parameters for this purpose since they can often be directly correlated with leaching of the common acid neutralizing carbonate minerals, and are not affected by leachate collection methods and storage. Alkalinity was determined on a more frequent basis; however, this parameter represented all forms of alkalinity (primarily carbonate species) and is potentially affected by laboratory conditions during leaching, the method used to leach the samples, and storage times. By definition, it is also not determined once acidic conditions occur.

Analysis of test residues yielded very low or negative NP's. This indicated that any readily reactive alkalinity as carbonates had been removed during the course of the test. A similar conclusion was reached for the waste rock and limestone columns. This was confirmed by petrographic examinations which indicated very little carbonate remained in acidic residues.

For the waste rock and limestone column study, the alkalinity consumption rate (mg $CaCO_3/m^2$/week) during pH-neutral conditions could be estimated by:

$$\{\text{Sulphate Release Rate.}(100/96)\}/([SO_4^{2-}]/[Ca^{2+}])$$

where $[SO_4^{2-}]/[Ca^{2+}]$ was estimated to be 0.5 to 0.6 (Section 8.5.4) and 100 and 96 are the mole weights of calcium carbonate and sulphate, respectively. The sulphate:calcium mole ratio factor indicates that about twice as much calcium carbonate is required to neutralize acidity generated by oxidation of sulphide than would be expected if the carbonate was completely converted to carbon dioxide (gaseous or dissolved). In reality, bicarbonate is formed.

9.5 ARSENIC AND HEAVY METAL LEACHING

It is not generally appropriate to compare metal release rates on a weight or area basis since metal concentrations are pH- dependant. City Resources (1988, Volume V) demonstrated that metal concentrations followed conventional pH dependency with lowest concentrations at pH neutral conditions, intermediate concentrations at alkaline pH, and highest concentrations at acidic pH. Therefore, Table 9-4 compares typical metal concentrations in leachates from three major types of tests under pH-neutral and acidic conditions.

TABLE 9-4
COMPARISON OF TYPICAL METAL CONCENTRATIONS IN LEACHATES (mg/L)

Test Type (1) / Metal	Metal Concentrations at Low pH (Typical Peak Values)				Metal Concentrations at Near Neutral pH (Typical Average Values)	
	HC (Waste Rock Pad Materials)	HC (Other Tests)	WRP	LC	HC (Other Tests)	LC
As	6	5	60	34	0.001	0.001
Cd	-	-	0.6	0.07	-	0.001
Cu	3	0.8	13	2.2	0.05	0.001
Pb	-	-	0.03	-	-	-
Hg	0.0035	0.0007	0.0005	0.00005	0.00005	0.00005
Zn	10	8	60	5.7	0.05	0.001
Leachate (L/g/week)	2.5	2.5	0.03	0.308	2.5	0.308

Notes:

1. HC - Humidity cells, WRP - Waste rock pads, LC - Limestone/Waste Rock leach columns.

Heavy metal concentrations under acidic conditions were greatest for the waste rock pads, followed by the humidity cells, and waste rock and limestone columns. Arsenic concentrations in waste rock and limestone column leachates were greater than humidity cells and waste rock pads. The differences in metal concentrations in the tests are in part be related to the differences in the leaching rate (Table 9-4), although the 100 times difference in rate between waste rock pads and humidity cells is much greater than the observed difference in metal concentrations. Metal concentrations in humidity cell leachates perhaps represent the real release rate (under acidic conditions) and have not reached a limit controlled by saturation. In waste rock pads, metal concentrations may be constrained by saturation.

Metal release trends were independent of sulphate release under pH neutral conditions, but correlated with sulphate under acidic conditions (see Section 9.2.1). This confirmed qualitatively that metal leaching occurs as a result of acid generation.

9.6 GENERAL COMMENTS ON THE USE OF KINETIC TESTS

The Cinola Project provided a unique opportunity to evaluate the applicability of different tests to addressing typical waste management issues. These issues may include:

- identification of acid generating rock types;
- initiation of acid generation;
- determination of acid generation trends and duration of acid generation;
- determination of quality of metal-bearing drainage and requirement for collection and treatment; and
- evaluation of waste management options.

Although the Cinola Project provided some interesting insights into the selection of appropriate tests, discussed below, it should be recognized that the mineralogy and lithology of the rock types is relatively simple (see Section 2.3.2) when compared to other metal deposit types. For example, many mineral deposits contain significant concentrations of several different types of reactive sulphide minerals (eg, pyrite and pyrrhotite), sulphide minerals in various forms (disseminated, fracture coatings), acid neutralizing minerals (eg. calcite, dolomite) and acid neutralizing minerals in various forms (disseminated, veinlets, etc.). The following conclusions regarding the applicability of the various tests should therefore be considered in the context of waste rock with relatively simple mineralogy.

9.6.1 Identification of Acid Generating Rock Types

Acid-base accounting provided a reliable prediction of potential for acid generation for rock with high sulphur concentrations relative to neutralizing minerals. Few tests were conducted on marginally acid generating waste rock (NP/MPA = 1 to 2), and no equivalent field tests for these particular materials were set up. Only one leach column contained rock with NNP>0 (NP/MPA>1) showing evidence of acid generation. The result for this column was consistent with current understanding of acid-base accounting (Cravotta *et al.*, 1990).

9.6.2 Initiation of Acid Generation

This is an important consideration when planning stockpiles of acid generating rock. The lag time before acid leachate is produced is controlled by the neutralization potential along the drainage flow path. Humidity cells tended to have the longest lag time (when normalized against neutralization potential) presumably due to the presence of optimal conditions for contact between acidic leachate and neutralizing minerals, although the lag was only about 30% greater than observed for the waste rock pads. When addressing this issue, humidity cells appear to be useful, although the reduction in contact time in waste rock piles must be addressed.

9.6.3 Determination of Acid Generation Trends and Duration of Acid Generation

For the relatively simple Cinola-type mineralogy, it appears that humidity cells showed acid generation trends and average rates comparable to both leach columns and field tests (when corrected for surface area differences). Sulphate release decay slopes for humidity cells and columns were also comparable. Humidity cells therefore appear reliable in this type of situation, although calibration using larger scale tests, such as columns is essential.

9.6.4 Determination of Quality of Metal-Bearing Drainage and Requirements for Treatment

Determination of drainage quality is a common objective of kinetic test programs since most studies must eventually provide input to water quality impact assessments. However, since most components of concern (including the heavy metals and arsenic) are controlled by complex solid-solution equilibria depending on pH and oxidation-reduction conditions, many tests cannot adequately simulate full-scale conditions. In the case of the Cinola Project, all tests determined that concentrations of arsenic, copper, mercury and zinc would probably exceed water quality criteria and effluent discharge guidelines. However, metal loadings calculated by adjusting leachate concentrations for rock mass and drainage quality varied considerably indicating that either loadings were test dependant, or were being constrained by pH conditions (see Section 9.5). The latter is most likely. Therefore, no single test can completely define the chemical mobility of these components. Humidity cells can provide useful information but must be supported by humidity cells using different liquid/solid ratios (decreasing ratio), and tests at other scales including columns of various sizes and on-site test piles.

9.6.5 Evaluation of Waste Management Options

Mixing of limestone with waste rock was evaluated at only one test scale for the Cinola Project. Although this method confirmed a delay in initiation of metal leaching and acid generation, data from on-site test piles would be needed. This would have allowed evaluation of limestone addition under quasi-realistic field conditions in which incomplete mixing would be expected to occur. Humidity cells would not have provided useful information since thorough limestone and waste rock mixing would have occurred during leaching. Column tests allow stable environments to develop in the vicinity of static waste rock and limestone particles.

10.0 CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

The following chapter presents overall conclusions of the Cinola project, "Lessons-Learned" from the study and suggestions for further research, where appropriate. The following discussion is intended to be constructively critical; however, many of the pitfalls could not have been identified at the time due to the limitations of contemporary knowledge. In addition, both the City Resources and MEND/BC AMD Task Force projects were constrained by project finances at various times.

10.1 OVERALL COMPLETION OF OBJECTIVES - CITY RESOURCES PROJECT

Specific objectives to be addressed by the City Resources test program were to:

- characterize all the rock types in the project area and determine their potential for acid generation;
- quantify the total capacity of various rock types to generate acid;
- determine the temporal changes in rates of acid generation in different rock types;
- determine the rates of acid generation for varying conditions involving differences in exposure to air and water;
- determine the effect of mixing limestone with waste rock on the delay or prevention of acid generation; and
- determine the metal leaching characteristics of the different rock types.

Conclusion

The City Resources project successfully addressed the majority of objectives. The majority of tests were operated for 20 weeks. As a result of the low neutralization potentials, this was adequate time to observe stable sulphate release under low pH conditions.

Lessons Learned and Implications for Other Studies

NNP thresholds for acid generation were the subject of discussions between City Resources and the regulatory agencies when it became clear that the West Pit Wall would be composed of Haida Mudstone with marginal potential to generate acid. This objective could have been addressed by the program had more tests contained marginally acid generating rock. Recent compilations of data (this study Section 8.5.2; Ferguson and Morin 1991) have shown that, in any case, determining acidic end points in this type of experiment can be difficult and very time consuming. If this type of issue is to be addressed in a kinetic test program, it is essential to consider the neutralization potentials of the test materials and the time frame for mine construction and approvals.

10.2 OVERALL COMPLETION OF OBJECTIVES - MEND/BC AMD TASK FORCE PROJECT

The following project objectives were defined for the MEND/BC AMD Task Force work: (Annex "A", Supply and Services Canada Contract No. 23440-2-9271/01-SQ, Appendix A, this report).

- "characterize six years of weathering in the four on-site waste rock pads and apply the results to understanding rock dump acid generation processes;
- evaluate the results of a column study of mixing calcareous rock with mine waste rock as a means to prevent the formation of acid drainage; and
- characterize material that has undergone over three years of weathering in humidity cells.
- evaluate and compare the performance of the various ARD test methods used in the project".

Conclusion

- Results from the Waste Rock Pad study were not sufficient to develop comprehensive conclusions regarding long term acid generation trends and consumption of sulphides. Nonetheless, a useful database has been built and the pads are still intact and available for further monitoring.
- Objectives with respect to the column study and humidity cells were satisfied.

10.3 TEST METHODS

Conclusions

- The majority of test methods were conventional procedures developed previously.
- The continuous wet-cycle humidity cell was designed for this project. Sulphate release rates were greater than the conventional wet-dry cycle cell and appeared to be closer to rates estimated for the on-site waste rock piles.

Lessons Learned

- Pre-test petrographic characterization of test materials should include descriptions of mineral grain sizes, forms and occurrence. Petrographic features should be documented with photomicrographs, photographs of samples and polished slabs, and sketches illustrating the principle rock features.

- Samples of test materials and polished thin sections should be archived for future testing.

- Size fraction analysis should include very fine particles, probably to particle sizes in the 1 μm range.

- The sequential leach procedures are an option for determination of the speciation of metals in test residues. The applicability of leaching procedures developed in other disciplines for rocks should be determined. Sub-samples should be leached prior to testing.

Recommendations for Research

- Investigate sequential leach procedures and other possible procedures for determining metal speciation, such as scanning electron microscope and microprobe.

10.4 LONG TERM HUMIDITY CELL STUDY

Conclusion

- Five humidity cells were operated for 140 weeks and demonstrated that, for this type of material, leachate chemistry changes could be classified into three stages, namely: (1) near neutral pH; (2) acidic, sulphate increasing; and (3) acidic, sulphate decreasing.

Lessons Learned

- Cinola project rock and mineralogy are relatively simple (see Section 9.6). Different trends are likely to be observed in more complex rock types, for example, where there is more than one iron sulphide or carbonate.

- Concentrations of dissolved components should be measured or determined in leachate to allow long term variation in leaching of minor components to be assessed. The selection of components to monitor is dependant on the types of minerals present.

- Tests should be conducted using material with elevated neutralization potentials to allow observation of changes in leachate chemistry prior to the on-set of low pH conditions.

- Tests with marginal potential for acid generation should be operated to allow assessment of ABA thresholds for acid generation.

Recommendation for Research

- Long term humidity cells on complex materials (for example, higher NP, complex sulphide mineralogy) are needed with regular measurement of parameters allowing more complete assessment of leaching characteristics, both before and after the onset of low pH conditions.

- Conduct a long term kinetic test program to assess marginally acid generating rock types.

10.5 ON-SITE WASTE ROCK PILE STUDY

Conclusions

- Four on-site waste rock pads showed trends in leachate chemistry over a period of five years. Leachate chemistry was dominated by seasonal variations in precipitation. Some overprinting by long term decrease in sulphate release was observed but could not be quantified.

- After six years of weathering, very little sulphide sulphur remains in the residue of one pad.

Lessons Learned

- The importance of maintaining a routine monitoring schedule for field tests was demonstrated, especially during major precipitation events such as the beginning of Fall rains. It was also apparent that data should be collected over complete annual cycles especially during the same precipitation events. At least three annual cycles would be required to define the decay in acid generation rates because seasonal climatic variations are superimposed over long term trends.

- Parameters should be selected and monitored continuously to fully document leaching of acid consuming minerals. These should include, in addition to the regulated heavy metals: potassium, sodium, calcium, magnesium, iron, aluminum, phosphate, and manganese.

- A better understanding of the effect of scale change between small test piles and large rock dumps needs to be developed before results from test piles can be applied to water quality predictions at larger scales.

Recommendations for Research

- Additional monitoring should be considered in the future to evaluate long term trends in acid generation.
- Low pH and metal-bearing leachate is continuing to be released by the pads despite the very low residual sulphur concentrations. Leachate conditions under depleted sulphur conditions should be investigated as these have implications to long term treatment costs at abandoned mines.
- Waste rock dump modelling projects should consider the application of results for small-scale piles to large piles.
- Initiate a long-term project where cell, columns and pad tests are conducted on rocks which can also be monitored in well characterized full-scale piles.

10.6 WASTE ROCK AND LIMESTONE MIXING STUDY

Conclusions

- Mixing of limestone with waste rock delayed the release of acid drainage. The delay increased exponentially with the quantity of limestone added. However, release of sulphate and zinc preceded acidic leachate. The delay in the appearance of increasing sulphate concentrations was directly proportional to the quantity of limestone added.
- The actual quantity of limestone required to prevent acid release in perpetuity was predicted to be twice the amount anticipated by acid-base accounting.
- Crushing of limestone resulted in better distribution of particles throughout the waste rock but probably did not increase availability of alkalinity. No evidence of loss of alkalinity by coating of particles by limonite was found in petrographic analysis or acid-base accounting of residues.
- Layering of limestone was not as beneficial as mixing throughout the rock mass.

Lessons Learned

- The height of columns is an important design consideration, since the appearance of significant conditions (such as, elevated metal concentrations and acidic leachate) is probably proportional to the height of the columns. However, columns should be high enough to allow stable flow paths to develop. This will be controlled by grain size, column diameter, and percolation rate.
- Rock in the columns was relatively fine. Particle size should be large enough that mechanisms of water and gas flow are comparable to large scale waste rock dumps.

- The effect of heterogeneities in alkaline particle distribution will probably control the extent to which results in this study can be applied to full-scale waste rock dumps.

Recommendations for Research

- The effect of heterogeneities (physical and chemical) on the variation in water quality from rock piles needs to be assessed to determine the applicability of this type of study to full-scale rock piles. This could be combined with the last recommendation in Section 10.5.

10.7 COMPARISON OF RESULTS FROM DIFFERENT TYPES OF TEST

Conclusions

- The Cinola Project demonstrated that kinetic tests at different scales produce similar sulphate production rates following correction for surface area effects. Sulphate production decay curves were also very similar and indicated control by a common process, probably the oxidation of pyrite.

Lessons Learned

- Evaluations of waste management approaches (limestone addition in this study) should include field scale tests to evaluate factors resulting from scale-up.

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March 3, 1994

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APPENDIX A

CINOLA GOLD ACID MINE DRAINAGE PROJECT YEAR 3 CONTRACTS

APPENDIX A.1

SUPPLY AND SERVICES CANADA
CONTRACT 015SQ.23440-2-9271

Supply and Services Canada
Approvisionnements et Services Canada

Supply and Services Canada
Science Branch
11C1, Phase III,
Place du Portage
Hull, Quebec K1A 0S5

CONTRACT - CONTRAT

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SSC file No. - N° de référence d'ASC
015SQ.23440-2-9271

Date of Contract - Date du contrat
04 Mar 1993

Contract No. - N° du contrat
23440-2-9271/01-SQ

Requisition No. - N° de la demande

Order office Bureau demandeur	Yr An	Serial No. N° de série
23440	2	9271

Financial Code(s) - Code(s) financier(s)
251-131-000000-307109-0468

Duty - Droits
not applicable

F.O.B. - F.A.B.
Destination

Goods and Services Tax - Taxe sur les produits et services
see herein

Destination
DEPT. ENERGY MINES & RESOURCES
CANMET - MSL DIVISION
555 BOOTH STREET
OTTAWA, ONTARIO, K1A 0G1
ATTN: VAN HUYSSTEEN, E.

Invoices - original and two copies are to be made out and sent to:
Factures - remplir et envoyer l'original et deux copies à:
SUPPLY AND SERVICES CANADA
SCIENCE BRANCH, 11C1 PLACE DU
PORTAGE, 11 LAURIER, HULL,
QUEBEC K1A 0S5
ATTN: JEAN ROUTHIER

Address enquiries to: - Adresser toute demande de renseignements à:
J. Valin

Area code code régional	Telephone No. N° de téléphone	Extension Poste	Telex No. N° de télex
819	956-1354		053-3703

You are requested to sell to Her Majesty the Queen in right of Canada, in accordance with the terms and conditions set out herein, referred to herein or attached hereto, the services listed herein and on any attached sheets at the price or prices set out therefor.

DELIVERY DATE: 31 May 1993

CINOLA GOLD ACID MINE DRAINAGE PROJECT-YEAR 3

Nous vous demandons de vendre à Sa Majesté la Reine du chef du Canada, aux conditions énoncées ou incluses par référence dans les présentes et aux annexes ci-jointes, les services énumérés dans les présentes et sur toute feuille ci-annexée, au(x) prix indiqué(s).

The vendor hereby accepts this contract - Le fournisseur accepte le présent contrat

Name, title of person authorized to sign (type or print)
Nom et titre du signataire autorisé (caractère d'impression)
Signature
Date: April 01/93

Return signed copy forthwith - Prière de retourner une copie dûment signée immédiatement

NORECOL ENVIRONMENTAL
CONSULTANTS LTD.
SUITE 250, 13571 COMMERCE
PARKWAY, RICHMOND, B.C.
V6V 2R2
ATTENTION: NIKO ZORKIN

@39T16

Crown's share:$20,000
GST -Crown's share:$ 1,400
Province of BC's share:$10,000

Total est. cost - Coût total est.
$31,400.00

For the Minister - Pour le Ministre
Johanne Valin

Canada

DSS-MAS 9400-10 (10/90)

TITLE:

CINOLA GOLD ACID MINE DRAINAGE PROJECT -YEAR 3

(Cost-shared project)

SECTION A: INTRODUCTION

DELIVERY DATE: MAY 31, 1993

INSTRUCTIONS, CONDITIONS AND CLAUSES INCORPORATED BY REFERENCE

1- DSS-MAS 9403-5 (12/92)

The Standard Instructions and Conditions DSS-MAS 9403-5 (12/92) entitled "Request for Proposal and Contract for Professional and Research and Development Services" set out in the Standard Acquisition Clauses and Conditions (SACC) manual, issued on 1 June 1991, Section 1, are hereby incorporated by reference and form part of this Contract.

2- DSS-MAS 9224 (01/12/92) AND OTHER CONDITIONS AND CLAUSES

The General Conditions set out in DSS-MAS 9224 Research and Development (01/12/92), as well as those conditions and clauses otherwise identified herein by number, date and title, all of which are set out in the SACC manual, are hereby incorporated by reference, pursuant to the Department of Supply and Services Act and to the Ministerial Order dated 22 May 1991 published in the Canada Gazette.

These general conditions, and any other supplementary conditions and clauses form part of this Contract as though expressly set out herein, and are subject to any other express terms and conditions contained herein.

The SACC manual may be obtained from the Canada Communications Group - Publishing, telephone (819) 956-4802.

Clauses and conditions referenced may also be viewed on the Open Bidding Service (OBS) electronic bulletin board .

PRIOR RIGHTS AND OBLIGATIONS

The Work undertaken by the Contractor from the 02 day of February 1993 and the date hereof shall be deemed to have been undertaken solely in support of its obligations and undertakings herein contained, and the benefits of this Preconctractual Work shall vest in and remain the property of Canada as if this Contract had been entered into on the 02 day of February 1993. All rights, title, and interest in and to the technical data, intellectual property, patents and trademarks, inventions and acquisitions, except as otherwise provided in the Contract, shall be and are hereby transferred and assigned to Canada.

The indemnity provisions of this Contract shall be deemed to apply to the aforesaid transfer. In consideration of the foregoing, the Contractor will be paid a sum for such Precontractual Work calculated in accordance with the Basis of Payment specified herein and the said sum shall form part of Canada's liability to the Contractor as set forth under Limitation of Expenditure.

SECTION B: REQUIREMENT

STATEMENT OF WORK

The work shall be performed in accordance with the Annex "A" : Statement of Work attached, which is forming part of this contract.

Figure 8-11a Column 2 residue (top of column is at right).

Figure 8-11b Column 2 residue near contact between acidic and less oxidized rock.

DELIVERABLE ITEMS:

1. MILESTONE REPORT

The Contractor shall submit a milestone report in two (2) copies to the Scientific Authority and in one (1) copy to the Science Contracting Officer on or before **March 31, 1993.** This report will consist of graphs and tables of the data, a draft outline of the content of the final report and of preliminary characterizations of weathered materials.

2. DRAFT FINAL REPORT

A draft of the final report shall be submitted on or before **April 30,1993** for review, comments and the approval of the Scientific Authority. It must be a comprehensive report on all facets of the Work and must include sufficient drawings, sketches, photographs and a discussion of problems and successes associated with the Work to facilitate a full and accurate evaluation of the Work by the Scientific Authority. The report will be prepared in accordance with good engineering/ professional practices and will include, as a minimum, the following: a title page , a table of contents, an executive summary, an introduction, a technical discussion with conclusions and include, as applicable, supporting graphs, tables and figures.

3. FINAL REPORT

After approval of the draft final report and on or before the delivery date of this contract , the Contractor shall submit ten (10) copies of the final report to the Scientific Authority designated herein. **The front page of the final report must indicate that the work was partially funded by the Canada/British Columbia Mineral Development Agreement under the MEND program. The final report shall contain an executive summary in both the French and the English language.** A copy of the covering letter accompanying the final report shall be forwarded to the Science Contracting Officer.

Final reports and any other reports prepared under this contract that may be circulated publicly will be bound in standard CANMET covers. These covers will be prepared by

CANMET's Technology and Marketing Division (TMD) through the Scientific Authority. The Contractor will request covers and if necessary instructions on overprinting the cover and on layout of the inside cover from TMD through the Scientific Authority one month before the expected date of printing of the reports.

4. DISCLOSURES CERTIFICATION

On completion of the Work under this Contract, the Contractor shall submit a completed disclosure certification to the Scientific Authority and to the Science Contracting Officer stating that all applicable disclosures were submitted or that there were no disclosures to submit under section 14 of General Conditions - Research and Development, DSS-MAS 9224.

SECTION C: AUTHORITIES

SCIENCE CONTRACTING OFFICER
Johanne Valin
Science and Professional Services Directorate
Supply and Services Canada
Place du Portage, Phase III, 11C1
11 Laurier Street
Hull, Quebec
K1A 0S5

TELEPHONE: (819) 956-1354
FACSIMILE: (819) 997-2229

The Science Contracting Officer named above is responsible for the management of this Contract and any changes to the Contract must be authorized by a formal contract amendment issued by that Officer. The Contractor is not to perform work in excess of or outside the scope of this Contract based on verbal or written requests or instructions from any government personnel other than the aforementioned Officer.

SCIENCE SENIOR PURCHASING ASSISTANT
Jean Routhier
Science and Professional Services Directorate
Supply and Services Canada
Place du Portage, Phase III, 11C1
11 Laurier Street
Hull, Quebec
K1A OS5

TELEPHONE: (819) 956-1340
FACSIMILE: (819) 997-2229

The Science Senior Purchasing Assistant named above is responsible for the administrative management of this contract with respect to claims for progress payments and enquiries.

SCIENTIFIC AUTHORITY
Mr. Van Huyssteen
EMR, CANMET, MSL Division
555 Booth Street
Ottawa, Ontario
K1A 0G1

TELEPHONE: (613) 992-1392

The Scientific Authority is responsible for all matters concerning the scientific and technological content of the Work under this Contract. Any proposed changes to the Scope of the Work are to be discussed with the Scientific Authority, but any resultant changes may be authorized only by a contract amendment issued by the Science Contracting Officer.

SECTION D: PAYMENT

BASIS OF PAYMENT - CROWN'S SHARE: FIRM PRICE

In consideration of the Contractor satisfactorily completing all of its obligations under this Contract, the Contractor shall be paid **a firm price of $20,000 (Crown's share of the total estimated cost shown at page 1 of this contract), GST extra.** No increase in the total liability of Canada or in the price of the Work or Services resulting from any design changes, modifications or interpretations of the specifications, will be authorized or paid to the Contractor unless such design changes, modifications or interpretations shall have been approved by the Minister prior to their incorporation in the Work or Services.

GOODS AND SERVICES TAX (GST)-APPLICABLE TO THE CROWN'S SHARE

The goods and services tax (GST) is not included in the amounts shown in the Basis of Payment clause. **The GST applicable to the Crown's share specified above, which is estimated at $1,400, is included in the Total Estimated Cost shown on page 1 of this Contract.** The GST, to the extent applicable, is to be shown separately on all invoices and claims for progress payments and will be paid by Canada. The Contractor agrees to remit to Revenue Canada - Customs and Excise any GST that the Contractor receives from Canada pursuant to this Contract.

CONTRACTOR'S SHARE OF THE TOTAL ESTIMATED COST

The Contractor is entirely responsible for financing $10,000 of the total estimated cost shown at page 1 of this contract via arrangements taken by the Contractor.

FUNDING BY FISCAL YEAR

Notwithstanding the Cost specified in the Basis of Payment, and unless otherwise authorized in writing by the Science Contracting Officer, the maximum amount which may be paid, in the period ending 31 March of the year specified is as follows:

1993 - $20,000 GST extra.

METHOD OF PAYMENT

1. Milestone payments will be made in accordance with the following Schedule of Milestones, provided that:

    (a) Contractor submits a claim for payment on form DSS-MAS 1111 (02/90), Claim for Progress Payment, enclosed;
    (b) all of the certificates appearing on the said form are signed by the respective persons indicated thereon or their delegate; and
    (c) all deliverables required for the milestone claimed have been received and accepted by the Scientific Authority.

2. The claim must show the following:

    (a) amount currently claimed;
    (b) total of all previous claims against the Contract and the extensions of the total to date;
    (c) deduction of holdback (if applicable)
    (d) requisition number (RN), Financial Code (FC), and Contract Number as shown on page 1 of this Contract;
    (e) Goods and Services Tax (GST) and Registration number.

3. The Contractor shall prepare and certify (signature required on reverse of form) an original and two (2) copies of its claim on form DSS-MAS 1111 (02/92). The claim will be forwarded to the Science Contracting Officer who will certify the claim and forward it to the Scientific Authority for certification and payment.

4. Payment by Canada to the Contractor for the Work shall be made:

(a) in the case of a milestone payment other than the final payment, within thirty (30) days following the date of receipt of a duly completed milestone claim on form DSS-MAS 1111 (02/90);

(b) in the case of a final payment, within thirty (30) days following the date of receipt of a duly completed final milestone claim, on form DSS-MAS 1111, or within thirty (30) days following the date on which the Work is completed, whichever date is the later;

(c) if Canada has any objection to the form of the milestone claim, within fifteen (15) days of its receipt, Canada shall notify the Contractor of the nature of the objection. "Form of the claim" means a claim which contains or is accompanied by such substantiating documentation as Canada requires. Failure by Canada to act within fifteen (15) days will only result in the date specified in subparagraphs 5(a) and (b) of this clause applying for the sole purpose of calculating interest on overdue accounts.

Milestone Schedule:

Milestone #1: at a firm price of **$20,000 plus $1,400 for GST** , **subject to a $10,000 holdback** provided that:

a) tasks 1. to 4. inclusively be completed on or before **31 March 1993** to the satisfaction of the Scientific Authority designated herein; and

b) the milestone report described herein be delivered on or before **31 March 1993** to and be accepted by the Scientific Authority designated herein.

Milestone #2: **release of the holdback of $10,000** , provided that:

a) the task 5 described herein be completed to the satisfaction of the Scientific Authority designated herein ;

b) the draft final report and the final report described herein **be respectively** delivered on or before **30 April 1993** and **31 May 1993** to and be accepted by the Scientific Authority designated herein;

c) all the other deliverable items described herein be delivered on or before **30 May 1993** to and be accepted by the Scientific Authority and by the Science Contracting Officer as applicable; and

d) the Milestone #2 claim be approved by the Science Contracting Officer and by the Scientific Authority designated herein.

C0101D DISCRETIONARY AUDIT	01/06/91
H0001D INTEREST ON OVERDUE ACCOUNTS	01/12/92
H3008C CONDITIONS PRECEDENT TO PAYMENT	01/06/91

SECTION E: TERMS AND CONDITIONS

K0017C 01/06/91
GENERAL CONDITIONS, DSS-MAS 9224

INTELLECTUAL PROPERTY CONDITION SUBSTITUTIONS

Clause **K3302D (01/12/92): Intellectual Property Rights** referenced in this document, replaces the following provisions of the General Conditions and Supplemental General Conditions:

DSS-MAS 9224: section 13 (Ownership of Technical Documentation and Prototypes), section 14 (Ownership of Inventions and Technical Information) and section 15 (License).

K3302D 01/12/92
INTELLECTUAL PROPERTY RIGHTS

K2100D 11/12/91
SOUTH AFRICAN/HAITIAN CONDITIONS

K2200D 01/04/92
CONFLICT OF INTEREST

REPLACEMENT OF PERSONNEL

In accordance with section 5 of General Conditions - Research and Development, DSS-MAS 9224, the Contractor shall provide the services of the following personnel to perform the Work required under this Contract: **Stephen J. Day.**

ANNEX "A"

OBJECTIVES AND DESCRIPTIONS

The Objectives of this project are to:

- Characterize six years of acid generation from four rock types in the on-site waste rock pads and apply the results to understanding rock dump acid generation processes;
- Evaluate a column study of mixing calcareous rock with mine waste rock as a means to prevent the formation of acid drainage; and
- Characterize material that has undergone over three years of weathering in humidity cells.

The project will include the following tasks:

1. Complete monitoring of columns 2 and 3 for:
   - Ph and conductivity every two weeks
   - SO_4 acidity, alkalinity and dissolved Ca, Mg, and Fe every month
   - dissolved copper, zinc, lead and arsenic every two weeks
2. Dismantling of the five columns
3. Analysis of column residues and one set of samples from the waste rock pad for:
   - particle size
   - total sulphur, sulphide sulphur
   - carbonate content
   - mineralogy
   - neutralization potential
   - acid generating potential
   - elemental composition of the residue and of the eluants for sequential leach (the sequential leach should include citrate dithionate bicarbonate and acid ammonium oxalate extractors)
4. Maintenance of the on-site waste rock pads intact to allow them to be revisited at a later date.
5. Generation of a well written report including the following:
   - the materials and methods and the reasons they were collected
   - presentation of results from this and previous years' research (contracts KA601-0-3388/01XSB and KA601-1-3158/01XSB), including all components of City Resources' acid generation test program
   - evaluate all the data collected, discussing: the success of the limestone amendment; the different methods for predicting the acid generation potential; the process of acid generation; the mobility of different elements; possible methods for early detection; the contribution of the work reported to improved AMD prediction; and recommend new directions for chemical prediction research.
   - review comments received for the Stage II report
   - note all persons who worked on the project and their areas of responsibility.

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APPENDIX A.2

BC ACID MINE DRAINAGE TASK FORCE CONTRACT

SCHEDULE "A"

SERVICES AND CONTACTS

The Contractor will provide the following services:

PHASE I

A. Description

1. **The objectives of this project are:**

    a) to characterize six years of acid generation from four rock types in the on-site waste rock pads and apply the results to understanding rock dump acid generation processes;

    b) to evaluate a column study of mixing calcareous rock with mine waste rock as a means to prevent the formation of acid drainage; and

    c) to characterize material that has undergone over three years of weathering in humidity cells.

B. SPECIFICATIONS

1. Continue monitoring columns 2 and 3 for:

    a) pH and conductivity every two weeks;

    b) SO_4 acidity, alkalinity and dissolved Ca, Mg, and Fe every month;

    c) dissolved copper, zinc, lead, arsenic every two weeks.

2. At the end of the year, dismantle all five columns.

3. Analyse the column residues and one set of samples from the waste rock pads for:

    a) particle size

    b) total sulphur, sulphide sulphur

    c) carbonate content

    d) mineralogy

    e) neutralization potential

    f) acid generation potential

    g) elemental composition of the residue and of the eluants from sequential leach (the sequential leach should include citrate dithionate bicarbonate and acid ammonium oxalate extractions).

4. Maintain the on-site waste rock pads intact to allow them to be revisited at a later date.

5. Produce a well written report including the following:

    a) the materials and methods, and the reasons they were collected;

    b) presentation of the results from this and previous years' research, and including all components of City Resources' acid generation test program.

    c) evaluate all the data collected, discussing: the success of the limestone amendment; the different methods for predicting the acid generation potential; the process of acid generation; the mobility of different elements; possible methods for early detection; the contribution of the work reported to improved AMD prediction; and recommending new directions for chemical prediction research;

    d) review comments received for the Stage II report;

    e) the report should note all persons who worked on the project and their areas of responsibility.

6. A well written draft report should be submitted to the Contract Manager on or before February 28, 1993.

PHASE II

A. DESCRIPTION

Prepare one camera-ready copy of the general report.

B. SPECIFICATIONS

1. Meet with members of the B.C. AMD Task Force Review Committee to discuss modifications/revisions of the draft report.

2. Prepare one camera-ready copy and five bound copies of the final report. Submit all copies along with a copy of the report on a $5^1/4$ inch computer diskette to the Contract Manager on or before March 31, 1993.

C. NOTICES

CONTRACT MANAGER:	Dr. William A. Price Resource Management Branch Ministry of Energy, Mines & Petroleum Resources Room 105, 525 Superior Street Victoria, British Columbia V8V 1X4 Phone: 356-5275
CONTRACTOR:	Norecol Environmental Consultants Ltd. 250 - 13571 Commerce Parkway Richmond, B.C. V6V 2R2 Phone: 273-7763

APPENDIX B

PROJECT RESPONSIBILITIES

APPENDIX B

PROJECT RESPONSIBILITIES

Project tasks were conducted by the following individuals (credentials and academic status indicated in parentheses):

Corporate Sponsor, Representative	City Resources (Canada) Inc. (to 1992, now defunct). Andrew Robertson (P.Eng. Geotechnical Engineer).
Experimental Design	Stephen Day (P.Geo., Geochemist), Kevin Morin (P.Geo., Hydrogeologist), Niko Zorkin (Ph.D., Biologist).
Laboratory Operations - Kinetic tests.	BC Research Corp. Overall management: Rik Vos Monitoring: Tim O'Hearn Water analyses: Herb Lanz
Laboratory Operations - Static tests.	Chemex Labs. Lloyd Twaites, Annie Christie
Petrographic work	Pre-1990 - Vancouver Petrographics 1990-1993 - Craig Leitch (P.Eng. Geologist), Stephen Day
Field Sampling	Various City Resources personnel prior to 1990. Desiree Ward (1990-91) Glen Beachy (1991-92)
Project Management	Stephen Day, Niko Zorkin
Data Interpretation and Report Preparation	Stephen Day.
Internal Report Review	David Harpley (P.Geo., Hydrogeologist)
Client Scientific Authorities and External Project Review	1990-91: Environment Canada: Keith Ferguson (P.Eng.) 1991-92: Environment Canada: Benoit Godin (Biologist) 1992-93: BC Energy Mines and Petroleum Resources: William Price (Ph.D., Soil Scientist), Energy, Mines and Resources Canada: Errol van Huyssteen.

APPENDIX C

THIN SECTION REPORTS

PETROGRAPHIC REPORT ON FIVE CRUSHED ROCK SAMPLES FROM CINOLA THAT HAVE BEEN EXPOSED TO HUMIDITY CELL TEST WORK

Report for:
Stephen Day,
Norecol Environmental Consultants,
Suite 700, 1090 West Pender Street,
Vancouver, B.C.
V6E 2N7.

Invoice attached

October 22, 1990

Samples submitted: HC2-3, 4; HC3-11, 20, 22.

SUMMARY:

The samples in this suite are crushed rock from the Cinola low-grade gold deposit that have been subjected to simulated weathering by humidifiying and leaching once a week for three years. They show relatively little signs of oxidation apart from minor rust stains on the surfaces of fragments. These limonite (hydrated iron oxide) stains in general do not penetrate the cores of the fragments, and the volume of limonite is small. However, in most samples there are a few fragments that have been entirely replaced by limonite. Widths of weathering rinds are therefore highly variable, and it is difficult to quantify them.

The original mineralogy of the fragments in these samples is mainly quartz (either coarse, up to 0.5 mm, and clear, or fine to very fine grained, 0.01 to 0.05 mm). In two samples (HC2-3 and 11) feldspar is recognizable, probably mainly plagioclase (albite), and there is minor sericite and in places green amphibole. Carbonate is found in only one sample (HC3-22), where it is abundant and probably largely calcite (SEM study would be required to confirm this). In this same sample and in HC3-20, black fragments contain minor to abundant ?amorphous carbon as very fine particles up to 20 microns. The only sulfide recognizable is in these two samples (HC3-20 and 22), and it is pyrite as anhedral grains up to 0.5 mm diameter. In both samples it is surprisingly unoxidized (only minor limonite developed on it). In other samples, where sulfides are not certainly identifiable in reflected light due to plucking problems during polishing, the development of limonite is more extensive. It is possible that in these, there has been partial removal of the sulfide. There is no noticeable weathering of silicates or carbonates.

CHB Leitch

Craig H.B. Leitch, Ph.D., P.Eng.
(604) 921-8780 or 666-4902

HC2-3: LIGHTLY OXIDIZED QUARTZ AND CONGLOMERATE FRAGMENTS WITH GENERALLY BARELY OXIDIZED PYRITE AND MINOR LIMONITE

This sample contains rock fragments of highly variable size (up to 2 cm diameter) and composition. Sulfide (mainly pyrite) is visible in the fragments that were cut with the diamond saw, in various stages of oxidation from fresh to honeycombed. Limonite is essentially restricted to the outside faces of the fragments. Both a thin section to show the variable clast lithologies and a polished thin section of a non-selected sample were prepared. The mineralogy in the thin section is indicative of strongly altered (silicified) coarse clastic rocks, or conglomerates, with a volcanic source:

Quartz	60%
Feldspar (mainly albite)	15%
Sericite (muscovite)	10%
Epidote	5%
Limonite	5%
Opaque (?pyrite, Fe-Ti oxides)	5%

Since the focus of this study is on the weathering or oxidation of these fragments, rather than on the petrology, I will not describe the lithologies in detail. Some of the fragments are composed of almost pure quartz (mainly secondary) while others contain clasts of ?volcanic or high-level intrusive rock with abundant highly albitized plagioclase and remnant mafic material (epidote and limonite).

Opaque material is evident in the thin section but is not identifiable there. In the polished thin section, plucking of these fragments was so severe (in spite of normal precautions) that the polish is very poor and no opaques remain in the surface of the section. However, solid grains of limonite with reddish- to orange-brown internal reflections (goethite), up to 0.2 mm across, appear to be after sulfide. Thin films of secondary (transported) limonite are also commonly developed along grain boundaries and fractures, particularly at the margins of fragments and pervasively through the smaller fragments, which form about 10% of the polished thin section.. Limonite development is only barely noticeable in the large fragments in the thin section.

The polished thin section contains a few exotic crystals of sea-green amphibole up to 0.25 mm long. The section is too thick to make positive identifications, but there does not appear to be any carbonate present.

In summary, due to the polishing problems it is difficult to be sure of the levels of sulfide originally present, but the hand specimen and thin section both suggest that oxidation of this sample has produced only surficial limonite in the larger (0.5 to 2 cm) fragments, while some of the smaller ones (less than 2 mm) have been completely weathered. Development of weathering rinds or rims is prominent only in the larger fragments.

HC2-4: LIGHTLY OXIDIZED QUARTZ AND QUARTZ-LIMONITE FRAGMENTS

This bag contains fine (1-4 mm) white to dark grey, lightly orange-brown rust-stained fragments. In the polished thin section, the same problems are apparent as in HC2-3, with plucking causing a very poor polish. However, the thickness is closer to 30 microns and in transmitted light most of the fragments can be seen to be made up to quartz, either as monomineralic crystals or aggregates of very fine grains:

Quartz	80%
Limonite (goethite)	10%
Opaque (possibly pyrite?)	5%
Muscovite	3%
Amphibole	2%

There is little to add in the description of this sample that has not been said for the previous sample. About half of the grains, particularly the ones composed of pure, coarse quartz, show no traces of limonite. Of the other 50%, about 30% show development of traces of limonite, especially around the margins. This is secondary (transported) limonite derived by weathering of sulfides that are, in general, not found in the fragments themselves.

Of the final 20% of fragments, about half contain minute (10-20 micron) anhedral to rounded opaques that may be sulfide or Fe-Ti oxides (none are present in the polished surface for identification purposes). The other half are so highly stained by limonite that nothing else is visible.

In summary, this sample shows similar minor oxidation to limonite, presumably from weathering of original pyrite, as found in HC3-2. The smaller fragments that contain opaques tend to be more heavily replaced by limonite, starting at the outside rims and proceding to pervasive development. The vast majority of the limonite has very pale yellowish-brown colour, and is probably goethite. In reflected light, some larger (up to 0.1 mm diameter) grains of limonite have pale red-brown internal reflections and may contain minor amounts of hematite. The widths of weathering rinds or rims are difficult to quantify, because while many are typically 10-20 microns (0.01 to 0.02 mm) thick, other grains may have limonite to their cores.

No carbonate is visible, and few of the silicate grains (quartz or amphibole) show any signs of weathering.

HC3-11: QUARTZ-MINOR PLAGIOCLASE LITHIC FRAGMENTS WITH WEAK LIMONITE STAIN

The submitted sample is composed of a bag of pale grey to very lightly iron-stained rock chips averaging about 2-3 mm in diameter, but ranging from rock powder to as much as 1 cm. In the absence of any sawn surfaces of the chips to examine, sulfides cannot be positively identified in this sample. There is no reaction to cold dilute HCl. In the polished thin section, which suffers from the same limitations as for HC2-3 (plucking causing poor polish), the mineralogy is dominated by quartz and feldspar:

Quartz (fine, in lithic fragments)	60%
Quartz (monomineralic, coarse)	15%
Feldspar (mainly ?plagioclase)	10%
Sericite	5%
Limonite	5%
Opaque (?sulfides)	5%

The rock fragments are dominantly fine-grained (0.01 - 0.05 mm diameter quartz, although in places there are vague relict, to obvious, 0.2 mm plagioclase microlites. The quartz forms anhedral, tightly interlocked grains, but the feldspar is subhedral to euhedral.

In places there are coarse ?feldspar grains (refractive index of this albitized material is very close to that of quartz, and there is no twinning) in the rock fragments. It is likely that the coarse monomineralic quartz fragments are merely large quartz grains that have broken free. Most of them are free of iron stain.

Some of the finer-grained lithic fragments contain minor amounts of other silicates, mainly very-fine-grained sericite (muscovite) flakes up to 10-20 microns long.

Most of the lithic grains show minor amounts of opaques, probably either sulfides or Fe-Ti oxides as subhedral to anhedral particles of 20-50 micron diameter. None of these are present in the surface of the polished section, so no sulfides can be positively identified. There are abundant (but not volumetrically important) limonite grains that have pale orangey-brown internal reflections and are probably mainly goethite.

Limonite is more weakly developed in this sample than in HC2-3 or 4. In places it spreads out from opaque grains, suggesting it is developed by oxidation of the opaques. In many places, however, it is present as extremely fine-grained (submicroscopic) films along grain boundaries and fractures, and is transported limonite. It does not show a preference for clast boundaries or rims in this sample.

HC3-20: RUSTY (QUARTZ-RICH) AND MINOR BLACK (?CARBONACEOUS) ROCK FRAGMENTS, WITH IDENTIFIABLE PYRITE

Orangey-brown rust-stained to black (?carbonaceous) chips of rock up to 0.5 cm diameter. Small fragments of both clear and milky white quartz are also visible. In polished thin section, the mineralogy differs slightly from the previous samples:

Quartz (fine-grained, in lithic fragments)	65%
Quartz (monomineralic fragments)	10%
Pyrite	10%
Carbon (?)	5%
Limonite	5%
Sericite	5%

There are the same monomineralic coarse quartz and clear fine-grained quartz fragments as in HC3-11; these are probably the quartz clasts seen in the hand sample. The dark clasts are brownish in transmitted light, with minor very fine semi-opaque grains. In the thin section, however, some of the pale brown material in the dark fragments (included with "limonite" in previous samples) is probably amorphous carbon, as submicroscopic (less than 1 micron) to microscopic (2-5 micron) grains. This tentative identification is based entirely on the colour of the black clasts in hand sample; positive identification would be difficult or impossible without a carbon analysis.

There are also larger opaque grains, up to 20 microns across, of sulfide (recognizable as pyrite in reflected light). Where found in the interior of clasts, they have no identifiable rims of limonite. They are not seen on the outside of clasts, suggesting they may have been weathered from these sites (or more likely, simply plucked during polishing). Recognizable limonite is mainly found as primary (non-transported) material, with opaques, inside the clasts. There are traces of limonite around the outermost rims of a few fragments, bearing out the hand sample observation of only minor rust staining.

There is apparently no carbonate present in this sample, and the silicates (quartz and minor sericite) are in general unweathered.

HC3-22: BLACK (?CARBONACEOUS) AND WHITE (QUARTZ-RICH) ROCK CHIPS WITH MINIMAL OXIDATION EVIDENT

This sample consists of 1-4 mm diameter rock chips of either black (?carbonaceous) or white (porous) character. The white fragments are considerably less abundant (20% of the total). There is no limonite, or rust stain, as in the other samples. In polished thin section, the mineralogy is approximately as follows:

Quartz	50%
Carbonate (partly calcite)	20%
Amorphous carbon (?)	15%
Sulfide (pyrite)	10%
Sericite	5%
Limonite	<1%

The principal difference between this sample and the other samples is the apparent lack of oxidation in hand specimen. The black clasts are probably rich in amorphous carbon (for the same reasons as in HC3-20, although in this sample the particles may be seen in reflected light to have low reflectivity of around 5%). This material is much more abundant in this sample than in HC3-20, and forms brown semi-opaque intergranular films and fine grains of up to 20 micron size. The rest of these clasts is made up of fine subhedral (rhombic) grains of carbonate up to 0.05 mm across, intimately mixed with finer quartz (0.01-0.02 mm) and carbon, plus scattered sulfide.

Sulfide is clearly visible in reflected light as anhedral to subhedral grains, especially where it occurs free as monomineralllic clasts up to 0.5 mm across. It is isotropic and probably mainly pyrite. It shows minor oxidation at the rims and along fractures to a limonite with bright red-brown internal reflections (goethite and hematite). In the carbonaceous clasts, most sulfide grains are anhedral and less than 0.05 mm in diameter. They do not show evidence of oxidation even where exposed at the margins of fragments, implying only slight weathering (as suggested by the lack of rust in the hand sample). Limonite content is really minimal in this sample.

The white clasts appear to be rich in carbonate, at least part of which is calcite (minor reaction to cold dilute HCl). However, it is difficult to observe the reaction in these small chips; more of the carbonate may be clacite than is apparent. In thin section, the carbonate forms coarse euhedral to subhedral grains up to 0.2 mm across, and may form monominerallic clasts up to 0.5 mm diameter.

PETROGRAPHIC REPORT ON SEVEN CRUSHED ROCK SAMPLES FROM CINOLA THAT HAVE BEEN COLUMN LEACHED

Report for:
Bruce Ott, Norecol Environmental Consultants Ltd.
Crestwood Corporate Center
Suite 250, 13571 Commerce Park Way
Richmond, B.C.
V6V 2R2.

Invoice attached
March 29, 1993.

Samples submitted: 2-21-435 col-1; col-2 top and mid; col-3 top and mid; col-4; col-5.

SUMMARY:

The samples in this suite are crushed rock from the Cinola low-grade gold deposit that have been subjected to simulated weathering by column leaching for 2-5 years. They show signs of moderate oxidation (especially the samples from the top in columns 2 and 3; other samples such as column 2 mid show only minor rust stains on the surfaces of fragments). These limonite (mainly goethite) stains in general do not penetrate the cores of the fragments, but form rims to a maximum of about 150 µm thick, and the volume of limonite is small (less than 10%). Widths of weathering rinds are highly variable, and it is difficult to quantify them. However, in most samples there are a few fragments and sulfides that have been entirely replaced by limonite, especially smaller fragments or where sulfides are exposed at the surface of the clast.

The original mineralogy of the fragments in these samples is mainly quartz (either coarse, and clear, vein quartz, up to 0.5 mm, or fine to very fine grained, 0.001 to 0.05 mm); there is minor interstitial sericite and rare green amphibole and ?zircon. In all samples some clasts are composed mainly of feldspar, probably mainly plagioclase (albite) as 0.1 mm microlites hosting rare ?K-feldspar phenocrysts. Carbonate is found in all samples except col-1 and 5, but is most abundant in col-2 mid (25%). It is probably largely calcite (SEM study would be required to confirm this). In a few samples, black fragments contain minor to abundant ?amorphous carbon as very fine particles up to 20 microns. Sulfides are common but not abundant in all samples, mainly pyrite as anhedral aggregate grains up to 0.5 mm diameter but including minor framboidal pyrite and marcasite (?replacing former bladed ?pyrrhotite). In most samples sulfide is largely unoxidized (except at margins of clasts; in a few, hematite is seen pseudomorphing pyrite).

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2-21-435 col-1: OXIDIZED, QUARTZ VEINED SILICEOUS SEDIMENT

Light tan coloured, crushed rock sample containing angular fragments mainly about 3 mm in size but occasionally up to 1.5 cm diamter. There is no reaction to cold dilute HCl, and the fragments are not magnetic. When wetted, about half show grey siliceous interiors with traces of limonite on outside surfaces. Mineralogy in polished thin section is:

Quartz (fine, possibly largely secondary)	80%
(coarse, possibly vein)	5%
Limonite (mainly goethitic)	5%
Sericite	5%
Feldspar (?plagioclase)	2%
Chlorite (?)	1%
Sulfides (pyrite)	<1%
Fe-Ti oxides (rutile, sphene)	<1%

The majority of the fragments in this sample are made up of very fine, highly anhedral, tightly interlocked quartz crystals that could be partly primary quartz grains from a sedimentary rock but are most likely mainly secondary. They range up to 100 µm in diameter but average less than 50 µm. There are all gradations from obviously sedimentary clasts composed of 50-100 µm grains set in a matrix of 5 µm grains, to veins of bladed, ?chalcedonic quartz up to 1 mm wide.

A small percentage of the siliceous clasts consist of single euhedral to subhedral crystals of clear quartz up to 0.75 mm in diameter. These may represent fragments of quartz veins. Rare dark, semi-opaque fragments appear to consist mainly of limonite, with a strongly ?flow-banded appearance caused by elongate, 0.1 mm long by 20 µm thick domains of very fine-grained quartz or alkali feldspar; these may have been felsic volcanics. A small percentage of fragments consist of 10-90% fine (25 µm) sericite, possibly after former feldspar. Limonite is mixed with the sericite.

A few fragments are composed mainly of fine laths of euhedral feldspar, probably plagioclase, up to 0.15 mm long. There is minor flecking of plagioclase by fine sericite; interstitial areas are composed of very fine-grained, blue-anomalous (moderate Fe) ?chlorite of about 10 µm diameter and spots of limonite up to 50 µm across, possibly after original Fe-Ti oxides in a volcanic or hypabyssal rock.

Most fragments contain about 3-5% very fine dispersed, intergranular limonite up to 25 µm in diameter; a few consist almost entirely of limonite. Deep red-brown colour of most limonite indicates mainly goethitic composition. The majority of the limonite is concentrated on outside rims of clasts, but a fair amount (perhaps 30%) penetrates interiors of clasts, mainly along fractures or where Fe-bearing primary phases were present (oxides, ?mafic minerals, sulfides). Sulfides are mainly fine-grained (5-50 µm) highly anisotropic pyrite or possibly marcasite in rounded clusters suggestive of framboids, or low-temperature origin; grains occur almost right to the margins of the clasts. One 100 µm grain of ?magnetite was seen; aggregates of rutile to 0.25 mm across are found in quartz.

2-21-435 col-2 mid: VIRTUALLY UNOXIDIZED SILICEOUS SEDIMENT, CARBONATE AND ?VOLCANIC FRAGMENTS WITH MINOR PYRITE

LIght grey crushed rock sample similar in size distribution to col-1 or somewhat coarser; there is a strong reaction to cold dilute HCl in some fragments, although none are magnetic. Limonite is not as obvious as in col-1. Mineralogy in polished thin section is approximately:

Quartz (largely secondary)	60%
Carbonate (mainly calcite)	25%
Feldspar	5%
Sericite	5%
Sulfide (mainly pyrite; minor marcasite)	3%
Limonite	1%
Fe-Ti oxides (rutile)	<1%

Most fragments in this sample are siliceous, composed of highly anhedral, tightly interlocking quartz crystals of 5-50 μm size. Some are cut by obvious quartz veins up to 1 mm thick, with subhedral quartz crystals up to 0.7 mm size. A second common type of clast consists of quartz ?grains of about 50 μm size in a matrix of extremely fine (5-10 μm) ?quartz, minor fine pyrite, Fe-Ti oxides and sericite.

Carbonate, probably mainly reactive calcite, forms mainly fine-grained (20-40 μm) masses up to 2 mm across, in places containing subhedral crystals up to 1 mm in diameter. There are no sulfides in these clasts. Lesser carbonate is found in thin irregular veins crossing siliceous clasts; the carbonate in these veins is not in contact with sulfides. Other clasts appear to be partly to almost entirely replaced by calcite.

A small proportion of the clasts consist of bladed feldspar crystals up to 0.3 mm long in a matrix of feldspar microlites averaging about 0.1 mm long. These appear to be ?felsic volcanic rocks; minor alteration to fine-grained sericite, ?chlorite and limonite is observed.

Sulfides are principally pyrite, as aggregates up to 1.3 mm across that are composed of subhedral to euhedral crystals about 20-50 μm in diameter. The pyrite is mainly isotropic, but anisotropic ?marcasite also occurs, in lath-shaped outlines suggestive of former ?pyrrhotite, and there is rare colloform/framboidal pyrite. Oxidation of sulfides is not apparent in this sample, even at margins of fragments. Limonite consists of a pale intergranular wash in some fragments and an extremely thin (5μm) film on the outside of other clasts. Some of the larger pyrite masses contain inclusions of subhedral ?rutile up to 100 μm long; rutile also occurs rarely in the siliceous fragments.

Limonite is less abundant in this sample than in col-1; note that although it contains more sulfide, the abundant calcite in this sample would tend to neutralize acid solutions generated by oxidation of the sulfide.

2-21-435 col-2 top: SILICIFIED, QUARTZ VEINED SEDIMENT AND RARE VOLCANIC CLASTS; MINOR PYRITE AND CARBONATE

Light brown, less randomly-sized crushed rock averaging about 3 mm. There is no reaction to cold dilute HCl; only rare clasts are attracted to a magnet. Limonite is abundant and is commonly found as cement to aggregated clasts. Rare grey siliceous clasts are also apparent. Mineralogy in polished thin section is approximately:

Quartz (mainly secondary)	70%
Sericite	10%
Limonite (mainly goethtite)	7%
Feldspar	5%
Sulfide (mainly pyrite, marcasite)	3%
Carbonate	3%
Chlorite	1%
Fe-Ti oxides (rutile)	1%

Most of the fragments in this sample consist of variable amounts of secondary quartz and are probably silicified sediments; a few are obviously volcanic. In the former, ragged, interlocked anhedral quartz crystals range from about 10 μm up to 100 μm in diameter. Most contain a few percent disseminated sulfide grains, some of which are oxidized to limonite. Sericite is more abundant in this sample than the preceding, forming fine subhedral flakes up to 20 μm diameter intergrown with the quartz in certain clasts. As in other samples, some clasts consist of 0.1 mm ?detrital quartz and mica grains in a very fine siliceous matrix; these may represent less altered sediments. Coarse subhedral to anhedral quartz crystals up to 0.5 mm diameter are found in veins cutting the clasts.

Volcanic clasts consist of euhedral feldspar microlites of about 0.1-0.15 mm length, partly altered to quartz and sericite and in places set in a very fine matrix of limonite and ?relict chlorite. Relief less than quartz suggests alkali feldspar, possibly albite or K-feldspar.

Carbonate clasts are as described in the mid sample from this column; although reaction was not seen in the hand sample, it is likely this is because the amount is too small, and the carbonate is also calcite. It is not found in contact with sulfides; as in col-2 mid, calcite clasts do not have limonite rims.

Sulfides comprise coarse, euhedral pyrite crystals up to 0.2 mm diameter, or aggregates to 1.5 mm across of fine subhedral crystals averaging 0.05 mm. Less common marcasite forms subhedral crystals to 50 μm long in certain clasts. Framboidal pyrite is not common. Minor rutile is present in euhedral to subhedral crystals up to 100 μm long

Most of the siliceous fragments are strongly rimmed by limonite, with substantial thicknesses up to 100 μm in some of mainly brown goethitic limonite. Many clasts show an extensive pale wash of intergranular limonite; in others sulfides are extensively to rarely completely oxidized to red-brown limonite (goethite and minor hematite). Oxidation is best developed in the margins of the clasts.

2-21-435 col-3 mid: SILICIFIED, VEINED SILICEOUS SEDIMENT AND FELSIC VOLCANIC FRAGMENTS; TRACE PYRITE, MINOR LIMONITE

Tan-coloured, relatively fine-grained crushed rock (most fragments under 1 mm, but rarely ranging up to 1 cm). There is no reaction visible to cold dilute HCl, and no magnetic fragments. Limonites are present but not as abundant as in col-2 top. Mineralogy in polished thin section is approximately:

Quartz (largely secondary)	75%
Feldspar (alkali feldspar)	15%
Sericite	5%
Limonite	3%
Carbonate (?calcite)	1%
Pyrite (trace marcasite)	1%
Rutile	<1%
Chlorite	<1%

Most fragments consist of fine, anhedral secondary quartz with traces of sericite and sulfide, cut by veins of anhedral quartz up to 0.5 mm thick. A lesser proportion consist of recognizable sedimentary fragments containing detrital quartz and muscovite grains to 0.1 mm diameter in anhedral, partly recrystallized 5-25 µm quartz, minor sulfide and sericite with traces of rutile and limonite.

A larger proportion of clasts than in other samples consists of feldspathic material, probably felsic volcanics. These are mainly fine euhedral to subhedral feldspar laths to 0.4 mm long and rare ?chlorite to 0.2 mm in a matrix of feldspar microlites averaging less than 0.1 mm long. In some clasts the feldspar laths are pseudomorphed by secondary quartz; in others, feldspars are set in a matrix of fine-grained ?limonite and quartz, and in others feldspars are partly altered to sericite.

Most clasts have very thin (10-15 µm) rims of limonite, rarely reaching 100 µm in thickness on small particles. There is only minor limonite in interiors of some feldspathic clasts. Rare carbonate (?likely calcite) composed of fine anhedral grains about 30 µm in diameter do not show rims of limonite.

Sulfides are mainly euhedral to subhedral pyrite crystals up to 0.5 mm diameter, variably oxidized to red-brown goethite and minor hematite where they are freed from the siliceous matrix or exposed at the margins of clasts. However, pyrite grains more than 20 µm from the margins are unoxidized. Rarely the pyrite forms rounded colloform/framboidal masses up to 0.05 mm diameter. Rare fine (25-30 µm) crystals of anisotropic marcasite are present in some clasts. Rutile is found as skeletal crystals up to 0.1 mm long in some clasts.

This is a less oxidized sample than col-3 top (and col-2 top, although it contains less sulfide than that sample).

2-21-435 col-3 top: SILICIFIED SEDIMENTS AND MINOR VOLCANIC ROCK, OXIDIZED ON MARGINS TO LIMONITE

Light rusty brown, oxidized crushed rock with maximum particle size about 1 cm; clasts are elongated and flat. There are a few aggregated fragments; no reaction to cold dilute HCl was observed. A few small limonitic clasts are strongly attracted to a magnet. In the polished thin section, mineralogy is approximately:

Quartz (largely secondary?; vein quartz)	80%
Limonite (amorphous goethite; hematite)	7%
Feldspar (alkali)	5%
Sericite	5%
Pyrite, marcasite	2%
Fe-Ti oxides (mainly rutile)	1%
Carbonate (?calcite)	<1%
?Carbonaceous matter	tr

Most clasts consist of secondary quartz of variable size, ranging from coarse clear quartz (mainly in veins up to 1 mm thick, composed of sub to euhedral crystals up to 0.5 mm across) down to the limint of resolution as anhedral highly interlocked irregular crystals replacing the wallrock.

Feldspathic clasts consist of rare euhedral ?former feldspar phenocrysts up to 0.5 mm across in a matrix of feldspar microlites. Both appear to be alkali feldspar, possibly K-feldspar phenocrysts and albitic plagioclase in the groundmass. Mafic minerals are not visible; there are minor amounts of Fe-Ti oxides, mainly rutile, as fine crystals to 0.05 mm diameter.

A few clasts consist almost entirely of sericite as matted fine subhedral flakes of about 20 μm diameter. These may be partially stained by amorphous intergranular limonite. In other clasts a network of yellow-brown (?rust stained) sericite occurs as veins crossing the silicified rock. Rare clasts of fine grained (20 μm) carbonate, probably calcite (lack of reaction to acid is because of the low abundance) are up to 1 mm across. One or two elongate semi-opaque clasts appear to be made up of opaque (partly limonite, partly ?carbonaceous matter) and minor quartz.

Opaques are principally iron sulfides, mainly pyrite as subhedral crystals of about 50 μm size but aggregating to 1.5 mm, and marcasite as fine 20-30 μm crystals replacing ?former pyrrhotite laths up to 0.5 mm long. In places the sulfides are partly to completely oxidized to limonite, including yellow-brown goethite and red-brown hematite. Rims of all clasts carry considerable limonite as coatings or replacements up to 150 μm thick; a few smaller clasts are entirely replaced by limonite. Oxidation is noticeably stronger in this sample than in the sample from the middle of the column, with sulfides essentially removed from the outer margins of all particles for up to 100 μm.

2-21-435 col-4: SILICIFIED, QUARTZ VEINED AND PYRITIZED SEDIMENT AND ?ALBITIC VOLCANIC ROCK; MINOR OXIDATION

Very pale tan coloured crushed rock, maximum particle size about 0.5 cm. Limonite content is low and pale in colour. No reaction to cold dilute HCl was observed; particles are not magnetic. Mineralogy in polished thin section is approximately:

Quartz (largely secondary)	80%
Feldspar (alkali)	10%
Sericite	5%
Limonite (goethite; very rare hematite)	3%
Pyrite (minor marcasite)	1%
Rutile	1%
?Carbonaceous matter	<1%
Carbonate	tr
Apatite	tr

As in other samples in this suite, the bulk of the fragments consist of highly silicified ?sedimentary rock composed of highly anhedral, interlocking fine quartz up to 0.2 mm diameter, probably mostly secondary. Quartz veins cutting these rocks are up to 0.5 mm thick, and consist of clear quartz as sub- to rarely euhedral crystals up to 0.5 mm in diameter. Fine sulfides are common in the silicified wallrock but not in the veins. Sericite forms fine subhedral flakes to 30 μm diameter in the wallrock; these may represent altered feldspar relics. Carbonate is very rare in this sample, occurring as fine-grained monomineralic clasts to 0.25 mm diameter.

This sample contains more feldspathic fragments than most samples in the suite. These are composed mainly of fine eu- to subhedral ?plagioclase microlites averaging about 0.1-0.2 mm in length. Sericite is found interstitially as fine subheral flakes up to about 20 μm size; mafic minerals are not observed, suggesting a felsic volcanic or hypabyssal intrusive. Rare apatite forms euhedral crystals to 0.15 mm long, and there are scattered groups of fine rutile crystals after former Fe-Ti oxides. Rare semi-opaque clasts consist of ?carbonaceous matter, minor sulfide and limonite, and fine granular quartz; these may have been carbonaceous argillites.

Sulfides are rare in this sample, consisting of fine subhedral pyrite to 50 μm diameter, rarely mixed with minor marcasite crystals to 20 μm diameter. Rutile is found as aggregates to 0.05 mm of subhedral 10-30 μm crystals. Although limonite is generally not abundant in this sample, there are several coarse (to 0.25 mm) cubic-shaped grains of limonite, partly hematite, that appear to be replacements of former pyrite (relict fragments of pyrite are visible in a few). Most limonite, however, is pale yellow-brown in colour and found only as minor coatings on margins of fragments (to 20 μm thick) and as replacements of certain crystals in the clasts, or pale washes of amorphous transported character in intergranular position.

2-21-435 col-5: HIGHLY SILICIFIED SEDIMENTARY AND VOLCANIC ROCKS; VERY MINOR PYRITE AND MODERATE OXIDATION

Pale brown sample of fine crushed rock containing clasts to 0.5 cm. Limonite is not abundant, present mainly as thin coatings on fragments. There is no observable reaction to cold dilute HCl, and no attraction to a magnet. In polished thin section, mineralogy is approximately:

Quartz (largely secondary)	85%
Limonite (mainly goethitic)	5%
Sericite	5%
Feldspar	3%
Sulfide (pyrite, marcasite)	<1%
Rutile	<1%
Carbonaceous matter	<1%
?Amphibole	<1%
?Zircon	tr

This sample consists of a high proportion of highly silicified ?sedimentary and minor volcanic rocks. Most clasts consist mainly of largely secondary quartz as anhedral, interlocking crystals up to 0.1 mm diameter but generally much finer (20 μm), with minor sericite, sulfide and limonite. Veins of quartz are highly irregular and up to 0.5 mm thick. Rare euhedral crystals of ?zircon to 100 μm long are present; these are likely to be detrital. Some ?sedimentary rock contains clasts of feldspathic material, similar to those described as separate fragments below. Others contain rare subhedral crystals of green ?amphibole to 100 μm long.

Feldspathic (igneous) clasts are not common; some show euhedral outlines of relict ?feldspar crystals to 0.5 mm long, now pseudomorphed by quartz, in a groundmass of ?albitic microlites of 0.1 mm length, and fine interstitial Fe-Ti oxides (mainly rutile as subhedral crystals to 25 μm diameter).

Sulfides are relatively rare and very fine-grained in this sample, forming aggregates to only 0.15 mm diameter of both eu- to subhedral 20 μm marcasite crystals and 50 μm pyrite. Sulfide shows oxidation to limonite only within the outer 0.1 mm of the clasts, where it is mostly removed.

Limonite is found as rims to the fragments up to 50 μm thick (a few clasts are completely replaced by limonite) and as replacements of sulfide grains. Rarely, intergranular films penetrate the centres of fragments as pale washes of transported limonite. Colour of limonite is almost entirely pale yellow-brown (goethitic), with only traces of red-brown hematite. The sample is moderately oxidized.

APPENDIX D

DETECTION LIMITS AND ANALYTICAL REPORTS

APPENDIX D
DETECTION LIMITS AND ANALYTICAL METHODS

TABLE 1
CITY RESOURCES PROJECT (1987 TO 1990)
WASTE ROCK PAD STUDY

PARAMETER	UNIT	DETECTION LIMIT	METHOD
Waters			
pH	none	none	Electrode
Sulphate	mg/L	0.005	Turbidimetry
Conductivity	umho/cm	5	Electrode
Alkalinity	mg CaCO3/L	1	Titration with 0.02N sulphuric acid
Acidity	mg CaCO3/L	1	Titration with 0.02M sodium hydroxide
Ag	mg/L	0.002	ICAP
Al	Not analyzed		
As	mg/L	0.001	FAA
B	Not analyzed		
Ba	Not analyzed		
Be	Not analyzed		
Ca	mg/L	0.05	AA
Cd	mg/L	0.0002	FAA
Co	mg/L	0.001	FAA
Cr	mg/L	0.001	FAA
Cu	mg/L	0.0005	FAA
Fe	mg/L	0.1	AA
Total Hg	mg/L	0.00005	FAA
K	Not analyzed		
Mg	Not analyzed		
Mn	mg/L	0.001	FAA
Mo	Not analyzed		
Na	Not analyzed		
Ni	mg/L	0.002	FAA
P	mg/L	0.003	Ascorbic acid
Pb	mg/L	0.001	FAA
Sb	mg/L	0.002	FAA
Se	Not analyzed		
Silica	Not analyzed		
Sn	Not analyzed		
Sr	Not analyzed		
Ti	Not analyzed		
V	Not analyzed		
Zn	mg/L	0.01	FAA
Rock			
Powder pH			
Sulphur	%	0.001	Leco Furnace - Infrared dectector
Sulphate	%	0.01	HCl leach, gravimetric
Sulphide	%	0.01	Nitric acid bromide digestion, gravimetric
Neutralization Potential	kg CaCO3/t	None	Sobek et al., 1978 Method

Notes:
1. ICAP = Inductively coupled argon plasma. AA = Atomic absorption, FAA = Flameless atomic absorption.

APPENDIX D
DETECTION LIMITS AND ANALYTICAL METHODS

TABLE 2
BC AMD TASK FORCE/MEND PROJECT (1990 TO 1993)
WASTE ROCK PAD STUDY

PARAMETER	UNIT	DETECTION LIMIT	METHOD
Waters			
pH	none	none	Electrode
Sulphate	mg/L	0.005	Turbidimetry
Conductivity	•mho/cm	5	Electrode
Alkalinity	mg CaCO3/L	1	Titration with 0.02N sulphuric acid
Acidity	mg CaCO3/L	1	Titration with 0.02M sodium hydroxide
Ag	mg/L	0.1	ICAP
Al	mg/L	0.01	ICAP
As	mg/L	0.001	ICAP
B	mg/L	1	ICAP
Ba	mg/L	0.05	ICAP
Be	mg/L	0.05	ICAP
Ca	mg/L	0.1	ICAP
Cd	mg/L	0.05	ICAP
Co	mg/L	0.05	ICAP
Cr	mg/L	0.04	ICAP
Cu	mg/L	0.001	ICAP
Fe	mg/L	0.1	ICAP
Total Hg	Not analyzed		-
K	mg/L	0.5	ICAP
Mg	mg/L	0.2	ICAP
Mn	mg/L	0.04	ICAP
Mo	mg/L	0.04	ICAP
Na	mg/L	0.5	ICAP
Ni	mg/L	0.04	ICAP
P	Not analyzed		-
Pb	mg/L	0.1	ICAP
Sb	mg/L	0.1	ICAP
Se	mg/L	0.001	ICAP
Silica	mg/L	1	ICAP
Sn	mg/L	0.5	ICAP
Sr	mg/L	0.04	ICAP
Ti	mg/L	0.2	ICAP
V	mg/L	0.05	ICAP
Zn	mg/L	0.04	ICAP
Rock			
Powder pH			
Sulphur	%	0.001	Leco Furnace - Infrared dectector
Sulphate	%	0.01	HCl leach, gravimetric
Sulphide	%	0.01	Nitric acid bromide digestion, gravimetric
Neutralization Potential	kg CaCO3/t	None	Sobek et al., 1978 Method

Notes:

1. ICAP = Inductively coupled argon plasma. AA = Atomic absorption, FAA = Flameless atomic absorption.

APPENDIX D
DETECTION LIMITS AND ANALYTICAL METHODS

TABLE 3
CITY RESOURCES PROJECT (1987 TO 1990)
HUMIDITY CELL STUDY

PARAMETER	UNIT	DETECTION LIMIT	METHOD
Waters			
pH	none	none	Electrode
Sulphate	mg/L	0.005	Turbidimetry
Conductivity	•mho/cm	5	Electrode
Alkalinity	mg CaCO3/L	1	Titration with 0.02N sulphuric acid
Acidity	mg CaCO3/L	1	Titration with 0.02M sodium hydroxide
Ag	mg/L	-	ICAP
Al	Not analyzed		
As	mg/L	0.001	FAA
B	Not analyzed		
Ba	Not analyzed		
Be	Not analyzed		
Ca	mg/L	0.05	AA
Cd	mg/L	-	FAA
Co	mg/L	-	FAA
Cr	mg/L	-	FAA
Cu	mg/L	0.03	AA
Fe	mg/L	0.1	AA
Total Hg	mg/L	0.00005	FAA
K	Not analyzed		
Mg	Not analyzed		
Mn	Not analyzed		
Mo	Not analyzed		
Na	Not analyzed		
Ni	Not analyzed		
P	Not analyzed		
Pb	Not analyzed		
Sb	Not analyzed		
Se	Not analyzed		
Silica	Not analyzed		
Sn	Not analyzed		
Sr	Not analyzed		
Ti	Not analyzed		
V	Not analyzed		
Zn	mg/L	0.0005	FAA
Rock			
Powder pH			
Sulphur	%	0.001	Leco Furnace - Infrared dectector
Sulphate	%	0.01	HCl leach, gravimetric
Sulphide	%	0.01	Nitric acid bromide digestion, gravimetric
Neutralization Potential	kg CaCO3/t	None	Sobek et al., 1978 Method

Notes:

1. ICAP = Inductively coupled argon plasma. AA = Atomic absorption, FAA = Flameless atomic absorption.

APPENDIX D
DETECTION LIMITS AND ANALYTICAL METHODS

TABLE 4
CITY RESOURCES PROJECT (1987 TO 1990)
LEACH COLUMN STUDY

PARAMETER	UNIT	DETECTION LIMIT	METHOD
Waters			
pH	none	none	Electrode
Sulphate	mg/L	0.005	Turbidimetry
Conductivity	•mho/cm	5	Electrode
Alkalinity	mg CaCO3/L	1	Titration with 0.02N sulphuric acid
Acidity	mg CaCO3/L	1	Titration with 0.02M sodium hydroxide
Ag	mg/L	0.0002	ICAP
Al	mg/L	0.02	ICAP
As	mg/L	0.001	FAA
B	mg/L	0.001	ICAP
Ba	mg/L	0.001	ICAP
Be	mg/L	0.001	ICAP
Ca	mg/L	0.05	ICAP
Cd	mg/L	0.05	ICAP
Co	mg/L	0.01	ICAP
Cr	mg/L	0.005	ICAP
Cu	mg/L	0.01	ICAP
Fe	mg/L	0.003	ICAP
Total Hg	mg/L	0.00005	FAA
K	mg/L	0.05	ICAP
Mg	mg/L	0.2	ICAP
Mn	mg/L	0.1	ICAP
Mo	mg/L	0.01	ICAP
Na	mg/L	0.05	ICAP
Ni	mg/L	0.005	ICAP
P	mg/L	0.2	ICAP
Pb	mg/L	0.05	ICAP
Sb	mg/L	0.1	ICAP
Se	mg/L	0.1	ICAP
Silica	Not analyzed		ICAP
Sn	Not analyzed		ICAP
Sr	mg/L	0.005	ICAP
Ti	mg/L	0.005	ICAP
V	mg/L	0.005	ICAP
Zn	mg/L	0.01	ICAP
Rock			
Powder pH			
Sulphur	%	0.001	Leco Furnace - Infrared dectector
Sulphate	%	0.01	HCl leach, gravimetric
Sulphide	%	0.01	Nitric acid bromide digestion, gravimetric
Neutralization Potential	kg CaCO3/t	None	Sobek et al., 1978 Method

Notes:

1. ICAP = Inductively coupled argon plasma. AA = Atomic absorption, FAA = Flameless atomic absorption.

APPENDIX D
DETECTION LIMITS AND ANALYTICAL METHODS

TABLE 5
BC AMD TASK FORCE/MEND PROJECT (1990 TO 1991)
LEACH COLUMN STUDY

PARAMETER	UNIT	DETECTION LIMIT	METHOD
Waters			
pH	none	none	Electrode
Sulphate	mg/L	0.005	Turbidimetry
Conductivity	•mho/cm	5	Electrode
Alkalinity	mg CaCO3/L	1	Titration with 0.02N sulphuric acid
Acidity	mg CaCO3/L	1	Titration with 0.02M sodium hydroxide
Ag	Not Analyzed		
Al	Not Analyzed		
As	mg/L	0.001	FAA
B	Not Analyzed		
Ba	Not Analyzed		
Be	Not Analyzed		
Ca	mg/L	0.05	AA
Cd	Not Analyzed		
Co	Not Analyzed		
Cr	Not Analyzed		
Cu	mg/L	0.0005	FAA
Fe	mg/L	0.05	AA
Total Hg	Not Analyzed		
K	Not Analyzed		
Mg	Not Analyzed		
Mn	Not Analyzed		
Mo	Not Analyzed		
Na	Not Analyzed		
Ni	Not Analyzed		
P	Not Analyzed		
Pb	mg/L	0.001	FAA
Sb	Not Analyzed		
Se	Not Analyzed		
Silica	Not Analyzed		
Sn	Not Analyzed		
Sr	Not Analyzed		
Ti	Not Analyzed		
V	Not Analyzed		
Zn	Not Analyzed		
Rock			
Powder pH			
Sulphur	%	0.001	Leco Furnace - Infrared dectector
Sulphate	%	0.01	HCl leach, gravimetric
Sulphide	%	0.01	Nitric acid bromide digestion, gravimetric
Neutralization Potential	kg CaCO3/t	None	Sobek et al., 1978 Method

Notes:

1. ICAP = Inductively coupled argon plasma. AA = Atomic absorption, FAA = Flameless atomic absorption.

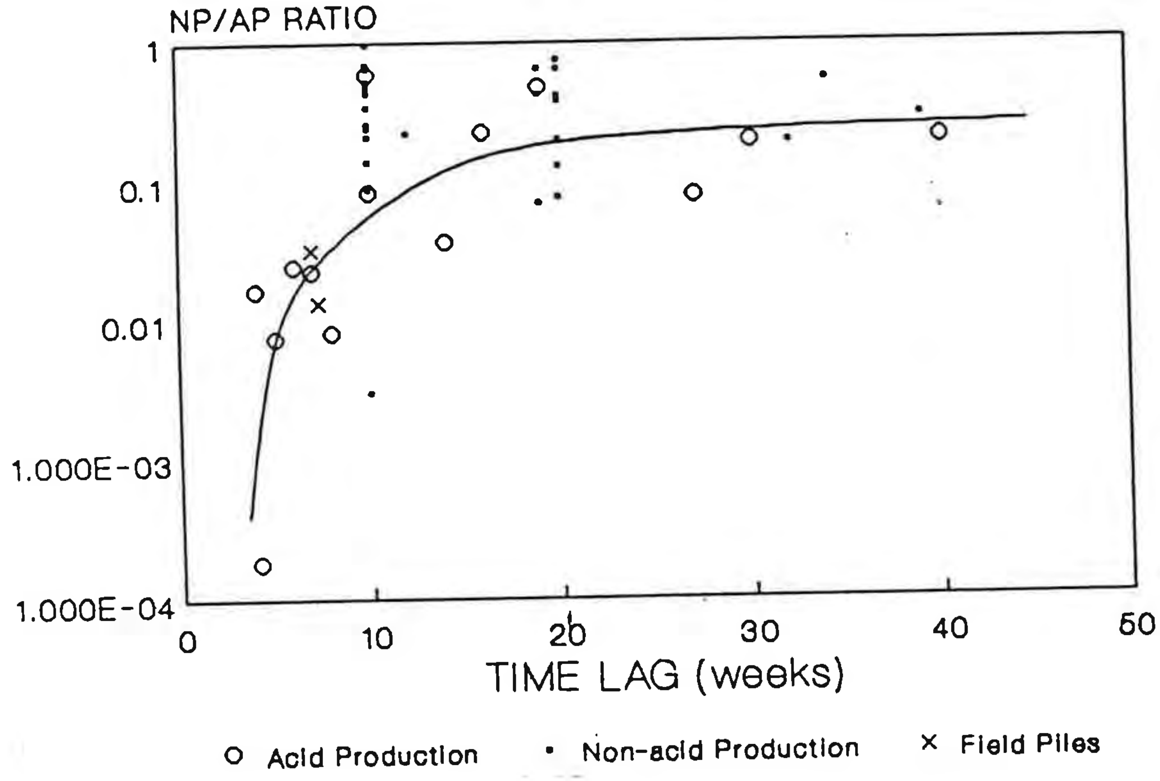
APPENDIX D
DETECTION LIMITS AND ANALYTICAL METHODS

TABLE 6
BC AMD TASK FORCE/MEND PROJECT (1991 TO 1993)
LEACH COLUMN STUDY

PARAMETER	UNIT	DETECTION LIMIT	METHOD
Waters			
pH	none	none	Electrode
Sulphate	mg/L	0.005	Turbidimetry
Conductivity	•mho/cm	5	Electrode
Alkalinity	mg CaCO3/L	1	Titration with 0.02N sulphuric acid
Acidity	mg CaCO3/L	1	Titration with 0.02M sodium hydroxide
Ag	mg/L	0.001	ICAP
Al	mg/L	0.01	ICAP
As	mg/L	0.001	ICAP
B	mg/L	0.006	ICAP
Ba	mg/L	0.01	ICAP
Be	mg/L	0.001	ICAP
Ca	mg/L	0.05	ICAP
Cd	mg/L	0.002	ICAP
Co	mg/L	0.001	ICAP
Cr	Not Analyzed		
Cu	mg/L	0.005	ICAP
Fe	mg/L	0.05	ICAP
Total Hg	mg/L	0.001	ICAP
K	Not Analyzed		
Mg	mg/L	0.1	ICAP
Mn	mg/L	0.003	ICAP
Mo	mg/L	0.002	ICAP
Na	Not Analyzed		
Ni	mg/L	0.008	ICAP
P	Not Analyzed		
Pb	mg/L	0.002	ICAP
Sb	mg/L	0.01	ICAP
Se	mg/L	0.01	ICAP
Silica	Not Analyzed		
Sn	Not Analyzed		
Sr	mg/L	0.1	ICAP
Ti	mg/L	0.004	ICAP
V	mg/L	0.0004	ICAP
Zn	mg/L	0.005	ICAP
Rock			
Powder pH			
Sulphur	%	0.001	Leco Furnace - Infrared dectector
Sulphate	%	0.01	HCl leach, gravimetric
Sulphide	%	0.01	Nitric acid bromide digestion, gravimetric
Neutralization Potential	kg CaCO3/t	None	Sobek et al., 1978 Method

Notes:

1. ICAP = Inductively coupled argon plasma. AA = Atomic absorption, FAA = Flameless atomic absorption.



AP = MPA = Maximum Potential Acidity

Figure 9-1
RELATIONSHIP BETWEEN TIME LAG
AND NP/AP
FERGUSON AND MORIN (1991)

January 1993 Norecol, Dames & Moore