PREDICTION AND PREVENTION OF ACID ROCK DRAINAGE FROM A GEOLOGICAL AND MINERALOGICAL PERSPECTIVE

MEND Project 1.32.1

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OF ACID ROCK DRAINAGE
FROM A GEOLOGICAL AND MINERALOGICAL PERSPECTIVE

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TABLE OF CONTENTS

SUMMARY

The aims of this project on prediction and prevention of acid rock drainage from a geological and mineralogical perspective are: 1) to clarify the susceptibility of different types of ore deposits to acid rock drainage problems; 2) to investigate the relative weatherability of common sulphide minerals; and, 3) to examine the role of a field geologist in acid rock drainage assessment, especially during mineral exploration.

Based on a literature survey and supplementary field investigations, seven common types of metallic mineral deposits occurring in western Canada are ranked according to acid rock drainage potential. The susceptibility of a deposit to develop acid rock drainage problems is largely determined by the net acid-generating potential of the prevalent mineral assemblages, accessibility of the reacting minerals to the weathering agents and potential mediation by iron-oxidizing bacteria. Generally, the alteration mineral assemblages about an orebody reflect well the acid rock drainage potential of the relevant rock types. A formula for assessing acid rock drainage potential based on field estimates of mineral abundance is suggested.

To determine the relative weatherability of common sulphide minerals, a kinetic-type weathering experiment using polished thin sections as starting materials has been conducted. Detailed examination of the prevalent sulphides in the sections with petrographic and scanning electron microscopes, augmented by electron microprobe analysis and determination of leachate chemistry by induction coupled plasma mass spectrometry (ICPMS) indicate the importance of trace element composition in affecting the stability of individual sulphides. Where different sulphides are in contact with each other, electrochemical processes are likely to be operative, further complicating the relative reactivity of the sulphides. Thus, a general weathering sequence for the common sulphides may not exist except at a local scale. To predict the rate of acid generation and metal release associated with sulphide oxidation, further work to clarify the inter-dependence of geochemical reactions, microbial mediation and electrochemical processes involved is required.

Well-trained to collect and interpret mineralogical and geological data, a field geologist can readily assess the acid rock drainage potential of geologic materials based on field observations. A practical checklist for field assessment of acid rock drainage potential during mineral exploration is suggested and the tasks of a geologist in acid rock drainage assessment at various phases of a pre-mine development project are briefly described.

In conclusion, inasmuch as acid rock drainage is a product of natural water-rock interaction, its prediction and prevention relies on a thorough understanding of the local geology and mineralogy. The involvement of a geologist in acid rock drainage assessment in every stage of a mining project may lead to a significant reduction in the cost of tackling the serious environmental problem and is thus highly recommended.

SOMMAIRE

Les objectifs du présent projet de prévision et de prévention du drainage rocheux acide se définissent comme suit du point de vue géologique et minéralogique : 1) déterminer les risques de drainage acide que présentent différents types de gisements de minerai; 2) étudier la résistance relative au degré d'altération de certains minéraux sulfurés courants; 3) définir le rôle du géologue de terrain dans l'évaluation du drainage rocheux acide, particulièrement dans le cadre d'une campagne d'exploration.

Une étude de la documentation et des essais in situ supplémentaires ont permis de classer selon leur potentiel de drainage acide sept types courants de gisements de minerais métalliques dans l'ouest du Canada. Les risques de problèmes de drainage acide dans un gisement sont déterminés en grande partie par le potentiel net de production d'acide des principales associations minéralogiques, le degré d'exposition des minéraux réactifs aux agents d'altération et la médiation potentielle des ferrobactéries. En général, l'altération des associations de minéraux autour d'un gisement reflètent assez fidèlement le potentiel de drainage acide des types de roches présentes. Les pages qui suivent proposent une formule permettant de déterminer le potentiel de drainage rocheux acide qui repose sur les évaluations sur place de l'abondance des minéraux.

Afin de déterminer la résistance relative au degré d'altération de certains minéraux sulfurés courants, une expérience de type cinétique a été effectuée avec des sections polies minces comme matériel de départ. Une étude détaillée des principaux sulfures des sections, réalisée à l'aide d'un microscope pétrographique et d'un microscope électronique à balayage, de même qu'une analyse par microsonde électronique et une analyse chimique des lixiviats par spectrométrie de masse ICP, indiquent que la nature des éléments en traces observés a une incidence importante sur la stabilité des différents sulfures. Il est en outre fort probable que des processus électrochimiques entrent en jeu lorsque plusieurs sulfures sont en contact les uns avec les autres, ce qui complique davantage la réactivité relative des sulfures. Par conséquent, il n'est pas possible d'établir de processus général d'altération pour les sulfures courants, sauf à l'échelle locale. Pour prévoir les taux de production d'acide et de libération de métaux liés à l'oxydation des sulfures, il est donc nécessaire d'effectuer d'autres études afin de clarifier l'interdépendance des réactions géochimiques, de la médiation microbienne et des processus électrochimiques.

Comme le géologue de terrain possède la formation nécessaire pour prélever et interpréter des données minéralogiques et géologiques, il peut aisément évaluer, grâce à des observations sur place, le potentiel de drainage acide des matériaux géologiques. Le présent rapport propose une liste de vérification pratique pour l'évaluation in situ du potentiel de drainage acide durant une exploration minérale et décrit brièvement les tâches du géologue au cours des diverses phases des travaux préparatoires à l'exploitation d'une mine.

En conclusion, compte tenu que le drainage acide résulte des interactions naturelles entre l'eau et les roches, il importe d'avoir une très bonne compréhension de la géologie et de la minéralogie locales afin de pouvoir prévoir et prévenir ce processus. Il est donc fortement recommandé d'avoir recours à un géologue pour l'évaluation du potentiel du drainage rocheux acide à toutes les étapes d'un projet d'exploitation minière, car sa participation peut entraîner une réduction considérable des coûts liés à la résolution d'éventuels problèmes environnementaux graves.

CHAPTER 1

INTRODUCTION

"An ounce of prevention is worth more than a pound of cure", runs the proverb. This surely applies to the management of acid rock drainage (ARD), or acid mine drainage (AMD) if it occurs in a mine environment. The fact that AMD can cause serious detrimental effects on the local ecosystem is well documented (e.g., Paine, 1987) and AMD control can be very expensive. For example, a $37.5M bond has to be posted for decommissioning the Equity Silver Mine near Houston, British Columbia, mainly for defraying the tremendous cost of abating acidic drainage (Patterson, 1992). Indeed, with legislation enforcing environmental protection expected to get stricter with time (Errington, 1992), it is apparent that finding technically mineable-grade mineralization is no longer a sufficient condition to ensure mining development. The cost of ensuring the health of the natural environment is a necessary component that has to be included in defining an orebody. Across Canada todate, a mining permit is unlikely to be granted if the AMD issues are not duly addressed. Thus to facilitate mining development, it is of paramount importance to perfect ARD/AMD assessment techniques.

PREVIOUS WORK

In a review of methods to predict AMD, Ferguson and Erickson (1987) noted that five general categories of methods are available. These are: (i) geographical comparison; (ii) paleoenvironmental and geological models; (iii) geochemical static tests; (iv) geochemical kinetic tests; and (v) mathematical models. AMD Prediction based on geographical comparisons applies only to similar mines located in close proximity to each other. The application of paleoenvironmental and geological models to date have been limited to studies of AMD associated with coal deposits (e.g. Caruccio et al., 1977; Williams et al., 1982). Mathematical models to predict AMD are complex and are still under development, especially for waste rock. Consequently, in practice, most AMD prediction relies heavily on geochemical static and kinetic tests. The details of a variety of commonly applied tests, as well as their advantages and disadvantages, have been documented in many technical manuals (e.g. B.C. AMD Task Force, 1989; Coastech Research Inc., 1991 (MEND Report 1.16.1b)).

Though the focus of the preceding five groups of methods is on pre-mine prediction of AMD, they are appropriate and are typically applied only at a relatively advanced stage of a mine development project, the permitting stage. Application of elaborate tests at this stage frequently leads to long delays in the prospective mine project. Failure to demonstrate, at this stage, that ARD is negligible or can be effectively controlled in perpetuity would mean a great loss in investment already spent during exploration. It is thus much more desirable to have simple predictive schemes available that can be applied at the exploration stage to effect an early assessment of ARD potential. The prospective predictive scheme should allow mineralization that can be exploited in an environmentally acceptable manner be differentiated from those that cannot be developed without inflicting a great cost to the environment. The knowledge of the potential environmental cost would facilitate redirection of valuable resources to discovering and developing more favourable targets.

CURRENT RESEARCH

The research presented in this report was initiated to partially address the need of ARD prediction during exploration. The purpose of the investigation is threefold: (i) to determine the relationship, if any, between mineral deposit types and ARD occurrences; (ii) to investigate the relative reactivity of common sulphides; and, (iii) to recommend simple field and laboratory measurements/observations that a field geologist can conduct to have an early assessment of ARD potential. The research findings will also facilitate interpretation of results of geochemical static and kinetic tests which requires more detailed information on the properties of various weathering minerals than is commonly addressed in the ARD prediction literature.

Report Layout

This report consists of six chapters. Chapter 1 outlines the need and scope of the research project. Chapter 2 examines the susceptibility of mineral deposits to ARD problems, deciphers the controlling factors and suggests a formulae for ARD assessment based on field estimates of mineral abundances. Chapter 3 addresses the weatherability of common sulphides and presents the findings of an exploratory weathering experiment using sulphide-containing polished thin sections as starting materials. Chapter 4 describes the role of a field geologist in pre-mine ARD assessment and suggests a checklist for assessing ARD potential during mineral exploration. Chapter 5 discusses the applicability, limitations and complexities of ARD prediction from a geological and mineralogical perspective; the relevance of mineralogy and geology to ARD prevention and abatement is also briefly addressed. The concluding Chapter 6 summaries the major findings of the research project and suggests a few areas for further investigation.

ACKNOWLEDGEMENTS

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CHAPTER 2

SUSCEPTIBILITY OF MINERAL DEPOSITS TO ARD PROBLEMS

SCOPE OF INVESTIGATION

From numerous ARD research conducted worldwide during the past 45 years, it is generally accepted that the five major ingredients for the occurrence of ARD are: (i) oxygen, (ii) water, (iii) sulphide minerals, (iv) lack of minerals with acid-neutralizing capacity; and, (v) presence of iron-oxidizing bacteria. Given appropriate hydrochemical and biogeochemical settings, the potential of a certain rock to generate acid depends both on the composition and mode of occurrence of the prevailing sulphides as well as the associated mineral assemblage. Whereas the detailed mineralogy of an ore deposit and hence the acid generating potential are highly site-specific, depending on the geologic environment of ore deposition, the possible number of combinations of mineral assemblages is limited. Consequently, it is highly probable that ore deposits of the same genetic type that occur in similar geologic environments will show comparable susceptibility to ARD problems. Climate will greatly affect the rate and extent of the development of ARD. However, the topic will not be considered at length here.

For reasons of easy access and availability of relevant information, this study focuses on metallic deposits of the Canadian Cordillera. The major mineral deposit types examined include massive sulphides, porphyries, epithermal Au-Ag mineralization, mesothermal vein Au and skarns. However, as will be evident in the descriptions and discussions detailed in subsequent sections, the same principles apply to other deposit types located anywhere. The underlining guideline is that an assessment of ARD potential should be based on the detailed geology and the entire mineral assemblage rather than a subset of the prevalent mineralogy.

To compare the susceptibility of various ore types to ARD problems, published and unpublished reports on the occurrence of ARD in operating and abandoned mines and prominent prospects were reviewed together with the detailed geology of the respective deposits. The emphasis of the review was on the correlation of the prevalent mineralization and alteration with the occurrence of ARD. The entire mineral suite occurring at a site was considered in the light of water-rock interactions under atmospheric conditions. To verify various conclusions deduced from the literature review, supplementary field examinations were conducted. During the course of the study, mining properties visited include Afton, Bell, Equity Silver, Eskay Creek, Island Copper, Premier, Ruttan, Skyline and Snip. The Ruttan Mine is located near the town of Leaf Rapids, northern Manitoba, and all the others are in British Columbia (see McMillan et al., 1991 for detailed locations). Furthermore, observations made from on-going research on Mount Washington (Kwong and Ferguson, 1990; Kwong, 1991 and 1992) and natural acidic drainage in the Yukon (e.g. Kwong and Whitley, 1992) have been incorporated in the present study.

RANKING OF MINERAL DEPOSIT TYPES ACCORDING TO ARD POTENTIAL

Largely based on the statistics of ARD occurrences, the nature and abundance of sulphide minerals, and, the distribution of potentially acid-neutralizing minerals, the common ore deposits found in the Canadian Cordillera can be ranked according to ARD potential as follows (with the most ARD-prone deposit type on top):

1. Sedimentary exhalative massive sulphides (SEDEX)
2. Volcanogenic massive sulphides (VMS)
3. Calc-alkaline suite porphyry deposits
4. Epithermal Au-Ag deposits
5. Mesothermal vein Au deposits
6. Alkaline suite porphyry deposits
7. Skarn deposits

These seven types of mineral deposits are divided into four groups and briefly described below in the context of ARD. A more detailed analysis of the controlling factors of ARD occurrence then follows.

Massive sulphide deposits

The massive sulphide deposits (1 and 2) are particularly susceptible to ARD problems sheerly because of the abundance of sulphide minerals present. Sedimentary exhalative massive sulphides (or sedimentary stratiform deposits according to Morganti, 1981) are generally hosted by siliceous and carbonaceous sediments which lack buffering capacity and are as well conducive to microbial colonization because of the ready availabilty of nurtrients and a carbon source. Original bedding planes are loci of inherent structural weakness where conduits, providing for access of the weathering agents, can readily develop during any syn- or post-ore-deposition structural adjustments. Furthermore, the prevalent sulphides are typically fine-grained and framboidal pyrite is commonly present. The Sullivan Mine in southeastern British Columbia and the Tom Deposit in east-central Yukon are good examples of this type of deposit (Morganti, 1981). ARD occurs in both localities (Errington and Ferguson, 1987; Kwong and Whitley, 1992).

Despite the common association with intensive silicification, which can effectively deplete the country rock of any neutralizing capacity, volcanogenic massive sulphide deposits are ranked behind sedimentary massive sulphide deposits with respect to ARD potential. Sulphide minerals in VMS are usually more euhedral and coarser-grained than those in SEDEX deposits. The more competent nature of the country rocks in VMS also renders portions of the sulphide minerals, particularly those in sub-ore material, less accessible for weathering.

Based on the tectonic setting and the associated volcanics, volcanogenic massive deposits can be divided into three types (Sawkins, 1976): Cyprus-type deposits (e.g. Chu Chua, Anyox) are copper-rich, and occur in mafic volcanic rocks in spreading ocean or back-arc ridges; Besshi-type deposits (e.g. Goldstream, Windy Craggy, Ruttan) occur in calc-alkaline volcanics and sediments in epicratonic rift environments; polymetallic Kuroko-type deposits (e.g. Westmin, Kutcho Creek, Eskay Creek and Britannia) occur in more felsic volcanic rocks in volcanic arcs. In Westmin and Ruttan, ARD occurs both in waste rock dumps and tailing ponds. The legacy of ARD from the Britannia Mine operation still poses a major reclamation challenge today. In the proposed development of the Windy Craggy deposit, ARD has been a major concern (Geddes Resources, 1990). Though the Eskay Creek deposit is classified as a VMS, it has some SEDEX characteristics. For example, a large portion of the ore (21B Zone) is hosted by a carbonaceous mudstone in which framboidal pyrite has been detected. ARD evaluation and monitoring are taking place at the property. Within the VMS subgroup, it appears that Kuroko-type deposits are most prone to the occurrence of ARD; Besshi-type deposits are less susceptible and Cyprus-type deposits are least likely to give rise to widespread ARD problems.

Porphyry Deposits

Porphyry deposits in the Canadian Cordillera are associated with either alkalic or calc-alkalic plutons (Ney and Holister, 1976). Alkalic deposits are generally smaller in tonnage, enriched in copper and gold (McMillan, 1991), and hosted by rocks with a higher mafic minerals content or silica undersaturation (i.e. diorite to syenite). Carbonate alteration is frequently a major component of the overall alteration pattern. For example, Kwong (1982, 1987) documented the occurrence of pervasive carbonate alteration (ankerite with some calcite), both vertically and laterally, in the Afton open-pit. ARD has not been identified in any of the present and past producers in this category (Afton, Ajax, Copper Mountain and Ingerbelle). Whereas more test work may have to be conducted to confirm the results, ARD assessments conducted to date at developing mines and important prospects with alkalic porphyry-type mineralization (e.g. Mount Milligan, Mount Polly (Cariboo Bell), Kerr, Lorraine, QR and Galore Creek) also suggest that ARD is unlikely to be a major concern.

Besides copper, calc-alkalic suite porphyry deposits are usually enriched in molybdenum (Ney and Holister, 1976). A typical deposit is about twice the size of an alkalic suite deposit, by a comparison of median tonnage (Cox and Singer, 1988). Related porphyritic host rocks generally ranges from granodiorite to granite (McMillan, 1991). The involvement of meteoric water in the hydrothermal alteration of shallow calc-alkalic suite porphyry deposits leads to more intensive leaching, depleting the host rocks of potentially acid-neutralizing minerals. Depending on the nature and extent of wall-rock alteration associated with ore deposition, many calc-alkalic porphyry copper with/without molybdenite mines witness minor to serious ARD problems (e.g. Bell Copper, Island Copper, Gibraltar and Equity Silver). Porphyry Mo (e.g Endako, Highmont) and other porphyry Cu-Mo deposits (e.g. Brenda, Highland Valley Copper) associated with plutons emplaced at a greater depth are apparently devoid of ARD problems.

Precious Metal Vein Deposits

Lode Au-Ag vein deposits can be divided into two fundamental categories, mesothermal and epithermal, according to the depth of mineralization. An excellent review on the two types of vein deposits is furnished by Panteleyev (1991). Mesothermal deposits commonly formed at intermediate depth (10-15 km) along steep faults and fold hinges in a wide variety of rocks. Veins are usually large, filled with coarsely crystalline gangue and sulphide minerals. The associated hydrothermal alteration is usually in the form of envelopes about the vein and consists of carbonate, albite, K-feldspar, sericite, chlorite and pyrite. Examples of mesothermal Au deposits in the Canadian Cordillera include the Bridge River Camp, the Ross River Camp, the Cariboo-Barkerville Camp, Snip, Frasergold, the Zeballos Camp, Surf Inlet and Golden Bear. Only small amounts of potentially acid-generating material are apparent at Snip and Frasergold. The limited width of the alteration envelopes and the presence of carbonates in ore-bearing quartz veinlets apparently hinders the development of ARD in mesothermal Au-Ag vein deposits.

Epithermal Au-Ag veins typically formed at shallow depth (<3 km) in deformation zones with faults, breccia, tensional openings in subaerial intermediate to felsic volcanic and subvolcanic rocks. They also occur in fossil geothermal fields and hot springs. Veins and stockworks generally have open-space filling and vuggy structures and the mineralization consists of microcrystalline material. Hydrothermal alteration is dominated by silicification but K-feldspar, propylitic, sericitic, argillic and advanced argillic alterations may also be locally important. Prominent examples of epithermal Au-Ag vein deposits in British Columbia include Premier Gold, Cinola, the Toodoggone Camp and Big Missouri (Panteleyev, 1991). Cinola and many deposits in the Toodoggone camp are potential acid generators and ARD concerns also prevails at Premier Gold and Big Missouri. The intense silicification, more extensive alteration zoning and the rarity of carbonates render epithermal deposits more susceptible to ARD than mesothermal deposits. Generally speaking, in both epithermal and mesothermal vein deposits, the extent and nature of alteration vary with depth and so is the ARD potential. This will be discussed in more detail in a later section on alteration patterns.

Skarns

Skarns are coarse-grained calcium or magnesium silicate mineralization formed at relatively high temperatures, during an intrusive event, by the replacement of original, frequently carbonate-rich rocks. Magnesium skarns, resulting from the replacement of dolomite, are characterized by mineral assemblages containing olivine, phlogopite, serpentine, spinel, Mg-rich clinopyroxene, orthopyroxene, pargasite and humite group minerals. Calcic skarns, resulting from the replacement of limestone or other calcareous rocks are characterized by assemblages dominated by garnet, clinopyroxene and wollastonite. Skarns can host ores of iron (e.g. Taxada Iron), copper (e.g. Craigmont), gold (e.g. Nickel Plate), molybdenum (e.g. Mount Copeland) and tungsten (e.g. Mactung). An excellent overview of skarn deposits is furnished by Ray and Webster, 1991). ARD is not known to associate with skarn deposits. The abundance of carbonate and reactive silicate minerals, the overall high metal/sulphur ratio in the prevalent sulphides, coarse mineral grain size and the massive nature of the host rocks all contribute to render skarn deposits least susceptible to ARD occurrence among the ore types examined in this study.

CONTROLLING FACTORS

From the general description of mineral deposit types to justify their ranking according to ARD potential, it is apparent that the alteration pattern about an ore body plays a central role in determining the ARD susceptibility. An alteration pattern encompasses the nature and extent of the alteration. In other words the important parameters include the composition and texture of the prevalent mineral assemblages, their spatial distribution, as well as the relative abundance of sulphide and acid-neutralizing minerals. Other important factors, implicit in the description, are the physical properties of the host rocks, possible microbial mediation of oxidation reactions and the mining method utilized in excavating the ores. All of these factors controlling the association of ARD with a mineral deposit are briefly discussed as follows:

Alteration Pattern

The importance of hydrothermal alteration patterns associated with an ore deposit in effecting ARD occurrence cannot be over-emphasized. It suffices here to consider a few examples pertaining to volcanogenic massive sulphides, porphyry deposits and epithermal precious metal deposits.

(i) Alteration pattern about a VMS deposit: Figure 1 depicts the characteristics of an idealized volcanogenic massive sulphide deposit (after Lydon, 1984). The sulphide lens, usually overlain and flanked by a thin siliceous iron cap, has a sharp contact with the overlying sedimentary or volcanic rocks and a gradational footwall contact into the stockwork zone. While pyrite is the dominant sulphide in most VMS deposits, zoning of other sulphide minerals is common in many massive sulphide lenses. Chalcopyrite with or without pyrrhotite occupying the base and central portions of the lenses generally give way laterally and upwards to sphalerite and galena. Four alteration zones are commonly associated with VMS deposits; these are (a) the footwall alteration pipe, (b) alteration in the ore horizon, (c) extensive alteration beneath the ore horizon, and, (d) hanging wall alteration.

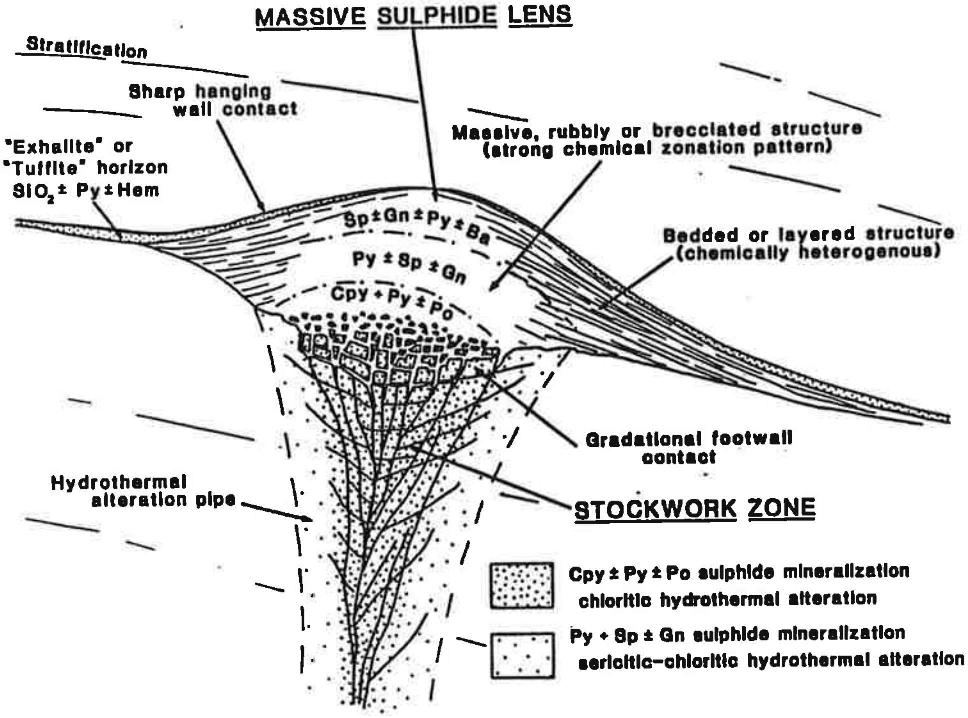


Figure 1. Essential characteristics of a volcanogenic massive sulphide deposit (after Lydon, 1984).

A composite representation of various alteration assemblages that have been reported for alteration pipes of VMS deposits is depicted in Figure 2 (after Lydon, 1988). Depending on the host rock composition, not all alteration assemblages are present in a particular deposit. Chlorite or chlorite-quartz alteration is most prominent in deposits hosted by mafic volcanics. In many MVS deposits in British Columbia, however, quartz-sericite alteration in the footwall rocks is most common. Generally, intense silicification occurs immediately adjacent to the overlying sulphide lens while sericite alteration is more widespread. In Rea Gold and Windy Craggy, the quartz-sericite alteration is so intense that the original composition and texture of the volcanic host rocks can no longer be discerned (Hoy, 1991). Less commonly, carbonate alteration (in the form of ankerite or siderite) also occurs in the footwall of some Kuroko deposits. Among the various alterations, silicic, aluminous, ferruginous oxide and sericitic assemblages have no acid-neutralizing value while chloritic, talcose and carbonate assemblages are characterized by increasing buffering capacity.

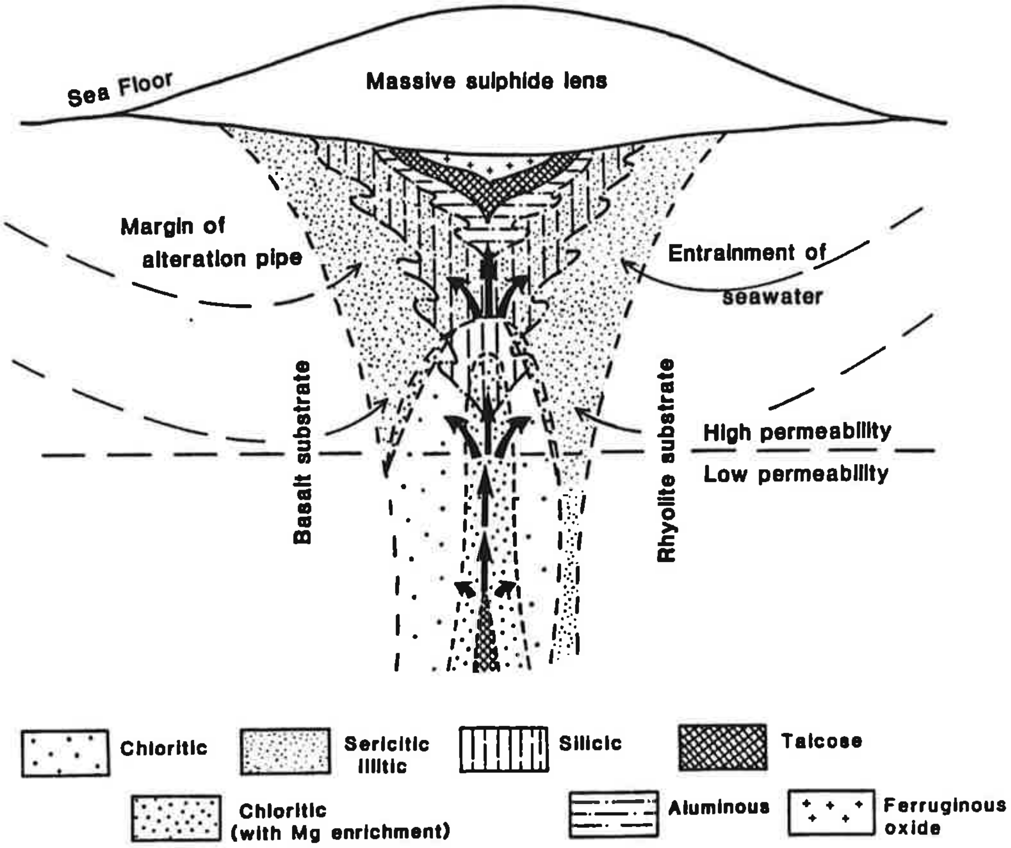
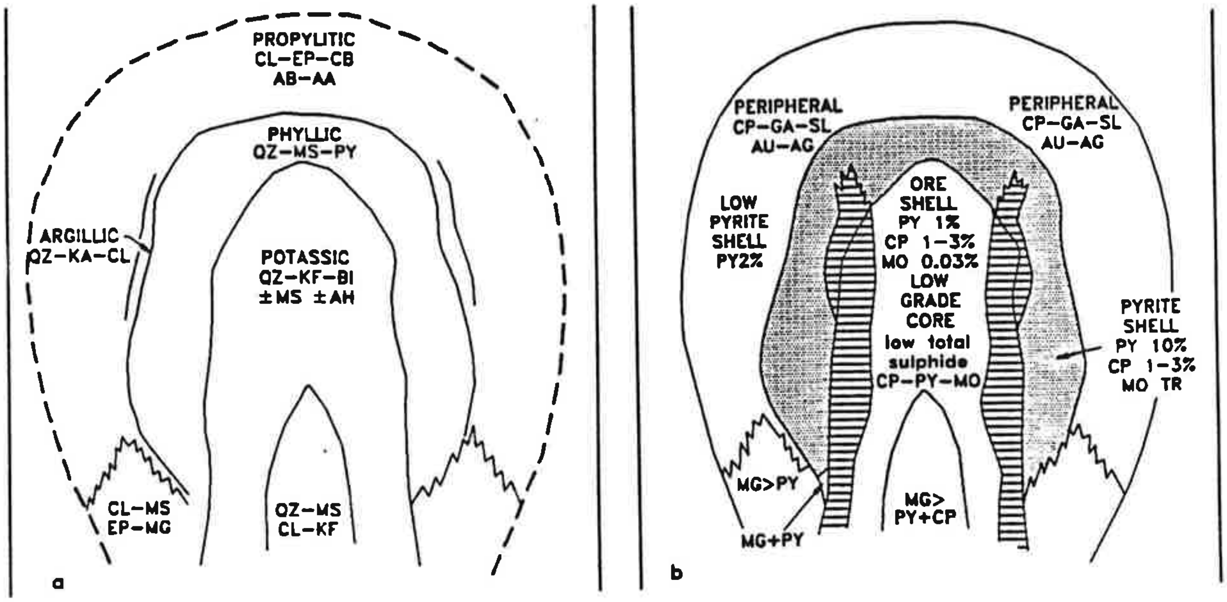


Figure 2. Alteration assemblages that have been reported for alteration pipes of VMS deposits (after Lydon, 1988)

Alteration within and along the ore horizon within a VMS deposit usually occurs as cross-cutting veinlets of quartz, sericite or chlorite and pervasive replacement by the same minerals and carbonate in the groundmass of sulphide grains and clasts. Extensive, semi-conformable alteration zones beneath the ore horizons are more commonly associated with Archean VMS deposits. Typical alteration include silicification and spilitization (giving rise to assemblages of epidote and quartz with or without albite and tremolite-actinolite) in deposits formed at water depth of >500 m, and, sericite-quartz (with or without dolomite) and chlorite-siderite/ankerite alterations in deposits formed under shallow water environments (Morton and Franklin, 1987). Alteration of hangingwall rocks, where present, is generally much less extensive or intense than footwall alteration. The alteration mineralogy is again largely determined by the host rock composition. The significance of these alterations to ARD is entirely dependent on the composition of the alteration mineral assemblages.

(ii) Hydrothermal alteration of porphyry deposits: A schematic section through a typical southwest United States porphyry copper deposit is shown in Figure 3 (after Guilbert and Lowell, 1974). Allowing for the effects of differences in local geology, the Guilbert and Lowell model is applicable to many calc-alkalic porphyry deposits in the Canadian Cordillera. The acid-neutralizing capacity of the four alteration types (Figure 3a) are in the order of propylitic > potassic >= argillic > phyllic. This, coupled with the sulphide distribution depicted in Figure 3b, render rocks in the phyllic zone most susceptible to acid generation, followed by those in the argillic zone, then the potassic zone, and lastly, the propylitic zone. With the abundance of total sulphides decreasing with depth (also evident by magnetite replacing pyrite as the predominant Fe-containing species) and the disappearance of phyllic alteration at depth, ARD susceptibility is also correspondingly diminished.



Abbreviations *QZ quartz, MS muscovite, CL chlorite, KF potassic feldspar, BI biotite, AH anhydrite, AB albite, AA adularia, CB carbonate, EP epidote, MG magnetite, AU gold, AG silver, CP chalcopyrite, PY pyrite, MO molybdenite, GA galena, SL sphalerite.*

Figure 3. A cross-section of an idealized porphyry copper deposit showing (a) alteration zones and (b) sulphide distribution (after Guilbert and Lowell, 1974).

The two most important parameters that control the extent of development of the various alteration zones are (1) the amount of meteoric fluid involved in the hydrothermal alteration, and, (2) the composition of the host rock. McMillan and Panteleyev (1988) has presented a model of hydrothermal systems with contrasting orthomagmatic and convective fluid patterns (Figure 4), which can be applied to interpret the

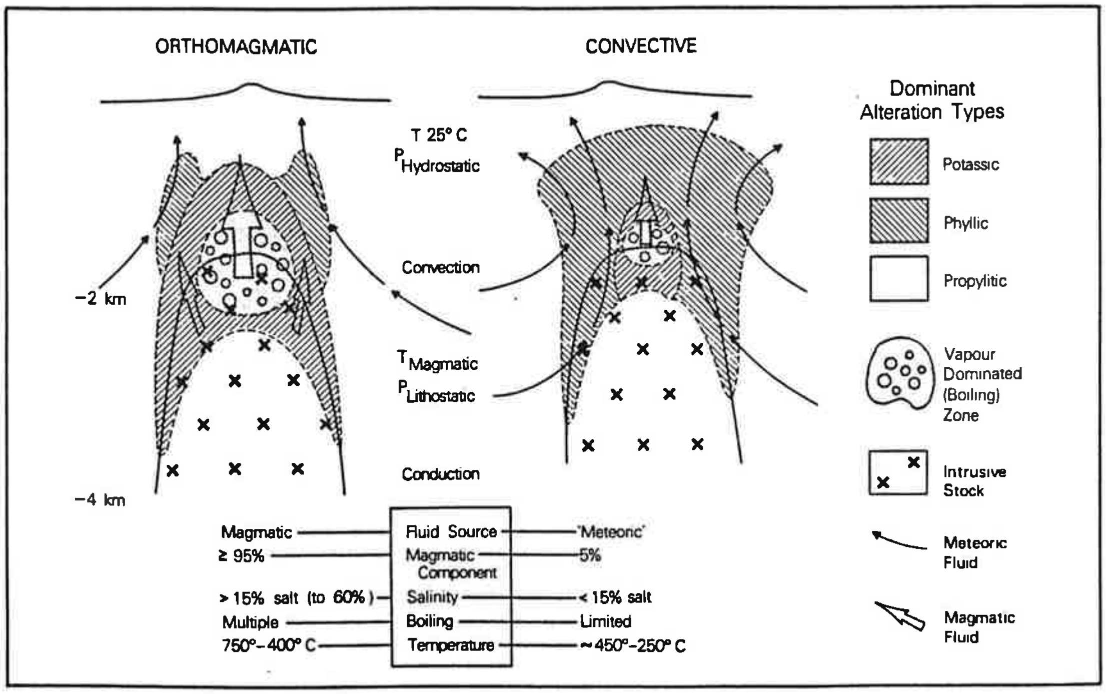


Figure 4. Variation in the development of alteration assembalges assocciated with two contrasting hydrothermal systems (After McMillan and Panteleyev, 1988).

ARD potential of alkalic and calc-alkalic suite porphyry deposits. Where a large amount of meteoric water is involved in a convective fluid flow system, phyllic alteration mineral assemblage with little acid-neutralizing potential are extensively developed. In contrast, if the fluid source in the hydrothermal system is mainly magmatic, potassic alteration predominates. Most of the alkalic suite porphyry deposits in the Canadian Cordillera are hosted by relatively mafic rocks and phyllic alteration zones are poorly developed. They are therefore less prone to ARD occurrence. In many calc-alkaline deposits, however, phyllic and argillic alterations are extensively developed. Coupled with the more silicic nature of the host rocks, they are more prone to ARD problems. Since the involvement of meteoric water in hydrothermal alteration also decreases with depth, even in the calc-alkalic suite, deposits formed at greater depth, e.g. most of the porphyry Mo deposits, are less likely to give rise to ARD.

(iii) Epithermal precious metal deposits: An idealized section of a bonanza epithermal deposit is illustrated in Figure 5 (after Buchanan, 1981). The extent of the hydrothermal alteration associated with precious metal mineralization has an inverse relationship with depth. In addition, mineral assemblages with little or no acid-neutralization capacity (e.g. silica, clay-alunite, argillic and phyllic alterations) are more extensively developed at shallow depths. The clay-alunite cap will in fact render acidic paste pH values. As reported by Panteleyev (1991), the Au/Ag ratio generally decreases with depth and finely disseminated gold mineralization amenable for open-pit mining can occur in the silica cappings (e.g. Cinola). With hydrothermal alteration limited to relatively narrow envelopes of precious metal veins and the dominance of mineral assemblages with potential acid-neutralizing capacity (e.g. propylitic alteration) at increasing depth, it is understandable that mesothermal vein deposits are less prone to develop ARD problems.

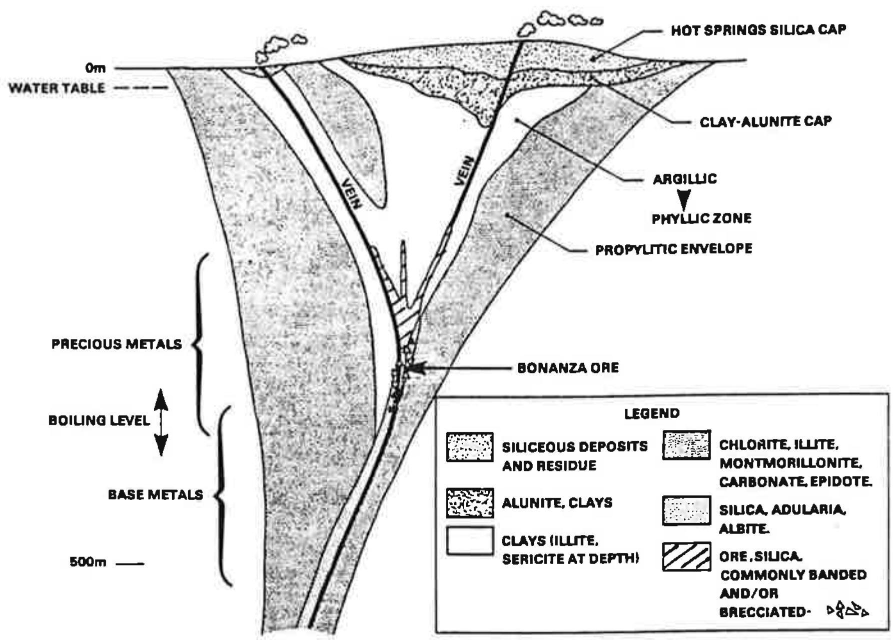


Figure 5. An idealized section of a bonanza epithermal deposit (after Buchanan, 1981).

Rock Competency

The exploitation of an ore deposit usually produces two main classes of mine waste, namely tailings and waste rock, either or both of which can give rise to AMD. Because of the relatively homogeneous nature of tailings, their acid-generating potential are largely determined by the nature and relative abundance of the prevalent sulphide and acid-neutralizing minerals. Depending on the competency of the host rocks, however, not all the sulphide minerals in a waste rock pile are amenable to weathering and involve in the acid generation process. For example, in the Ruttan Mine near Leaf Rapids, northern Manitoba, the 57 million tonnes of waste rock stockpiled on the surface comprises of quartzite, chlorite-mica schist, volcanic-clastics and locally granite. The waste piles contain up to 10% sulphide minerals (of which about 70% is pyrite and the rest are pyrrhotite, chalcopyrite and sphalerite). Among the four waste rock types, only sulphide-bearing chlorite-mica schist is highly reactive and becomes extremely friable upon weathering. Massive pyrite clusters embedded in the schist are >75% weathered based on a cursory examination of various rock piles. In contrast, sulphides enclosed in large blocks of quartzite, massive volcanic-clastics and granite remain fresh. Protected from exposure to the weathering agents except possibly along fractures, the bulk of the sulphide minerals contained in these competent rocks will not be oxidized for a long time.

The competency of a rock can, however, change with the extent of weathering of the major mineral components. In the case of chlorite-mica schist at Ruttan, the inherent schistosity probably provides access of water and air for the oxidation of sulphides; the acid generated will attack the silicate minerals leading to a cycle of ever increasing rate of disintegration of both the silicate hosts and the sulphide minerals. At the Island Copper Mine on Vancouver Island, British Colombia, a prominent waste rock type in a waste dump, the North Waste Dump, is pyrophyllite-altered andesite. Compared to an unaltered andesite, a fresh pyrophyllite-altered andesite may have a comparable competency. However, pyrophyllite is not stable under atmospheric conditions; it readily weathers to kaolinite in a friable state, rendering any embedded sulphides susceptible to oxidation. As neither pyrophyllite nor kaolinite has any significant acid neutralizing capacity, a pyrophyllite-altered andesite containing the same amount of sulphide minerals as an unaltered andesite will have a higher acid generation potential.

In conclusion, given the same sulphide mineral contents, a waste pile with more incompetent rocks (whether inherent or induced by weathering of a major mineral phase), will more readily give rise to ARD than one comprised largely of competent rocks.

Potential Microbial Mediation in Sulphide Oxidation

The effect of microbial mediation in enhancing the rate of pyrite oxidation is well exhibited in ARD associated with sulphidic coal spoils (Paigne, 1987). Though it is generally accepted that microbes are ubiquitous even under extreme physical conditions (e.g. above-atmospheric pressures, sub-zero temperatures, etc.), they flourish only under conditions of an optimum range of pH and temperature and abundant supply of a carbon source. For example, T. Ferroxidans, the principal group of bacteria capable of enhancing the oxidation of a wide variety of metallic sulphides, functions best in an acidic pH range of 2 to 5 and an optimum temperature range of 30-40°C; it can utilize carbon dioxide as the main carbon source (see, for example, Knapp, 1987). Thus, in rocks with a high carbon content and fast reacting sulphide minerals to render an acidic moiety, microbial sulphide oxidation predominates over chemical oxidation. Largely effected by the environment of deposition, sedimentary rocks contains more readily available nutrients and organic carbon for the consumptiuon of microbes than igneous rocks. Authigenic sedimentary sulphides are usually more poorly crystalline and fine-grained in nature than those in igneous rocks. Moreover, fast weathering silicate minerals with significant buffering capacity are ususally depleted prior to sedimentation and lithification. Consequently, unless carbonates are major components in the prevalent mineral assemblages, microbially mediated sulphide oxidation is more likely to occur in sedimentary rocks than in igneous rocks. This explains why acid mine drainage problems are so commonly associated with sulphide-rich coal deposits world-wide and why SEDEX deposits are considered to have a higher ARD potential than VMS deposits.

Mining Method

The occurrence of mineral zoning about an ore deposit is a rule rather than an exception. Examples of sulphide mineral zoning about a generalized VMS deposit and a typical cal-alkaline porphyry copper deposit have been given in Figures 1 and 3, respectively. If an orebody is surrounded by largely non-calcareous rocks having abundant sulphide minerals with no economic value, then the method employed to mine the ore will greatly affect the potential acid production for the overall mining operation. Mining schemes involving minimum disturbance of the barren sulphide-rich rock will produce the least amount of acid resulting from sulphide oxidation. Since open-pit mining usually involves a higher ratio of produced waste rock to ore relative to underground mining, the former may not be an environmentally acceptable option in sulphide-rich terrains despite its lower cost. It must be cautioned, however, that depending on the local topography and hydrologic regimes, underground mining does not necessarily guarantee minimal acid production. This is especially true for metal sulphide deposits located along a hill side. Tunnel systems created during a mining operation and left open after mine closure provide ready access of oxygen and moisture for sulphide oxidation. The Britannia Mine, British Columbia, and Iron Mountain Mine, California (Nordstrom et al., 1990), provide good examples of the legacies of ARD production at old underground workings. Plugging and backfilling of underground workings, wherever practical, should be incorporated in new underground mining operations to minimize acid generation.

FIELD ASSESSMENT OF ARD POTENTIAL

To predict the ARD potential of an ore doposit upon exploitaion, it is necessary to estimate the amount of mine waste that is going to be produced and then determine the sum total of net acid production from each component of the mine waste. In theory, the calculation of the net acid generation from a given amount of mine waste is straight-forward given sufficient knowledge of the mineralogical composition of the mine waste. In reality, complications brought about by differences in mineral textures and rock competency, potential microbial mediation in the sulphide oxidation process, as well as the lack of comprehensive data on mineral weathering dictate that approximations must always be made. In the following, a field-based acid-base-accounting procedure from a mineralogical perspective is presented.

Estimate of Maximum Acid Production

In the context of acid rock drainage, the most important source of acidity derives from the oxidation of sulphide minerals. Extended from his study of the chemical oxidation of some Ni-rich massive sulphide deposits in Western Australia, Thornber (1975) emphasized the importance of metal/sulphur ratio in controlling the net amount of acid produced by the oxidation of sulphides and gave a formulae relating the two parameters as follows:

$$\text{Number of } H^+ \text{ ions produced per sulphide atom} = 2(1-r) \qquad (1)$$

where r = average metal/sulphur atomic ratio in the primary sulphide assemblage. A negative number means that alkalinity in the form of OH^- is produced. If the metal concerned is iron, then the Thornber (1975) formulae must be modified to account for the fact that Fe^{2+} released during oxidation reactions will undergo a further oxidation to Fe^{3+} , rendering two more H^+ ions for each iron atom hydrolysed in the following overall reaction:

$$4Fe^{2+} + O_2 + 10H_2O = 4Fe(OH)_3 + 8H^+ \qquad (2)$$

The modified Thornber formulae would read,

$$\text{Number of } H^+ \text{ ions produced per sulphide atom} = 2(1-r+p) \qquad (3)$$

where p = proportion of ferrous iron in the metal sulphide assemblages. The modification is required whenever Fe^{3+} is not stable relative to $Fe(OH)_3$, which is generally true at pH ≥ 3 under atmospheric conditions. In their investigation of supergene enrichment at a porphyry copper deposit in Northern Chile, Alpers and Brimhall (1989) also re-iterated the importance of metal/sulphur ratio in the acid generation process and the subsequent effect on the composition and texture of secondary minerals formed during supergene alteration.

Estimating Bulk Buffering Capacity of Geologic Material

Under acidic conditions, carbonate minerals (e.g., calcite, dolomite and magnesite) readily dissolve and render carbonate alkalinity which results in an increase in solution pH. Because of the fast reaction rate, carbonate minerals (especially calcite) have been widely quoted in the acid rock drainage literature as the only species that possess any practical neutralization potential. However, carbonates dominate only in a few rock types like limestone, dolomite and marble while the majority of geologic materials are composed of silicates. Silicate weathering as a proton sink is a well established observation (e.g. Longnan, 1969; Ollier, 1984) and is particularly evident in recent work on acid rain research (e.g., Sverdrup, 1990; Moss and Edmunds, 1992). To assess the buffering capacity of mine wastes, silicate minerals therefore must also be considered.

Based on soil acidification studies, Sverdrup (1990) divided the common soil minerals into six groups according to the pH dependency of their dissolution rate and the rate itself (Table 1).

Table 1. Grouping of minerals according to their acid-neutralization capacity (After Sverdrup, 1990).

Group Name	Typical minerals	Relative reactivity*
1.Dissolving	calcite, aragonite, dolomite, magnesite and brucite	1.0
2. Fast weathering	anorthite, nepheline, olivine, garnet, jadeite, leucite, spodumene, diopside and wollastonite	0.6
3. Intermediate weathering	epidote, zoisite, enstatite, hypersthene, augite, hedenbergite, hornblende, glaucophane, tremolite, actinolite, anthophyllite, serpentine, chrysotile, talc, chlorite, biotite.	0.4
4. Slow weathering	albite, oligoclase, labradorite, vermiculite, montmorillonite, gibbsite and kaolinite.	0.02
5. Very slow weathering	K-feldspar and muscovite	0.01
6. Inert	quartz, rutile and zircon	0.004

*Based on 100% mineral abundance (i.e., a mono-mineralic soil).

The relative weathering rate of the six groups of minerals as a function of their abundance is shown in Figure 6. It can be seen that, for all practical purposes, minerals in the slow weathering, very slow weathering and inert groups, do not react much with H^+ ion and are thus poor sinks for acidity. Even for minerals in the intermediate and fast weathering classes, the minerals have to occur in excess of ≈10% and ≈5%, respectively, before they may become practically effective in neutralizing acidity.

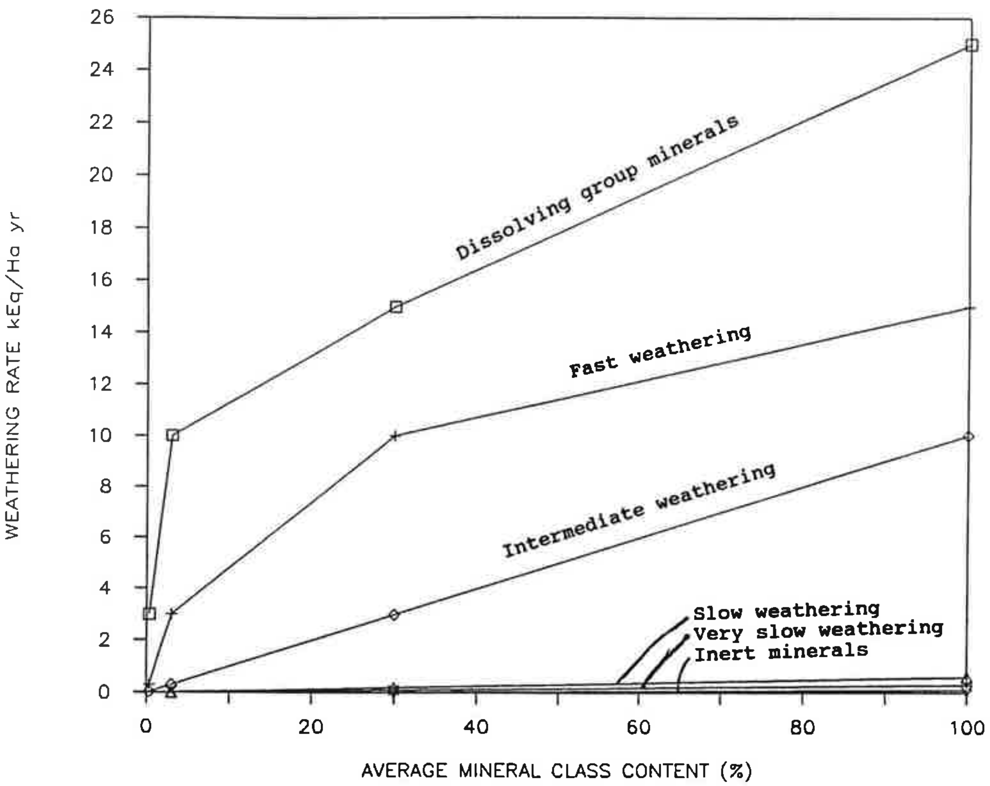


Figure 6. Weathering rate of rock-forming minerals in relation to mineral content. (Based on data from Sverdrup, 1990.)

In the original work of Sverdrup (1990), the weathering rate of a bulk soil sample, W, is approximated by the following equation:

$$W = \sum_{n=1}^{6} xm_n . W_n \qquad (4)$$

where n is the number of mineral weathering classes, xm_n and W_n are the fraction and weathering rate of each mineral class, respectively. The weathering rate is expressed in terms of kilo-equivalents (of cations released) per hectare in a year from a one metre thick soil with a soil solution pH (1:1 soil to water) of 5. As a first approximation in applying these results to estimate the net buffering capacity of a geologic material in acid rock drainage studies, one can ignore the dependency of weathering rate on mineral abundance and define the relative reactivity of the rock forming minerals with respect to the carbonates, on a monomineralic basis (i.e., 100% abundance). The numbers thus derived are shown in the last column of Table 1. Again, it is evident that one can practically ignore all minerals in the slow weathering, very slow weathering and inert groups in the acid neutralization process. Since two moles of H^+ can be neutralized by a mole of carbonate mineral, on a molar basis, the effective buffering capacity, b, of a mine waste can be calculated from the following equation:

$$b = 2\sum_{n=1}^{3} xm_n'W_n' \qquad (5)$$

where xm_n' = molar proportion of minerals in group n and W_n' = relative reactivity of the mineral group n. As shown in Table 1, W_n' = 1.0, 0.6 and 0.4 for mineral groups 1, 2 and 3, respectively. b is expressed as the potential number of moles of H^+ ion that can be neutralized by the non-sulphide components of the mine waste. If ferrous iron is a significant cation in the non-sulphide minerls, Equation 5 must again be correspondingly modified to account for the acidity produced during its oxidation and hydrolysis in an oxygenated solution.

Acid-base Accounting According to Mineral Constituents

Considering the acid-generating and the acid-neutralizing components of the mine waste together, a net acid production index M (analogous to the net neutralizing potential, NNP, of the commonly used acid-base-accounting method) can be defined as follows:

$$M = 2x_s(1-r+p) - 2\sum_{n=1}^{3} xm_n'W_n' \qquad (6)$$

where x_s = molar proportion of sulphide minerals in the mine waste. The mine waste is classified as acid generating if M>0. It should be noted that the expression for M is derived mainly for field assessment of acid rock drainage potential without the benefit of chemical analyses. In dealing with relatively homogeneous mine waste like tailings, a visual estimate of the bulk mineral constituents is appropriate. When waste rock or exposed outcrops (or pit wall) are involved, estimates of mineral abundance should be based on the exposed mineral assemblage unless there is evidence of deep weathering. Since the derivation of M involves many simplifications and ignores the dependency of mineral weathering on important variables like pH, moisture and texture, its application to vigorous predictive modelling has to await further refinement and field validation. However, the expression does take the entire mineral assemblage into consideration and is simple to apply given a minimum proficiency in field mineral identification. It also accounts for the variation in buffering capacity of various alteration mineral assemblages discussed earlier.

As an illustration, a rock undergone pervasive sericite alteration composed essentially of only quartz and very fine-grained muscovite has no buffering capacity. The presence of even a trace amount of Fe-containing sulphide or a sulphide with a metal/sulphur ratio of less than unity will eventually lead to net acid generation according to Equation 6. In contrast, a fresh gabbro containing 30, 15, 50 and 5 modal % respectively of olivine, pyroxene, plagioclase and opaque sulphides theoretically can, depending on the iron contents of the olivine and pyroxene, contain up to about 5 modal % of pyrrhotite without giving rise to an acid rock drainage situation. In applying Equation 6, mineral abundances in terms of modal percent are converted to a relative molar basis by dividing the modal abundance of a specific mineral by its molar volume (i.e. gram molecular weight / density). In the gabbro example, 5 modal % pyrrhotite actually repersents 7 wt. % pyrrhotite or 2.6 wt. % total sulphur. Though this theoretical amount of pyrrhotite required to render net acid generation appears to be high compared to that reported by Lapakko (1987), it amply illustrates the capacity of silicate minerals to neutralize acidity generated by sulphide oxidation. Acid -base accounting based on field estimates of mineral abundances is useful in rendering a rough estimate of ARD potential of geologic material in the absence of detailed chemical analyses.

CHAPTER 3

WEATHERABILITY OF COMMON SULPHIDES

From a survey of acid mine drainage occurrences in British Columbia, Errington and Ferguson (1987) noted that the time lag for acid mine drainage to appear in metallic mines might be several years and the problem might last for several decades. Inasmuch as acid generation is ultimately derived from the oxidation of metallic sulphides, a better understanding of the factors controlling the weatherability of common sulphides is required to predict the onset and duration of acid mine drainage. At the commencement stage of this research project, it was intended to derive such information from kinetic test results detailed in a collection of environmental assessment reports corresponding to various mining projects, which are available in the regional library of Environment Canada located in North Vancouver. However, it was soon found out that few of these reports contain sufficient mineralogical data to allow reasonable deductions. Consequently, an exploratory weathering experiment using sulphide-containing polished thin sections as starting material was conducted to investigate the behaviour of various sulphide minerals and mineral assemblages upon exposure to the weathering agents. Because of the tentative nature of the experimental results, they are presented and discussed here together with a review of pertinent information in the literature on sulphide oxidation.

The Weathering Experiment

The experimental design was similiar to the traditional humidity cell experiment. Ten polished thin sections cut from sulphide-containing handspecimens collected from various minesites were placed face-up in a plastic, perforated thin-section shelf inside a sealed, rectangular plastic container. Controlled airflow through the system was via two glass side-stems installed at opposite ends of the plastic container. After thorough cleaning of the thin sections in a sonic bath, the weekly wet-dry cycle commenced with passing dry air through the system for three days, followed by three days of moist air. On the seventh day, each section was taken out of the system and immersed in a stock solution containing 100 ml deionized distilled water for 30 minutes. The pH, Eh and conductivity of the stock solution was then measured. The cycle was repeated for 20 weeks. At the end of the experiment, the stock solutions were analyzed by induction coupled plasma mass spectrometry. Prior to the start and at the end of the weathering experiment, the polished sections were examined thoroughly under a petrographic microscope and a scanning electron microscope; selected sulphide grained were also analyzed quantitatively for major and minor element content by electron microprobe. During the course of the experiment, selected areas in each thin section were examined monthly under a petrographic microscope to monitor the degree and progress of oxidation.

Table 2 gives a summary of the sulphide and gangue mineralogy and the leachate chemistry of the "oxidized" thin sections (the stock solutions). Plates I to XIII illustrate some of the oxidation features observed through the petrographic and scanning electron microscopes. Evidently, mineral heterogeneity, both in chemical composition and in crystal structure, can greatly affect the weatherability of sulphides. Moreover, enhanced oxidation of some sulphide minerals through galvanic reactions can readily occur in mixed sulfide assemblages. Supplemented with relevant information from the literature, the data set is discussed in the next three sections.

Table 2. Mineralogical composition and leachate chemistry of specimens used in the weathering experiment.

	Ruttan	Snip	Eskay	Premier	IC-Ncap	IC-logr	IC	WC-1	WC-7	Pyrr
Al (*)	1.15	1.13	0.62	0.43	1.83	0.59	0.51	0.45	0.75	0.39
(#)	0.043	0.042	0.023	0.016	0.068	0.022	0.019	0.017	0.028	0.014
Si	6.37	5.39	4.12	2.11	4.69	3.32	1.99	6.15	4.48	4.88
	0.227	0.192	0.146	0.075	0.167	0.118	0.071	0.219	0.159	0.174
Ca	9.96	21.78	7.53	14.57	10.80	11.44	17.5	11.25	9.05	23.47
	0.249	0.543	0.188	0.364	0.269	0.285	0.437	0.281	0.226	0.585
Mg	2.40	2.03	2.02	1.39	2.34	1.83	1.57	1.78	1.91	1.45
	0.099	0.084	0.083	0.057	0.096	0.075	0.065	0.073	0.078	0.06
S	81.49	53.14	41.43	11.88	44.59	38.3	12.48	18.72	28.34	35.17
	2.54	1.66	1.29	0.37	1.39	1.19	0.39	0.58	0.88	1.10
Fe	17.22	3.14	2.17	2.25	1.54	2.21	2.17	2.41	5.51	3.25
	0.308	0.056	0.039	0.040	0.027	0.040	0.039	0.043	0.099	0.058
Ni	0.15	0.08	0.08	0.04	0.08	0.14	0.04	0.10	0.15	0.45
	0.003	0.001	0.001	0.001	0.001	0.002	0.001	0.002	0.003	0.008
Cu	0.49	0.27	0.19	0.15	0.23	0.15	0.23	0.27	0.23	0.22
	0.0077	0.0042	0.0029	0.0023	0.0036	0.0024	0.0035	0.0041	0.0035	0.0034
Zn	0.91	0.54	0.72	0.64	0.88	0.52	0.62	0.40	0.41	0.60
	0.0138	0.0082	0.0109	0.0098	0.0134	0.0079	0.0095	0.0060	0.0062	0.0091

	Ruttan	Snip	Eskay	Premier	IC-Ncap	IC-logr	IC	WC-1	WC-7	Pyrr
%Sulfide	20	11.7	82.1	64.9	20.3	6.1	12	17.9	44.9	48.1
Compo.	15py 5po tr cp,sp py>2mm 50%po <2mm	9.0py 0.5po 2.7sp 0.5cp	66.4sp,gn te, bo. 15.7py	31.5py <2mm 21.6cp 8.0<2mm 13.6>2mm 11.8sp 9.3<2mm 2.5>2mm	20.0py 19.4<2mm 0.6>2mm 0.3cp,sp	2.2py 2.2cp 1.7sp	10.1py 9.9<2mm 0.2>2mm 1.9cpy <2mm	7.0po 6.0py <2mm 4.9cpy <2mm	44.4po 0.5cp 8.2<2mm 36.7>2mm	43.4po+pl 39.1>2mm 4.3<2mm po/pl=3/1 0.6py <2mm 4.1cpy <2mm
Gangue	Bio, Chl Cpx	Q, Carb Feld,Bio	Q,Ms,Plag C	Q,Cc,Chl	Clay,Q,Cc Plag	Q,Ms,Cc Chl	Q,Ms,Cc	Chl,Q,Feld	Chl	Q, Carb. Chl

Abbrev.: py=pyrite; cpy=chalcopyrite; po=pyrrhotite; sp=sphalerite; gn=galena; bo=bournonite; te=tetrahedrite; pl=pentlandite; Bio=biotite; C=carbon; Carb=carbonate; Cc=calcite; Chl=chlorite; Cpx=clinopyroxene; Feld=feldspar; Ms=muscovite; Plag=plagioclase; Q=quartz.

Note: * refers to the amount (in ug) of element leached into solution; # gives the amount in terms of ug-atoms.

Notes for Interpreting The Plates

The following plates illustrate some of the sulphide oxidation features observed in the polished sections through the petrographic and scanning electron microscopes. Indications of oxidation are taken as:

1) extent of surface tarnishing,
2) pitting of mineral surfaces,
3) build up of oxidation products.

Numbers on mineral grains designate the locations where microprobe analyses were performed; however, they are also used in the captions to refer to the grains. Because of the exploratory nature of the weathering experiments, the results and conclusions drawn should be considered as tentative at best. Further research is required to confirm the many findings of the experiment.

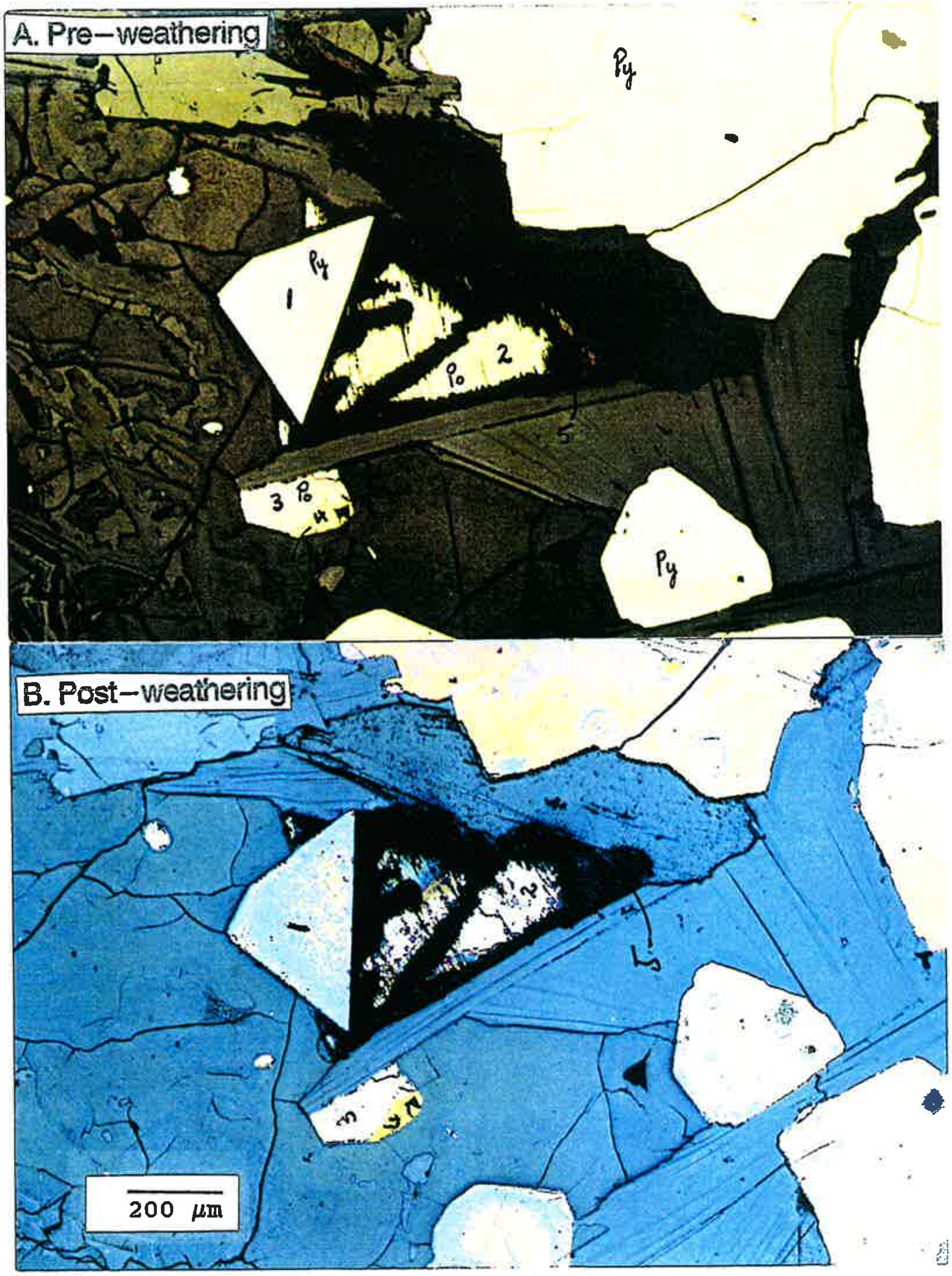


Plate I. Weathering of sulphides in the Ruttan specimen: An illustration of the reactivity of pyrrhotite (po) relative to pyrite (py) and the influence of grain morphology on weathering rate. While the euhedral pyrite grains are only slightly tarnished (the scratch mark in the upper right hand corner of photomicrograph B reveals fresh pyrite underneath), destruction of pyrrhotite is evident along the irregular grain boundaries and micro-fractures penetrating the anhedral grain 2. Trapping of moisture along the fractures may have enhanced the weathering of the pyrrhotite. The original weathering may have been initiated by a galvanic reaction between grains 1 (py) and 2 (po). Note that pyrrhotite (grain 3) adjacent to chalcopyrite (grain 4) shows little sign of weathering.

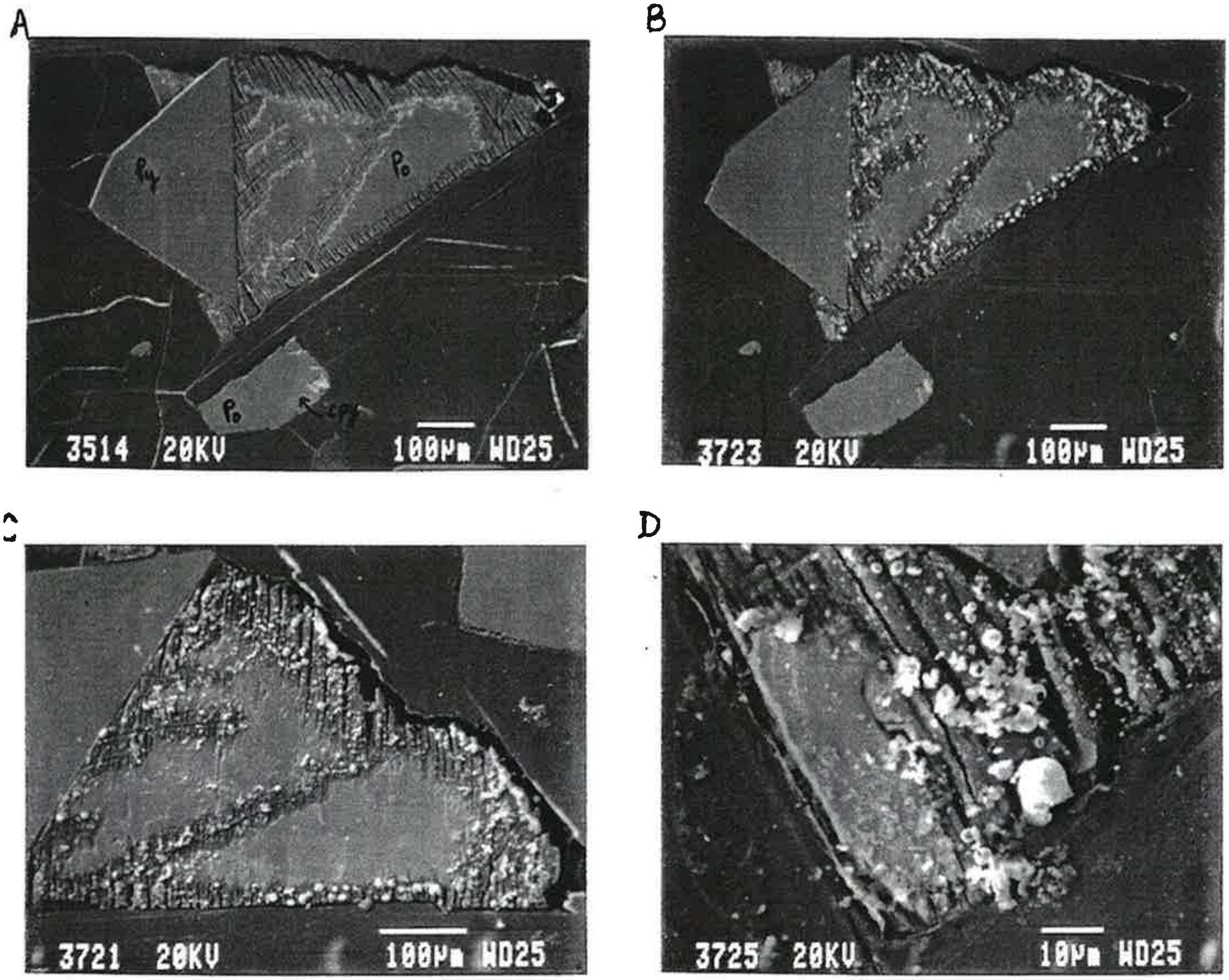


Plate II. Scanning electron photomicrographs of selected sulphide grains illustrated in Plate I (A was taken prior to and B through D after the weathering experiment). Note the lack of pitting in the pyrite and composite pyrrhotite-chalcopyrite grain in B while the pyrrhotite grain is replaced by iron oxide (dark rims) and coated with a mixture of elemental sulphur (globular as enlarged in C and D), ferric hydroxide and possibly some iron sulphate.

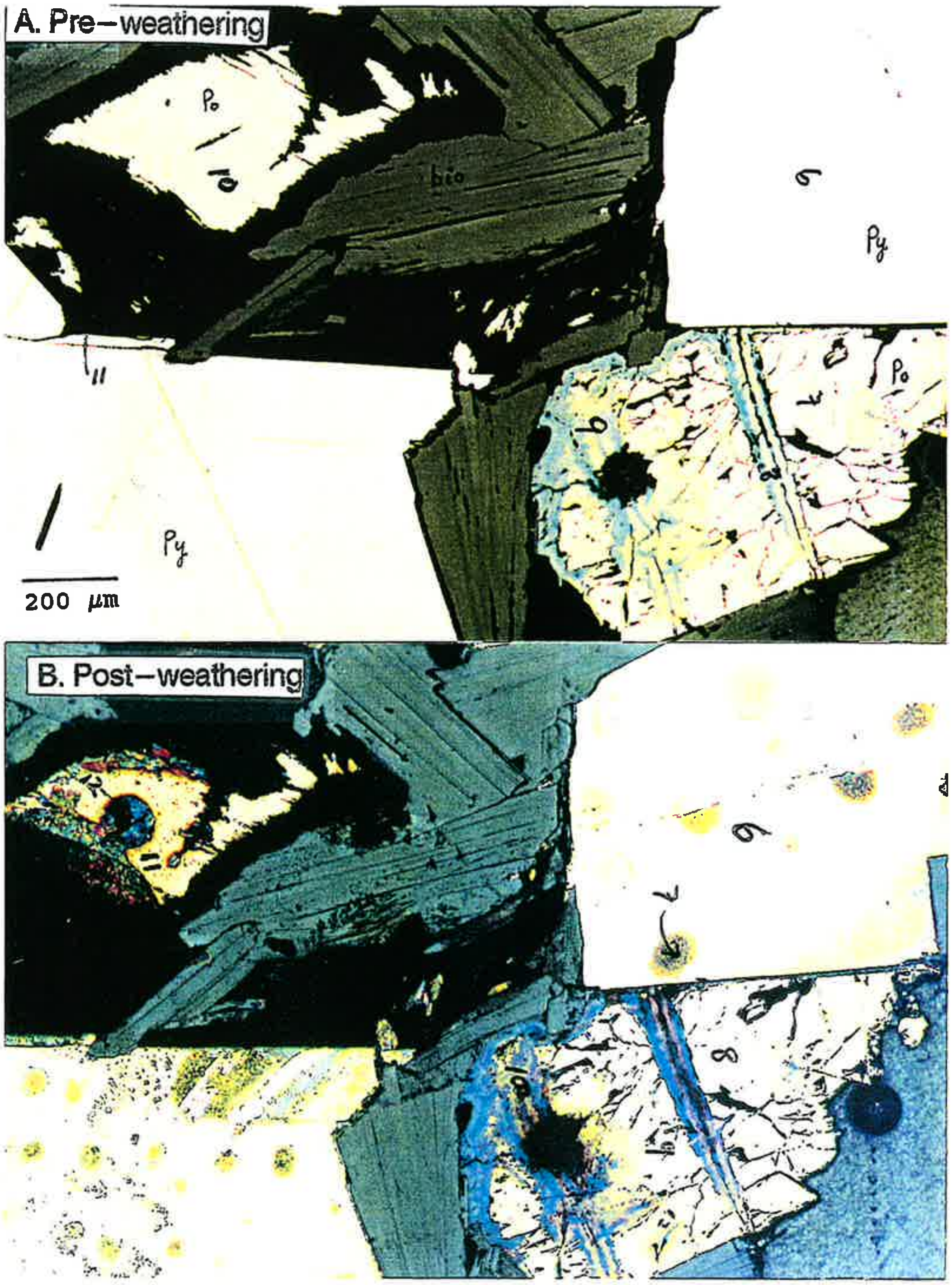


Plate III. Oxidation of pyrite (py) and pyrrhotite (po) in the Ruttan specimen. After 24 wet-dry cycles, pyrite only shows spotty tarnish while the anhedral pyrrhotite grain enclosed by biotite (bio) is heavily tarnished and replaced by iron oxide (black) and the more euhedral grain adjacent to pyrite shows intensified replacement by covellite (blue). The susceptibility of pyrite to tarnishing is apparently controlled by the trace element content. Spot 7 in photomicrograph B, for example, contains trace copper.

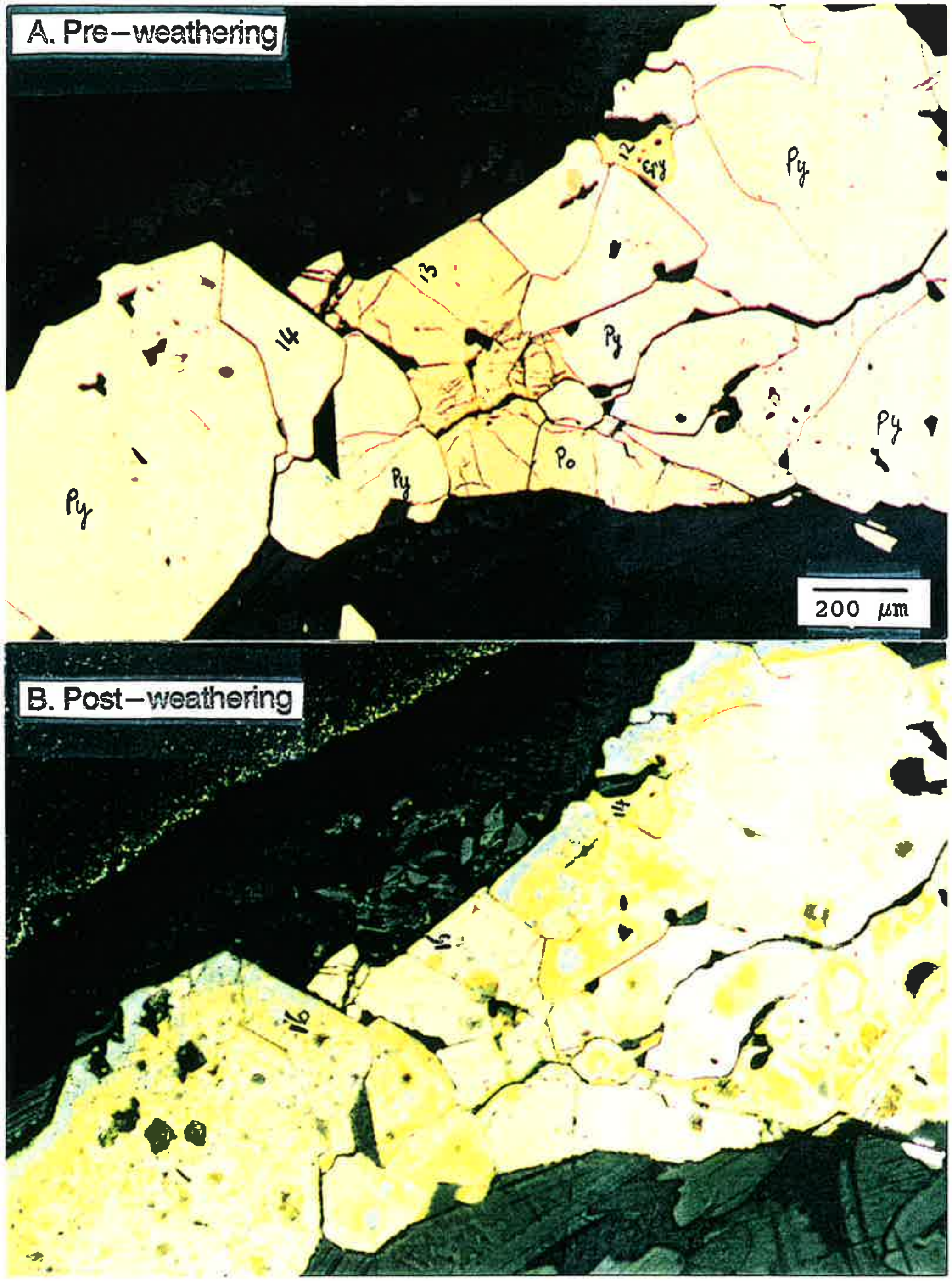


Plate IV. Weathering of sulphides in the Ruttan specimen: Example of compositional control on weatherability. Two types of pyrite are illustrated in this pair of photomicrographs. The heterogeneous grains (e.g. lower left; Zn-containing in this case) weathers faster (i.e., shows a greater density of pitting) than the more homogeneous grains. The equally large pyrrhotite (po) grain shows incipient alteration only along major fractures while the small chalcopyrite (cpy) grain remains intact.

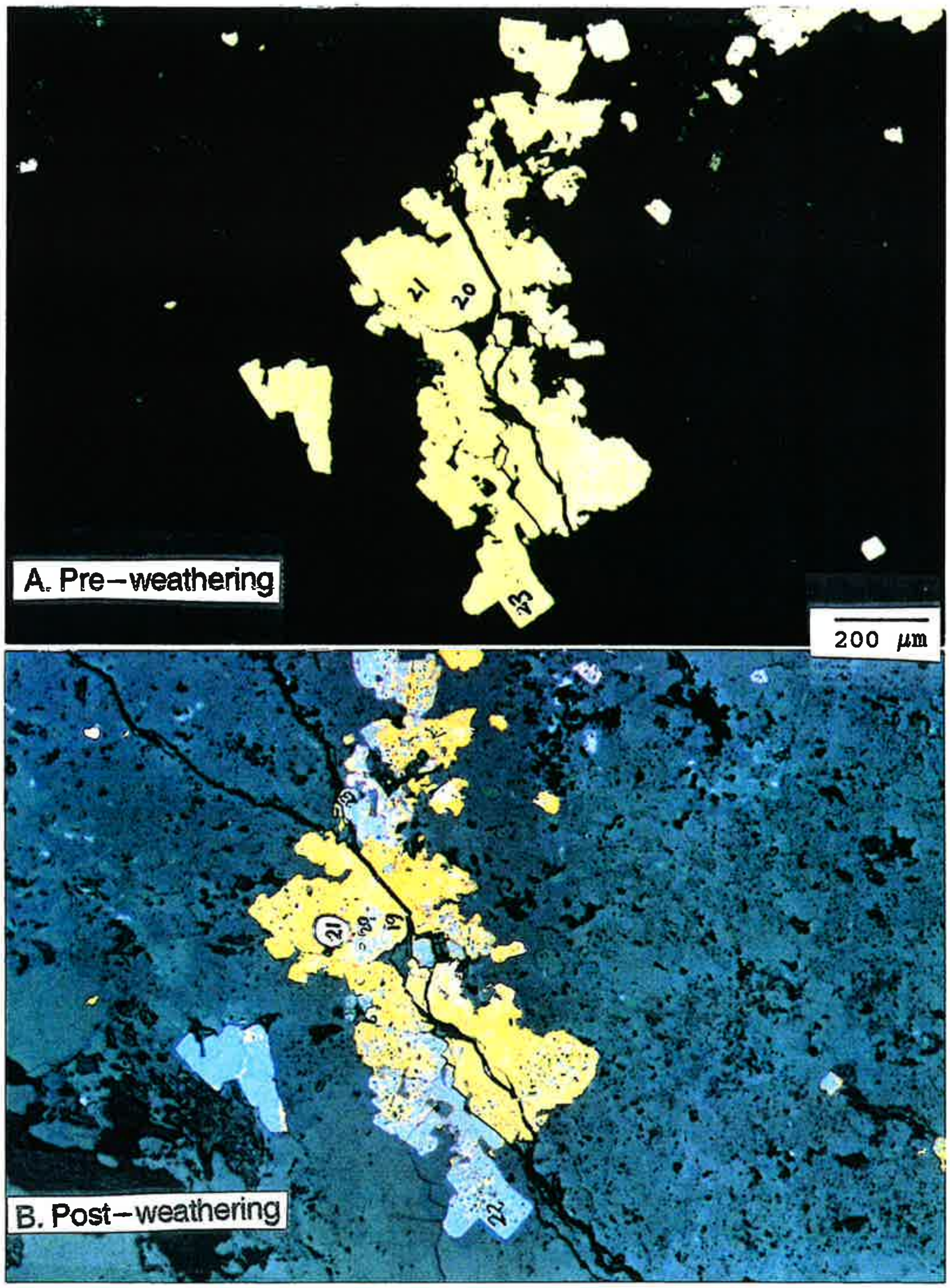


Plate V. Oxidation of pyrite in the Snip sample. Despite the euhedral morphology, pyrite grains in this section are readily weatherable because of their heterogeneous composition. The most common trace elements detected by electron microprobe analyses include Pb, Co and Zn (up to 0.18, 0.11 and 0.02 wt.%, respectively). In contrast, the included pyrrhotite (grain 21 in both photomicrographs) shows no sign of alteration. It contains 0.22 wt.% Co+Ni but no Pb.

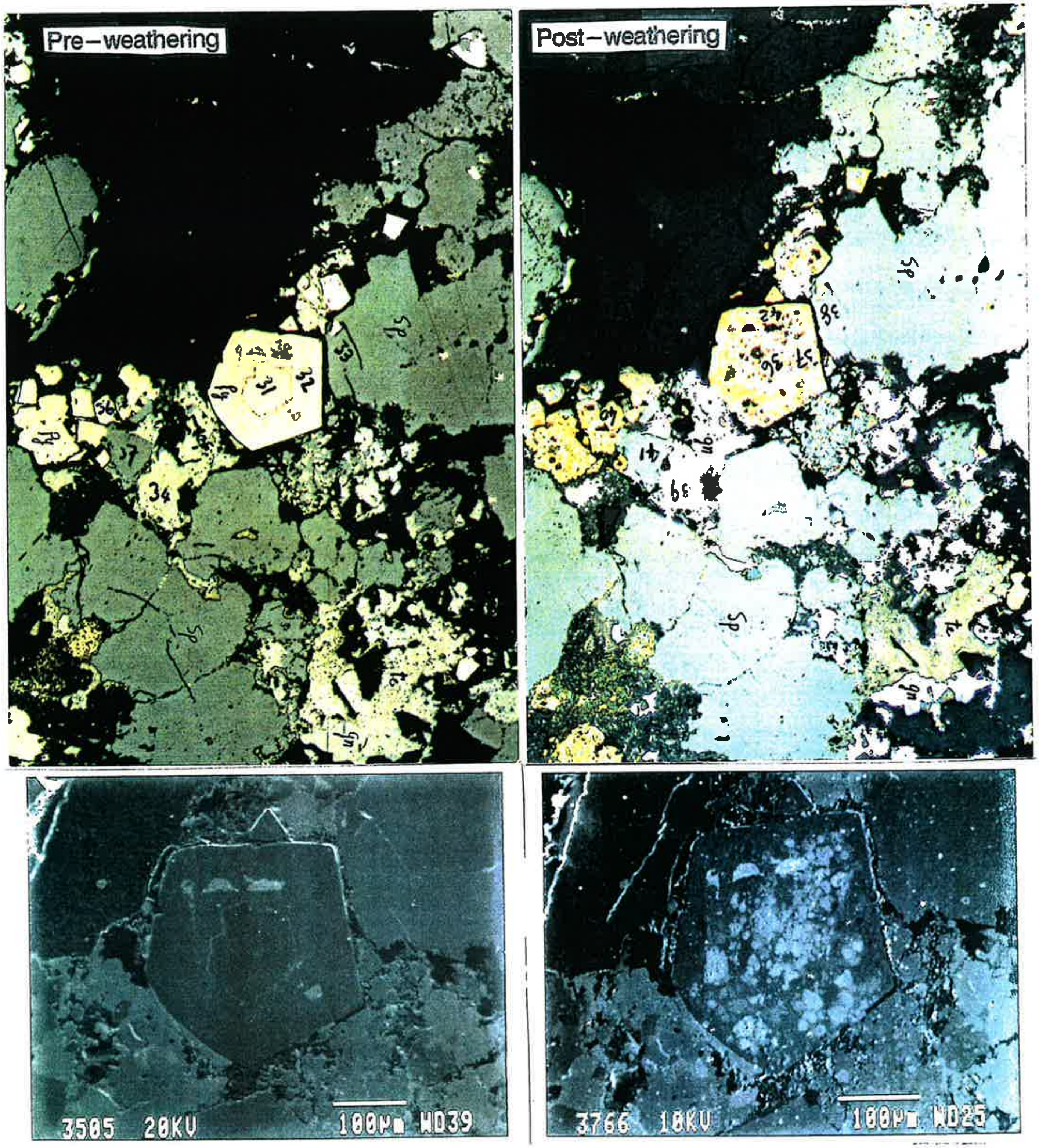


Plate VI. Weathering of sulphides in the Eskay section. Though the highly euhedral, pyrite (py) grains are readily weathered, apparently due to the high Pb content (0.26-2.44 wt.%, some of which must occur as included galena). Large patches of sphalerite (Sp) and galena (gn) remains fresh and tetrahedrite (te) is readily tarnished.

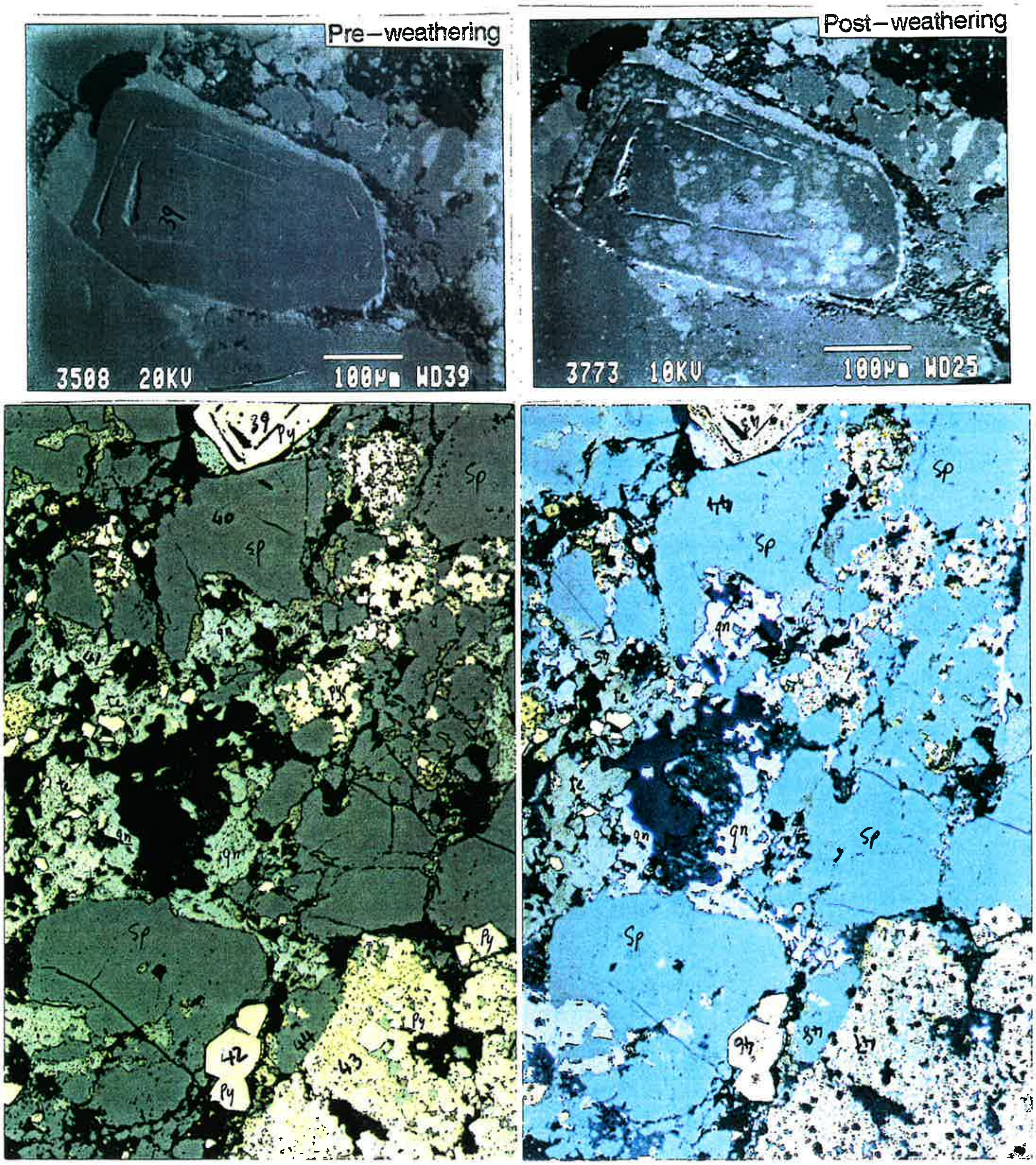


Plate VII. Sulphide oxidation in the Eskay section. Pyrite (py), regardless of grain-size, is highly weathered due to its heterogeneous composition. Tetrahedrite (te) is also readily tarnished. In contrast, despite minor pitting, sphalerite (sp) and galena (gn) are relatively unaltered.

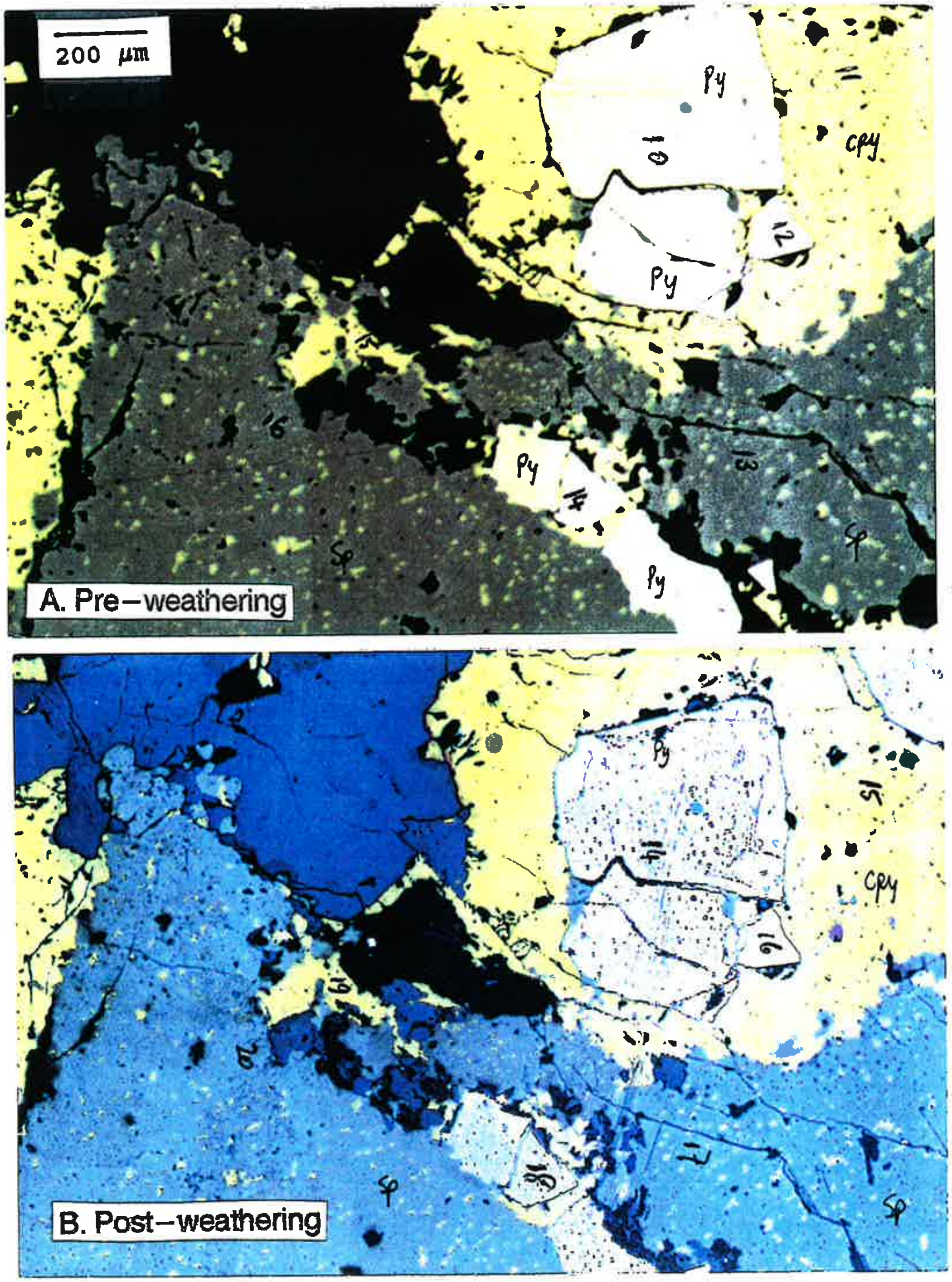


Plate VIII. Sulphide weathering in the Premier specimen. Pyrite (py) with included blebs of sphalerite shows prominent tarnish and extensive pitting at the end of the weathering experiment (e.g. Grains 14 and 18 in Photomicrograph B). An apparently homogeneous pyrite grain (labelled 16 in B) remains intact despite its high Cu content (0.19 wt.%). Large patches of sphalerite (sp) with abundant exsolved chalcopyrite also shows incipient pitting whereas chalcopyrite, especially the large patches, is only slightly tarnished.

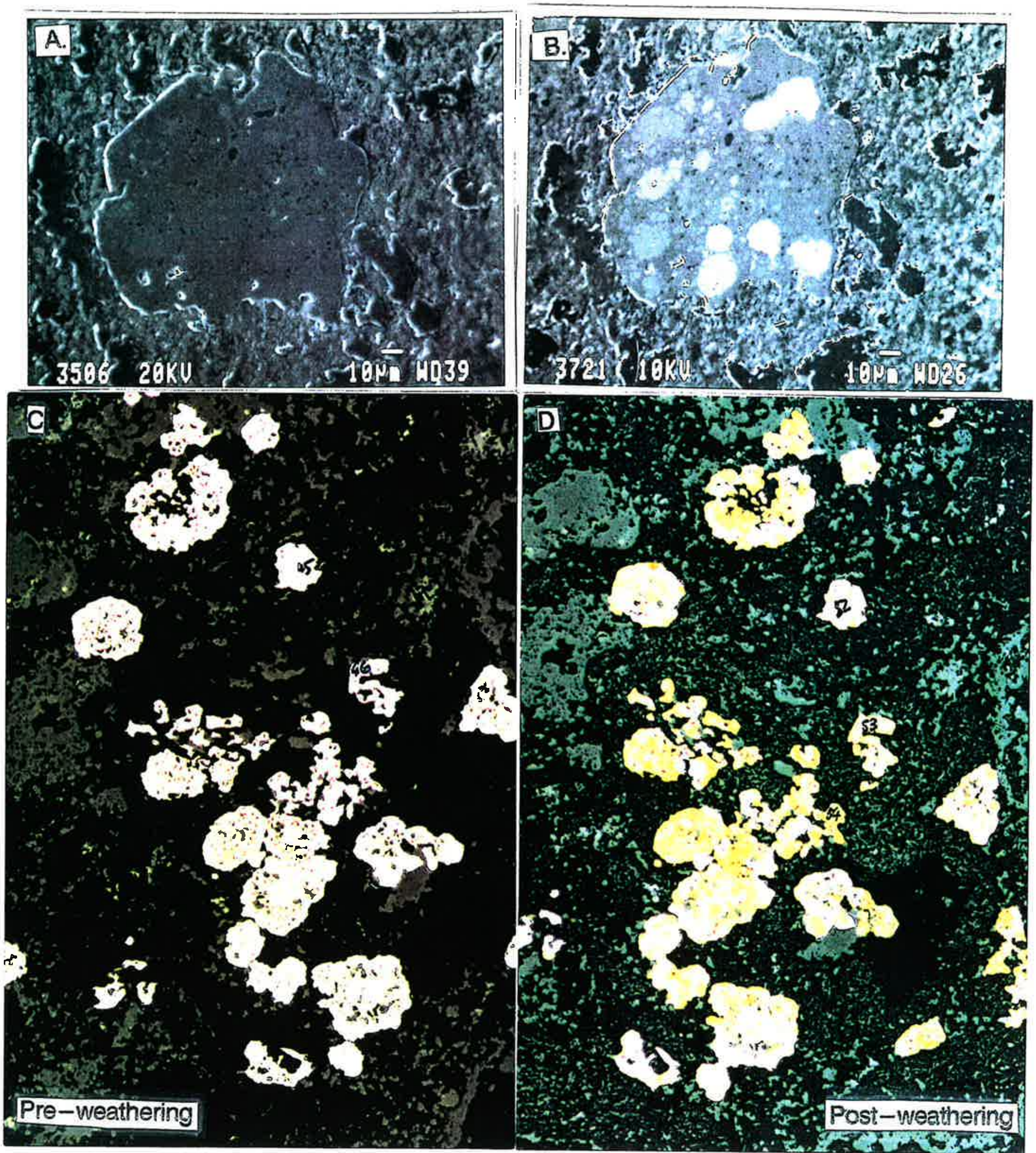


Plate IX. Oxidation of disseminated pyrite in the IC-Ncap specimen. The pyrite grains vary from subhedral to anhedral but all are apparently highly heterogeneous in composition and are very susceptible to oxidation (e.g. scanning electron photomicrograph B shows the detailed post-weathering features of grain 52 in photomicrograph D).

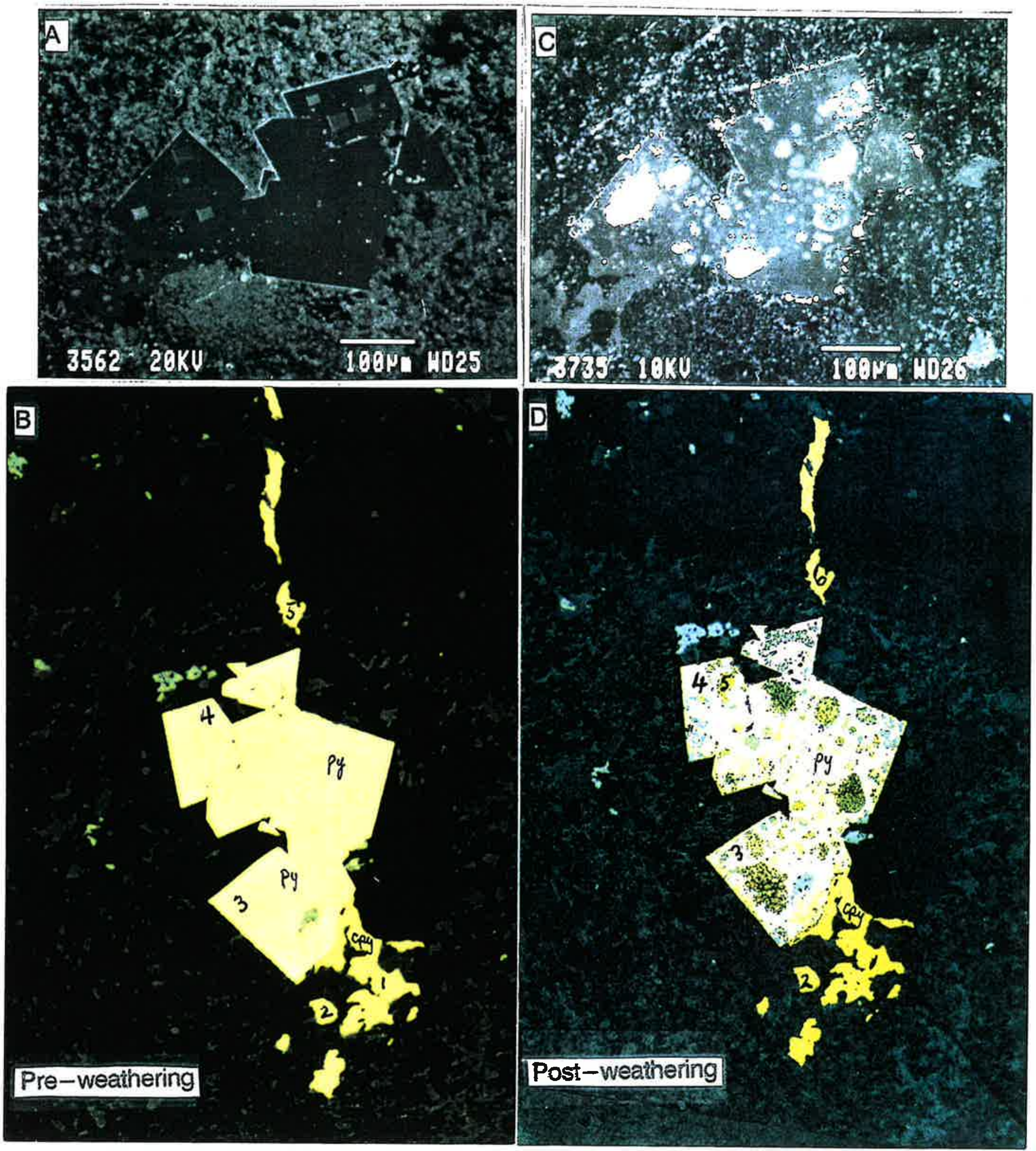


Plate X. Relative weatherability of pyrite (py) and chalcopyrite (cpy) in the IC-logr section. Though being more euhedral and coarser, py is more readily altered than cpy. (Note: Rectangular marks in A were created by the electron beam during analysis; as is evident in the post-weathering electron photomicrograph C of the same area, they did not affect the weathering of the py grains.)

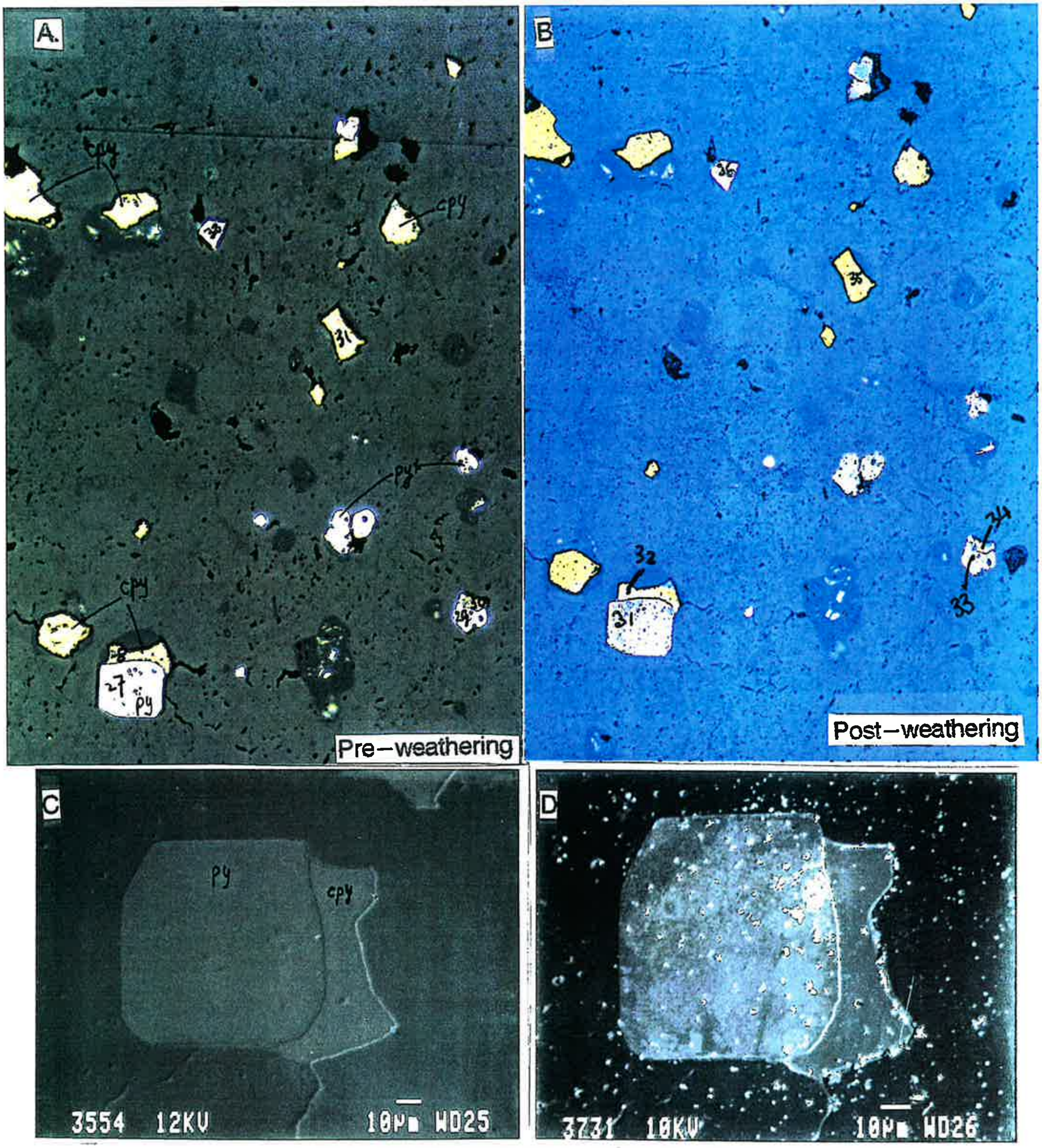


Plate XI. Weathering of disseminated sulphides in the IC specimen. Pyrite (py) appears to be more readily weathered than chalcopyrite (cpy). Even the close contact of the mineral pair (grains 31 and 32 in photomicrograph B and their enlargement in scanning electron photomicrograph D) did not enhance the weathering of chalcopyrite; the heterogeneous nature of the pyrite might have arrested galvanic reactions between the minerals.

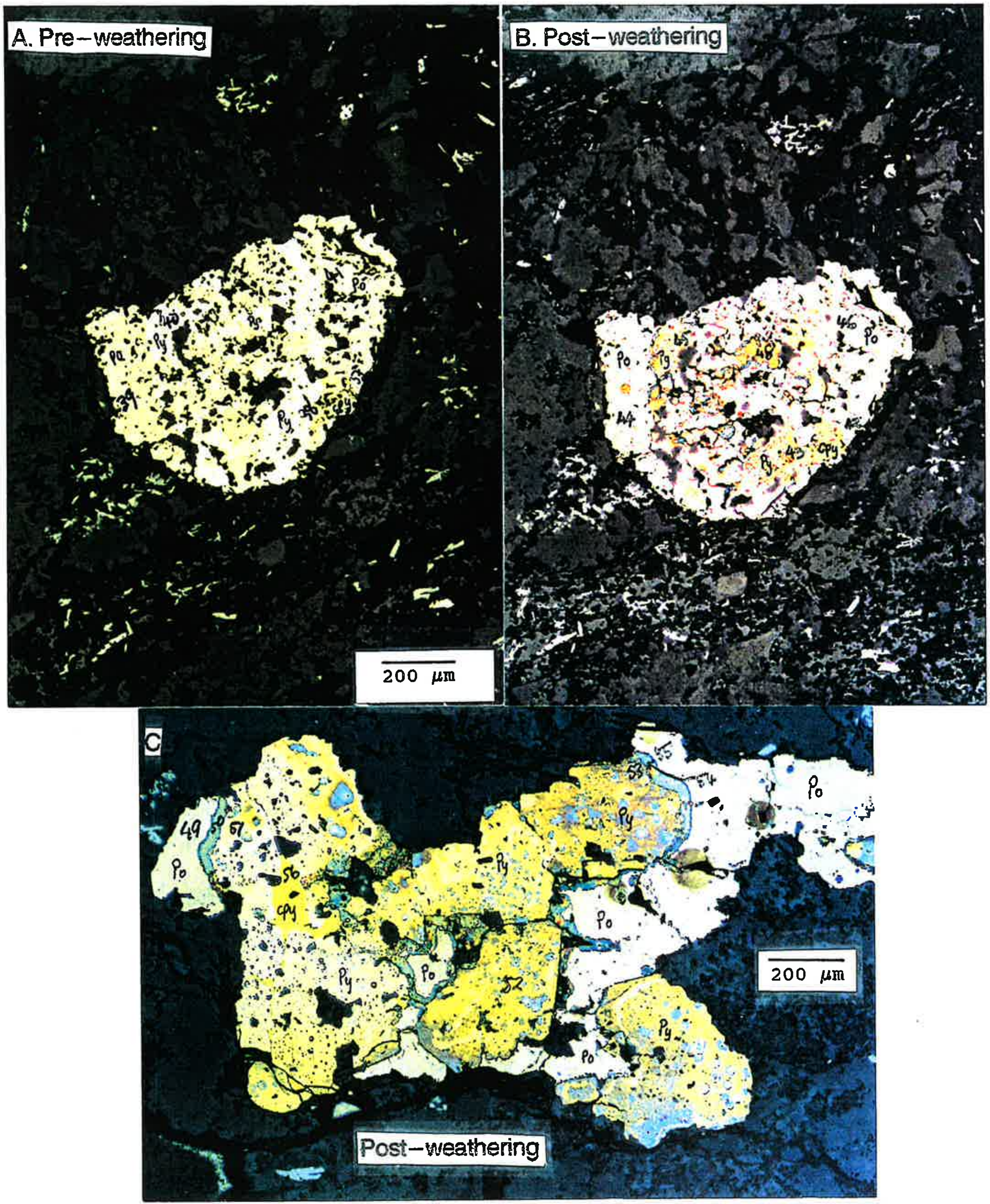


Plate XII. Weathering of sulphides in the WC-1 section. While pyrite (py) is intensively tarnished with the progress of weathering, alteration of pyrrhotite (po) is evident only along contacts with pyrite (blue zones in photomicrograph C) and major defects (e.g. large cracks). Chalcopyrite (cpy), in contrast, is only slightly tarnished. (Note: Photomicrographs A+B and C show oxidation features at two different areas of the same section.)

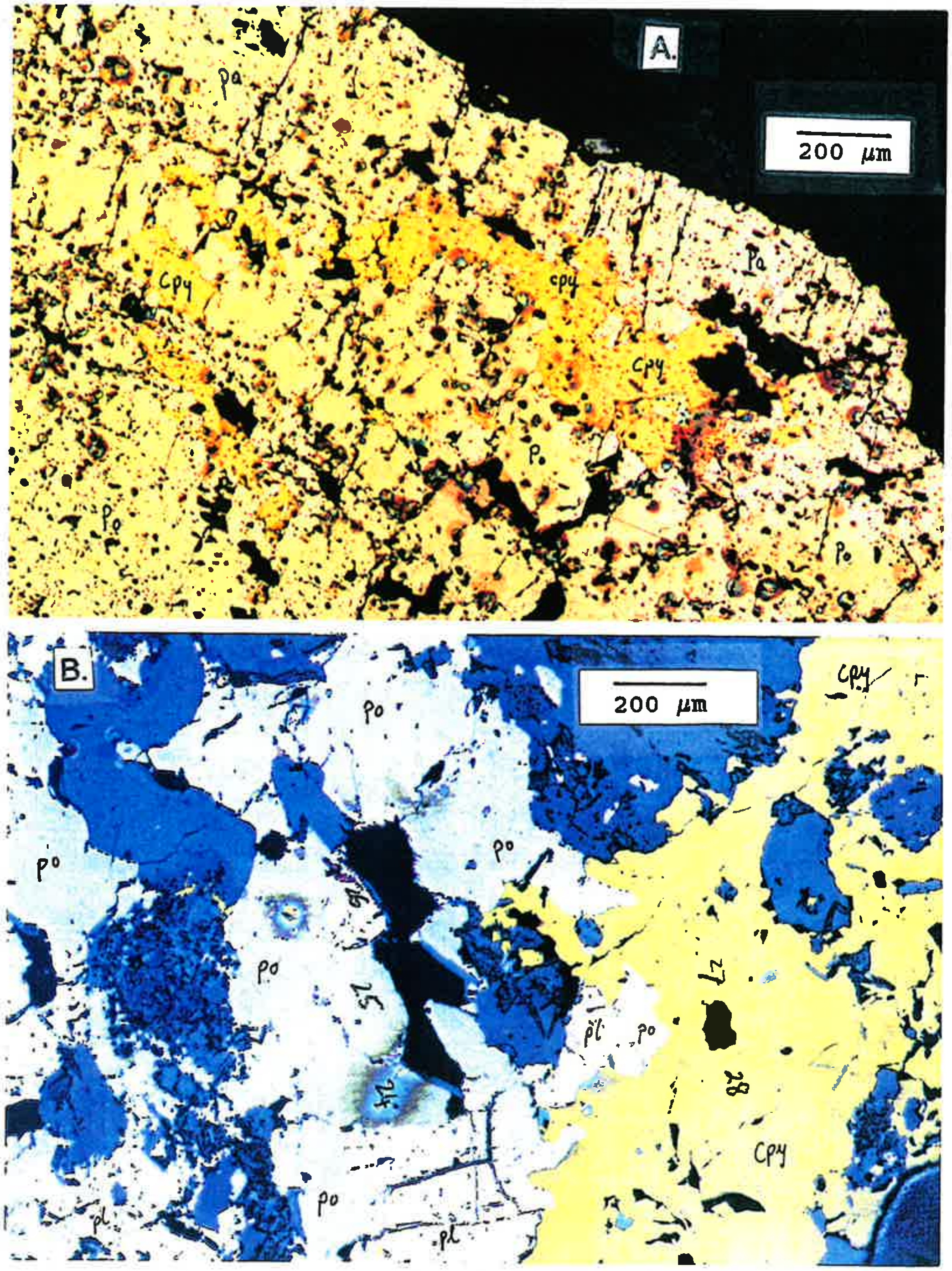


Plate XIII. Weathering of sulphides in specimens WC-7 (A) and Pyrr (B). In A, the alteration of both pyrrhotite (po) and chalcopyrite (cpy) has started from structural defects (mainly fractures) in the mineral grains. Likewise in B, neither pyrrhotite (po) nor pentlandite (pl) shows prominent sign of alteration except along a few fractures; chalcopyrite (cpy) is slightly more extensively tarnished. (Both A and B are post weathering photomicrographs.)

Oxidation of Individual Sulphides

Pyrite

Because of its natural abundance and because it is usually of no economic value, pyrite is the most widespread sulphide mineral that can be found in any mine waste. By virtue of its low metal to sulphur ratio, it is also one of the most potent acid generators upon oxidation. Thus it is not surprising that studies of pyrite oxidation have dominated the acid mine drainage literature for the past five decades. Excellent recent reviews on the subject are provided by Lowson (1982), Nordstrom (1982) and de Haan (1991). Although molecular oxygen is the overall oxidant in the oxidation of pyrite, recent research has indicated that ferric iron is the direct oxidant over a wide range of pH conditions (Moses et al., 1987; Brown and Jurinak, 1989; Moses and Herman, 1991). Whereas the detailed mechanism of pyrite oxidation remains unclear and a variety of intermediate alteration products may be involved (Goldhaber, 1983), it is generally accepted that the effective surface area and microbial mediation can greatly affect the rate of oxidation (McKibben and Barnes, 1986; Nordstrom, 1982). On the other hand, little is known about the influence of trace element content on pyrite weatherability.

Of the ten sections used in the weathering experiment (Table 2), pyrite is the dominant sulphide in five (Ruttan, Snip, Premier, IC-NCap, and IC) and a major sulphide component in another three (Eskay, IC-logr and WC-1). The pyrite grains in these sections show varying degrees of tarnish (Plates I and III to XII), the colour and the intensity of which appear to vary with the type and amount of trace elements present. The tarnish layer is generally less than 1-2 µm thick. Electron microprobe analyses showed that foreign elements incorporated in the pyrite grains include Co, Ni, Cu, Zn, Pb, Bi, As, Au and Ag. These elements may occur as substitutional (e.g., Co, Ni and, to a very limited extent, Cu for Fe; As for S) or interstitial (e.g., Au, Ag and Bi) impurities, or as minute inclusions of separate mineral phases (e.g., Pb as galena, Zn as sphalerite, Cu as chalcopyrite). The incorporation of both interstitial impurities and mineral inclusions in pyrite will cause local strain in the crystal structure, rendering the pyrite more susceptible to alteration.

The heterogeneity in composition of many apparently uniform, euhedral pyrite grains are readily brought out in the weathering experiment (Plates III to XI and XIIb). Using the intensity of tarnishing and the pitting density as indicators of weatherability, it is apparent that the more heterogeneous is a pyrite grain, the faster it will oxidize. This is particularly true if the foreign elements occur as separate mineral phases included in the host pyrite grain (e.g., see pyrite in the Eskay section, Plates VI and VII). For substitutional impurities, Co and Ni appear to protect the sulphide from weathering while As appears to enhance the process. The observation is in agreement with a generalization in semi-conductor physics (Shuey, 1975) that, for substitutional impurities, substitutions from the right in the periodic table (such as Co for Fe) make donor defects (leading to the development of positive effective charge) and substitutions from the left make acceptor defects (giving rise to effective negative charge). Since pyrite oxidation inevitably involves the heterogeneous electron transfer between an adsorbed oxygen or ferric ion and the pyrite surface (see review by de Haan, 1991), a positive effective charge will suppress the electron transfer process (and hence the oxidation of pyrite) and a negative effective charge on a pyrite surface will have the opposite effect. However, in view of the wide variation in composition of the pyrite grains examined and the limited number of analyses performed, the observation is somewhat conjectural from a statistical viewpoint. The establishment of a more quantitative relationship between the trace element composition of pyrite and its weatherability has to await more detailed analyses.

From comparing photo-micrographs of the sections taken at different times during the course of the weathering experiment, many pyrite grains acquired the tarnish within the first month and changed little afterwards. The change in Fe/S atomic ratio of pyrite with weathering is depicted in Figure 7. Fresh pyrite has a narrow range of Fe/S atomic ratio between 0.49 and 0.51 while tarnished pyrite renders a wider range of 0.47 to 0.55. An increase in Fe/S atomic ratio reflects the partial retention of Fe in the form of hydrated iron oxide. A decrease in the Fe/S ratio, on the other hand, implies preferential leaching of Fe relative to S from the grain surface. Most of the pyrite grains showing a decreased Fe/S atomic ratio have chalcopyrite as the closest neighbour. Because of the metastability of secondary copper sulphides (e.g., covellite and chalcocite), incipient weathering of chalcopyrite may release the constituent ferric ion, which in turn may have accelerated the oxidation of the neighbouring pyrite. Rapid release of ferrous iron is effected while the oxidation of sulphide sulphur to dissolved sulphate (involving the transfer of eight electrons) lags behind. This results in the observed reduced Fe/S ratio in the affected pyrite surface. Alternatively, the temporary retention of intermediate alteration products such as elemental sulphur on the pyrite surface may also account for the reduced Fe/S ratio. A more sensitive surface analytical technique than electron microprobe analysis is required to resolve the issue.

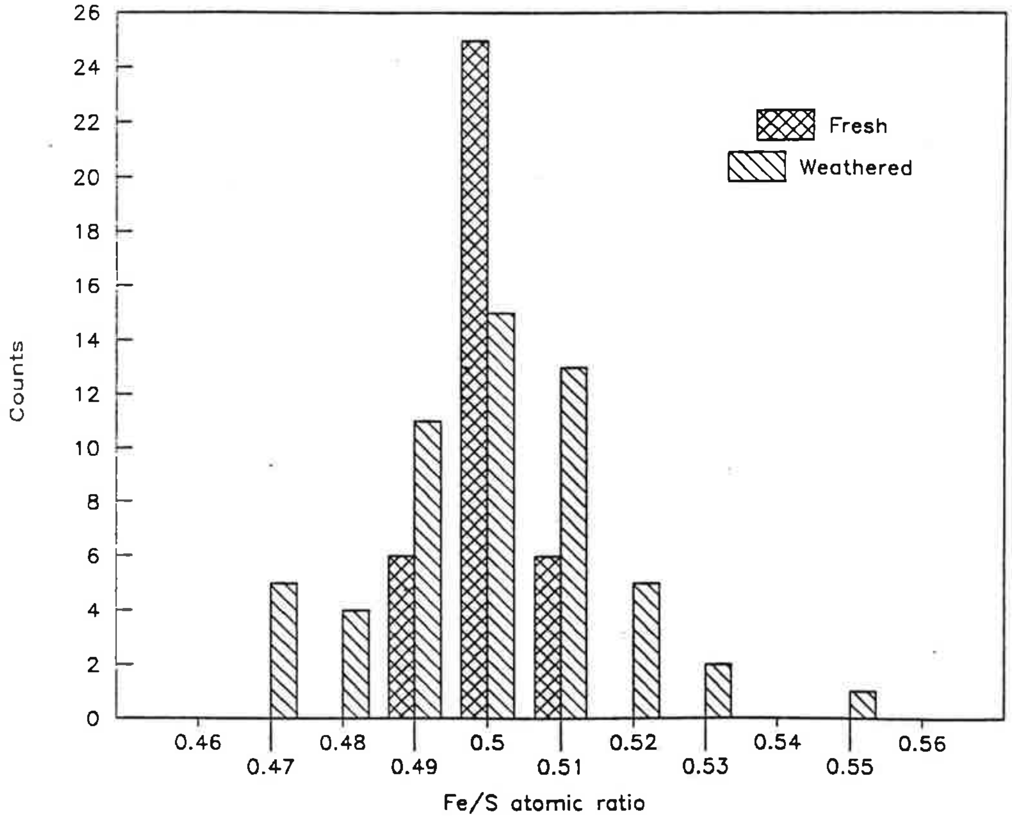


Figure 7. Change of Fe/S atomic ratio in pyrite with weathering.

Pyrrhotite

Though ample field evidence has been documented in the acid mine drainage literature that pyrrhotite, among the common sulphide minerals, is most susceptible to alteration (e.g., Blowes and Jambor, 1990; Kwong and Ferguson, 1990), only a few quantitative measurements have been made to date to assess its oxidation rate (e.g., Nicholson and Scharer, 1992). The variable composition of naturally occurring pyrrhotite, the dependency of mineral stability on crystal structure (hexagonal pyrrhotite being more susceptible to alteration than monoclinic pyrrhotite; see, for example, Nickel et al., 1977) and the rather complex sequence of mineral transformations involved in pyrrhotite alteration (Kwong and Ferguson, 1990) all contribute to complicate experimental designs to assess its oxidation rate.

In the weathering experiment, four thin sections (Ruttan, Pyrr, WC-1 and WC-7) contain significant amount of pyrrhotite (5 to 44 modal percent, Table 2). Among these, rapid alteration of pyrrhotite is observed only in the Ruttan section (Plate I to III). Alteration of pyrrhotite in the WC-7 and Pyrr sections are locally associated with prominent crystal defects (Plate XIII) while more widespread tarnishing and well developed alteration rims along contacts with pyrite are apparent in the WC-1 section (Plate XII). Based on the Fe/S atomic ratio obtained by electron microprobe analysis, most of the pyrrhotite in these sections are monoclinic though a small amount of admixed hexagonal pyrrhotite may be present in the sections Pyrr and WC-7. In view of the high Ni content of pyrrhotite in the Pyrr section and the high Co content in the WC-7 section (Table 3), the most important parameter effecting the relative stability of pyrrhotite in these sections may well be the trace element content. Thus, with the lowest combined Ni and Co content, pyrrhotite in the Ruttan section oxidized faster than pyrrhotite in the other three sections. The effect of closest neighbour will be discussed in a later section devoted to the oxidation of assemblages of sulphide minerals.

Table 3. Trace element content of pyrrhotite in four sections

Sample	Trace element* : mean wt.% ± std. dev. (# analyses)	
Ruttan	Co: 0.11 ± 0.012 (5) Ni: 0.01 ± 0.006 (5)	Cu: 0.02 ± 0.010 (5) Pb: 0.04 ± 0.032 (5)
WC-1	Co: 0.13 ± 0.049 (8) Ni: 0.08 ± 0.012 (8)	Cd: 0.007 ± 0.004 (8) Cu: 0.021 ± 0.031 (8)
WC-7	Co: 0.30 ± 0.048 (5) Ni: 0.01 ± 0.014 (5)	Cd: 0.008 ± 0.007 (5)
Pyrr	Co: 0.11 ± 0.018 (4) Ni: 0.88 ± 0.059 (4)	

* Only include metals that appear in >50% of grains analyzed.

As shown in Figure 8, oxidation of pyrrhotite generally results in an increase in Fe/S atomic ratio. This reflects the loss of S as dissolved sulphate and the partial retention of Fe as hydrated iron oxide. The formation of elemental sulphur as an intermediate alteration product is evident in the Ruttan section (Plate IId). However, it is much less abundant than hydrated iron oxide. Field observations at Mount Washington suggest that the formation of elemental sulphur and marcasite as intermediate alteration products of pyrrhotite is partially in response to a fluctuating water table. These minerals are unlikely to form under permanently saturated conditions.

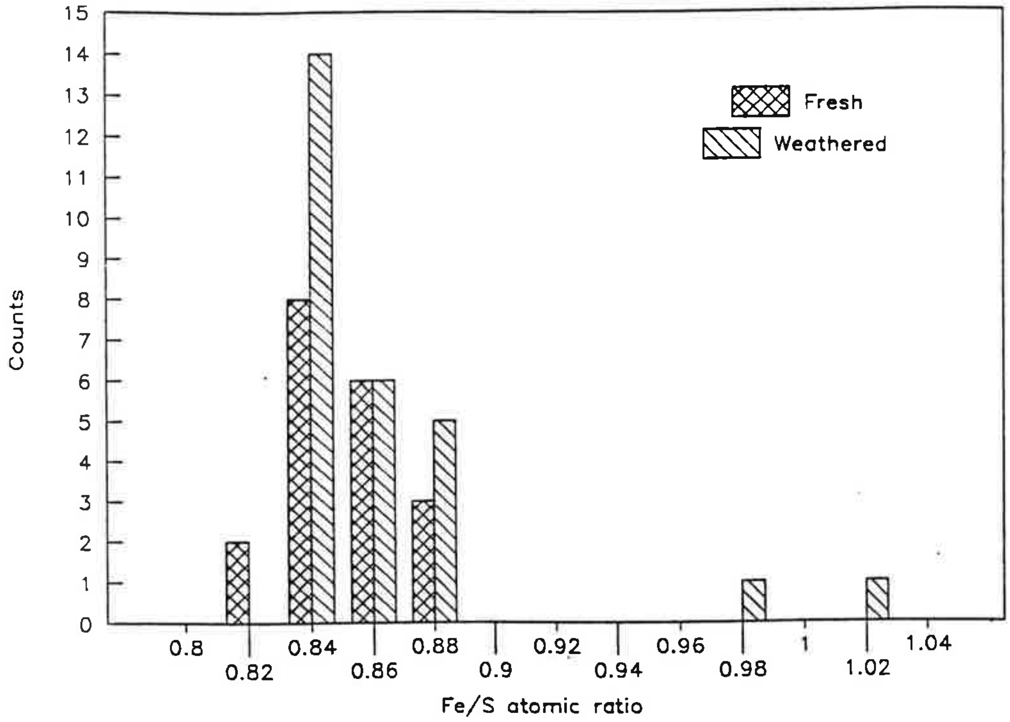


Figure 8. Change of Fe/S atomic ratio in pyrrhotite with weathering.

Chalcopyrite

Whereas it is generally recognized that chalcopyrite is unstable under atmospheric conditions, its behaviour upon weathering is complicated by the ready formation of a variety of secondary copper minerals (including covellite, chalcocite, brochantite, chalcanthite, malachite, etc.) depending on the local solution chemistry. Semi-quantitative laboratory investigations (e.g., Steger and Desjardins, 1978) suggest that the mineral is more reactive than pyrite but less so than pyrrhotite. Hydrometallurgical studies (e.g., Dutrizac and MacDonald, 1974) indicate that ferric ion leaching may enhance the decomposition of chalcopyrite. A more recent attempt to quantitatively determine the reaction rate of chalcopyrite with ferric ion is furnished by Chermak et al. (1992).

With the exception of the Eskay sample which is devoid of chalcopyrite, all the thin sections used in the weathering experiment contain chalcopyrite, ranging in quantity from trace amounts (Ruttan and IC-Ncap) to about 22 modal percent (Premier). Intensified tarnish is the only sign of oxidation observed in the chalcopyrite grains contained in these sections. Pitting is not readily discernable. Electron microprobe analyses indicate that the simulated weathering has effected notable changes in the chalcopyrite composition. The range in (Cu+Fe)/S atomic ratio is widened and the Fe/Cu atomic ratio prominently reduced (Figure 9). The preferential leaching of Fe and incipient formation of a secondary copper sulphide mineral like chalcocite or covellite may account for the observed changes in composition. Since the Fe in chalcopyrite occurs in the ferric state, its release and subsequent hydrolysis to form ferric hydroxide will lead to acid production. The acid thus generated, if not neutralized in situ, will eventually enhance the dissolution of chalcopyrite.

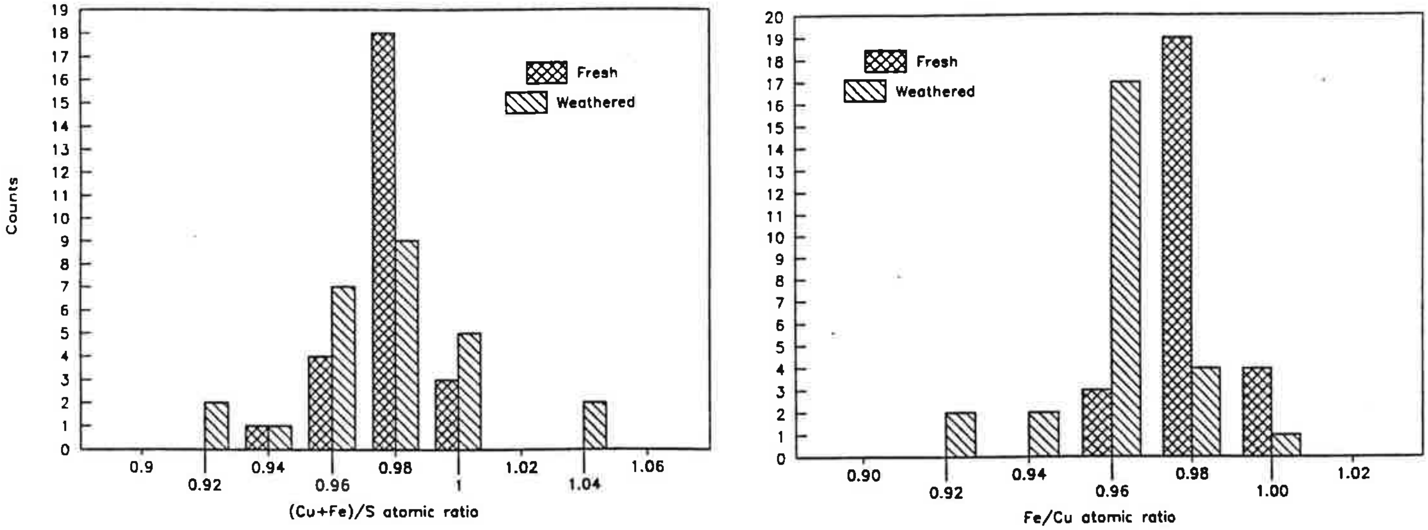


Figure 9. Changes of (Cu+ Fe)/S and Cu/Fe atomic ratios in chalcopyrite with weathering.

Other Sulphides

Besides pyrite, pyrrhotite and chalcopyrite, other sulphide minerals occurring in one or more of the thin sections involved in the weathering experiments include sphalerite, galena, pentlandite, tetrahedrite and bournonite. The behaviour of all of these minerals during weathering have been described in a voluminous literature on supergene alteration (e.g. Nickel et al., 1974; Blaine and Andrew, 1977; and, Andrew, 1980). Quantitative measurements of the oxidation rates of the sulphides except pyrite are sparse. In addition to pyrrhotite and chalcopyrite, some data are available for sphalerite and galena (Boulegue et al., 1992; Chermak et al., 1992) but not for the rest of the minerals.

Based on observations in four sections containing sphalerite (IC-logr, Premier, Snip and Eskay), large patches of sphalerite are not particularly reactive under near neutral conditions. However, the weatherability of the mineral is apparently enhanced if sphalerite contains abundant blebs of exsolved chalcopyrite (see Plate V). Galena, tetrahedrite and bournonite are mainly found in the Eskay section (Plates VI and VII). Tetrahedrite is readily tarnished during the weathering experiment while galena appears to be intact except for small grains included in pyrite. The behaviour of bournonite is not clear because it occurs only sparingly as very fine grains intermixed with tetrahedrite and galena. Pentlandite occurs only in the Pyrr section together with pyrrhotite and chalcopyrite. Under the conditions of the weathering experiment, it does not show appreciable oxidation except along structural defects (Plate XIII). Because only a limited number of electron microprobe analyses have been performed on sphalerite, galena, tetrahedrite, bournonite and pentlandite, the effect of trace element content on the weatherability of these minerals cannot be ascertained.

Oxidation of A Sulphide Mineral Assemblage

As is evident in Plates I through XIII, sulphides in geologic materials, especially ore samples, rarely occur individually but in association with each other. It has long been observed that the presence of two or more sulphides in an ore can significantly increase the rate of reactivity. Ritcey (1989), for example, in discussing acid mine drainage associated with sulphide-rich tailings, re-iterated this fact by referring to earlier work by Flann and Lukaszewski (1970) on the oxidation of pyrrhotite in ores and concentrates. When a sulphide mineral assemblage is exposed to the weathering elements, especially in the presence of a continuous film of water adhered to the minerals, preferential weathering through a galvanic process commonly occurs. Sato (1960a, 1960b and 1992) discussed the details of electrochemical oxidation of simple binary sulphides and Mehta and Murr (1983) provided observations on galvanic interaction in acid-bacterial leaching of mixed metal sulphides. In essence, when two sulphides are in contact with each other in an electrolyte solution, the oxidation of the mineral lower in the electrochemical series is accelerated whereas the sulphide higher in the electrochemical series is galvanically protected. Pyrite has been shown in many experimental studies to act cathodic to other sulphides, enhancing their oxidation (and dissolution) when mixed together (Peters, 1976).

Figure 10 (after Sato, 1992) is a graphical representation, in a Eh-pH framework, of the electrochemical series of selected sulphide minerals and hence their relative resistance to oxidation. Lines (a) and (b) in the diagram represent respectively the lower and upper stability limits of water. From an electrochemical perspective and for the seven binary sulphide minerals depicted, argentite (Ag_2S) is most resistant and pyrrhotite (FeS) least resistant to oxidation under supergene conditions. It is important to note that the order of the electrochemical series changes with pH. Thus, under acidic conditions, pyrite is cathodic to covellite (CuS) but the reverse is true under alkaline conditions. Moreover, since the electrode potential (Eh) of a sulphide mineral in an electrolyte solution varies with the chemistry of the electrolyte as well as the compositional heterogeneity of the sulphide mineral itself (Shuey, 1975), allowance must be made for possible variations in the order of the electrochemical series resulting from a higher dissolved metal activity than the 10^{-6} value used for constructing Figure 10, and also from possible deviations in the sulphide stoichiometry. The driving force for galvanic reactions between a pair of sulphides in contact with each other in an electrolyte solution is the difference in electrode potential of the two sulphides. Based on the data presented in Figure 10, one would expect the galvanic dissolution of a sulphide (other than argentite) in contact with pyrite to occur more readily under acidic conditions because of a generally larger difference in potential between the sulphide-pair than under alkaline conditions. The position of chalcopyrite, a ternary sulphide, in the electrochemical series is not well established. Data reviewed by Shuey (1975) and Karaivko et al. (1977) indicate that chalcopyrite has an electrode potential comparable to but smaller than that of pyrite. However, most of the electrode potential measurements were made without proper control or detailed determination of the electrolyte composition. Thus they cannot be directly compared with those of the binary sulphides depicted in Figure 10.

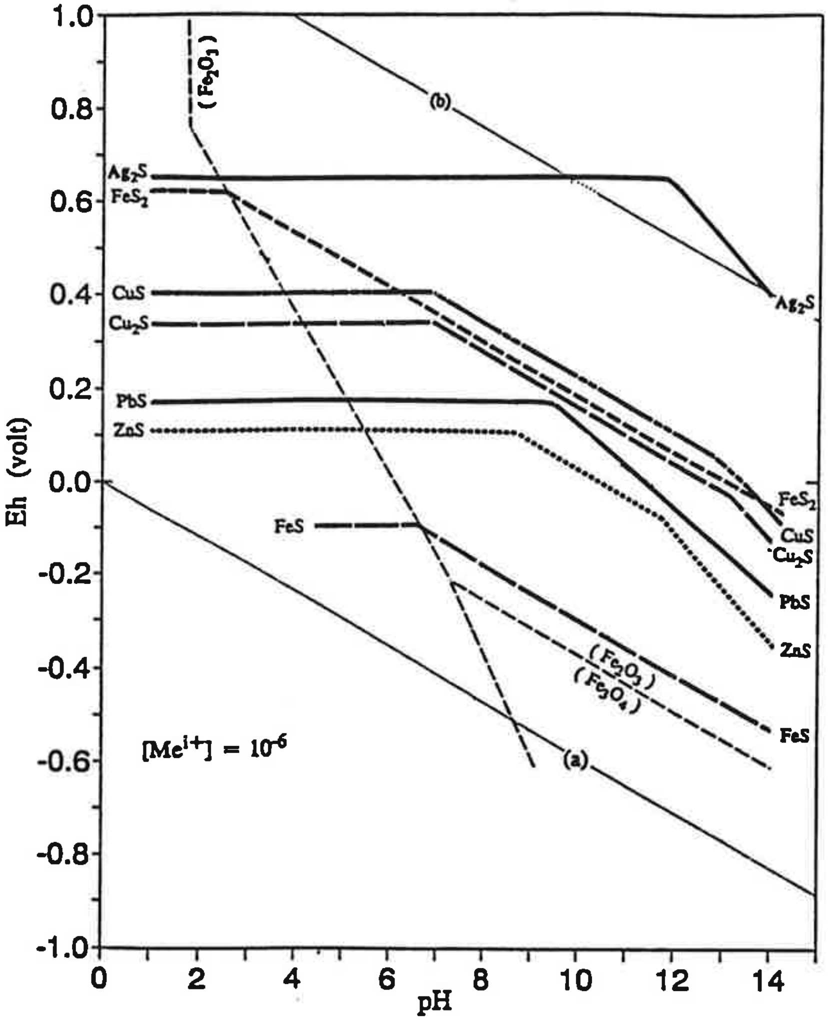


Figure 10. A graphical representation of the electrochemical series of selected binary sulphides (after Sato, 1992). The mineral with a higher electrode potential (Eh) is cathodically protected in the galvanic dissolution process involving a pair of sulphides.

In the weathering experiment, given the short duration of each wet-dry cycle and the frequency of leaching (weekly), a strong electrolyte solution is unlikely to have developed in any of the polished thin sections except perhaps in very localized areas. Galvanic reactions among contacting sulphides in the sections are therefore not likely to have proceeded to any great extent. Nonetheless, evidence of galvanic effect is observed in the weathering of some contacting pyrite-pyrrhotite grains in the Ruttan (Plate I) and WC-1 (Plate XIIc) samples. In the pyrite-pyrrhotite pair depicted by Plate I, trapping of moisture in microfractures in the highly weathered pyrrhotite grain may have enhanced its galvanic dissolution during the experiment. The formation of an alteration zone in pyrrhotite adjacent to pyrite in WC-1 may have started in the field prior to sample collection. The weathering experiment may have just accentuated the effect.

Further evidence of possible galvanic reactions occurring during the weathering experiment lies in the preferential leaching of zinc from sections, such as Ruttan and IC-Ncap, which contain only trace amounts of sphalerite. The leachates of these samples, however, contain more dissolved zinc than those of the thin sections like Eskay and Premier which have sphalerite as a major sulphide component (Table 2). Anodic dissolution of the finely disseminated sphalerite surrounded by or included in pyrite can best account for the release of zinc into solution. In addition, though the Eskay sample contains about three times as much sphalerite as the Premier sample, their leachates have about the same amount of dissolved zinc (Table 2). Galvanic reactions between sphalerite and the included chalcopyrite in the Premier section (Plate VIII) have probably enhanced the rate of sphalerite dissolution.

Whereas galvanic reactions between pyrite and chalcopyrite have been extensively exploited in the extraction of copper from chalcopyrite in many hydrometallurgical schemes (Peters, 1976; Murr, 1980) there is no evidence of such reactions occurring in the weathering experiment. In the Premier and IC sections (Plates VIII and XI), for example, pyrite appears to be more weathered than the neighbouring chalcopyrite. Since the difference in electrode potential between the sulphide-pair is small, factors like heterogeneity in pyrite composition, incipient replacement of chalcopyrite by covellite and non-attainment of acidic conditions in the electrolyte bridge can all contribute to impede the galvanic process. Similarly, the lack of anodic dissolution of galena in contact with pyrite in the Eskay section (Plates VI and VII) can be attributed to the heterogeneity of pyrite and the de-activation of the galena anode by a thin coating of highly insoluble lead sulphate (anglesite).

Oxidation of Sulphides in A Rock

Except in a massive sulphide lens, sulphides do not usually occur as rock-forming minerals. In most metal sulphide deposits, non-sulphide minerals predominate in the prevalent rock units. While, as illustrated in the previous two sections, the intrinsic properties of the sulphides (chemical composition, crystal structure, defects density and distribution, etc.), largely control their weatherability, the rate of oxidation of sulphides also varies with the ambient physio-chemical settings. Of particular importance is the presence of a fluid phase (e.g., oxygenated water) that facilitates the oxidation process by providing for a variety of reactions to occur at the fluid-mineral interface as well as serving to remove oxidation products from the interface, that may otherwise impede further reactions. The nature and extent of reactions occurring at a sulphide-solution interface is very much dependent on the composition of the solution, which in turn is influenced by the enclosing mineral assemblage (except at very high flow rates). Therefore, rock-forming minerals that occur together with a sulphide or an assemblage of sulphides also indirectly affect the rate of oxidation of the latter. To elucidate the oxidation of sulphide minerals in a rock, both the chemical and physical aspects of mineral-solution interaction have to be considered.

Chemical aspects

Since all sulphide minerals were formed in the presence of an oxygen-depleted fluid under conditions far removed from the oxygen-rich atmosphere of the earth surface (Brimhall and Crerar, 1987), they are unstable when exposed to an oxygenated environment. In the presence of a contacting fluid phase, the relative stability of sulphide minerals can generally be assessed with the aid of pH-Eh diagrams provided the persistence of metastable mineral phases, either primary or formed during oxidation, is taken into consideration (Sato, 1992). Since, under acidic conditions, most metals tend to remain in solution as dissolved ions and a variety of processes (including microbial mediation and electrochemical reactions) readily occur to accelerate the oxidation of various sulphides, the ability of the associated non-sulphide minerals to control the solution pH is perhaps the most important factor influencing the rate of oxidation of sulphides in a rock. In-situ neutralization of the acid generated during sulphide oxidation by reactions with the associated non-sulphide minerals usually lead to the formation of secondary mineral coatings on the reacting sulphides. Depending on the nature and thickness of the coatings thus formed, oxidation of the relevant sulphide(s) occurs at a reduced rate or is totally arrested.

Mineral-solution interaction involving rock-forming minerals, especially non-silicates, in a sulphide-containing rock also affect the oxidation rate of the associated sulphides by modifying the composition and ionic strength of the solution concerned. As an example, upon investigating the mechanism of pyrite oxidation in aqueous mixtures, Brown and Jurinak (1989) found that pyrite oxidation rates increased linearly with substrate concentrations of $CaCO_3$ and $NaHCO_3$ whereas solutions of Cl^- and SO_4^{2-} inhibited pyrite oxidation. Thus dissolution of halite and gypsum in a sedimentary rock containing pyrite would impede the oxidation of pyrite while the dissolution of carbonate would enhance the process. While other iron sulphides are likely to behave similarly as pyrite, the influence of different salt types and ionic strength on the rate of oxidation of other metallic sulphides is not clear.

In the weathering experiment with polished thin sections containing varied amounts and kinds of sulphide and non-sulphide minerals, a notable observation in the leachate chemistry is the excess of sulphate (expressed in terms of μg-atoms S in Table 2) relative to metals released into solution for the duration of the experiment. This reflects the retention of metals on the oxidized sulphide surfaces as secondary mineral coatings. The coating formation was probably enhanced by the absence of a highly acidic film of solution ever developed on the reacting mineral surfaces. This is evident from the fact that with the exception of the Ruttan thin section leachate, which showed a drop in pH value of 0.7 units in 20 weeks, all leachates rendered a pH values within 0.2 units of the initial values of 5.6. In other words, there is no significant net production of acid during the course of the experiment except for the Ruttan section. Buffering of solution chemistry by the associated non-sulphide gangue minerals is a major factor in maintaining the near-neutral pH of the leachates for many of the samples tested.

Physical aspects

The extent that a mineral assemblage can affect the chemistry of an associated liquid phase (solution) is largely determined by the duration of contact between the reacting minerals and the solution. The longer the contact time, the more closely the solution chemistry will be governed by the relevant mineral-solution equilibria. Since the rate of heterogeneous reactions involving a gas-solid or solid-solid couple at ambient temperatures without the intervention of a liquid phase is extremely slow, the most intensive sulphide weathering occurs under conditions transitional from unsaturated to saturated. This is reflected in the field by the supergene mineralization process occurring in response to a fluctuating water table in sulphide-rich terrains. Above the saturated zone, rapid sulphide oxidation depends on the trapping of sufficient moisture to facilitate and maintain the oxidation process. Temporary depletion of moisture will lead to the formation of efflorescent minerals and arrest the sulphide oxidation. Data obtained in a long-term leaching experiment using columns containing rock chips with 2.2 wt.% S and an NP (neutralization potential) to AP (acid generation potential) ratio of 2:1 indicate that whereas a longer antecedent drying period led to the release of a larger amount of oxidation products in a flushing event, the overall sulphide oxidation rate increased with more frequent flushing (Kwong, unpublished data). In other words, the build-up of protective coatings on the reacting sulphides varies directly with the total length of antecedent drying periods, given the same total amount of water passed through each column.

In the weathering experiment employing polished thin sections, the smooth mineral surfaces cannot retain any moisture during the drying cycles except possibly a very small amount held by capillary action in micro-fractures. The formation of coatings on the oxidizing sulphides is therefore expected. This is evident on some pyrite grain surfaces (e.g., see Plate I). The lack of dissolved Pb detected in the leachates (thus not shown in Table 2) also suggest possible coating of galena with thin films of highly insoluble anglesite. Moreover, the relative low dissolved Cu content of the leachates except that for Ruttan and the observed increase in Cu/Fe ratio in weathered chalcopyrite suggest that the formation a secondary copper sulphide mineral as an incipient oxidation product is more favourable than the dissolution of chalcopyrite under the conditions of the experiment. Extending these results to the field, it is clear that in assessing sulphide weatherability in a rock and potential metal leaching, the local hydrological conditions must be considered in detail. Moreover, except in rare occasions with massive sulphide orebodies, sulphide oxidation in a gigantic galvanic corrosion cell as proposed by Thornber (1975) is difficult to realize, especially under conditions such that insulating coatings readily form on the reacting sulphides.

CHAPTER 4

ASSESSMENT OF ARD POTENTIAL DURING MINERAL EXPLORATION

Role of A Geologist in Assessing ARD Potential

Inasmuch as acid rock drainage is a product of natural interaction between water and sulphide-containing rocks, detailed information on the local geology and mineralogy is essential in assessing the ARD potential of a mineral prospect. As is evident from previous chapters addressing the susceptibility of mineral deposits to ARD problems and weatherability of common sulphides, ARD prediction does not have to totally rely on chemical analyses. Field identification of the prevalent sulphide mineral assemblage(s) together with an estimate of their abundance sheds light on the potential acid production while the recognition of alteration mineral assemblages allows a rough estimate of buffering potential of the associated gangue minerals. During the exploration and feasibility study phases of a mine development project, detailed geological and mineralogical information is inevitably collected by the field geologists. Moreover, special field conditions that facilitate sulphide oxidation will be most readily observed by the person walking the ground. Consequently, though it is not traditionally the role of a geologist to tackle environmental issues, a geologist is in fact best equipped to conduct an early ARD assessment of a property. Provided additional environmental observations and measurements are taken, a geologist can also assess the ARD potential of various rock units on a regional scale. Thus, a field geologist has a significant role to play in pre-mine ARD prediction. The tasks to be accomplished, however, varies slightly with the progress of a mineral exploration/development program. These are briefly described as follows:

Reconnaissance mapping phase

At this stage, the main concern of a geologist in ARD prediction is to identify and delineate rock units with differing acid-generating or acid-neutralizing potentials. This can be achieved by examining the mineralogical content of the prevalent rock types, their competency as well as the nature and extent of weathering. In highly altered outcrops, the identity of secondary minerals, if present, should be ascertained. Where natural acid rock drainage occurs, the possible source should be investigated. Generally, pH, Eh and conductivity measurements along a drainage system, however small, coupled with observations of biofilm formation and deposition of oxidation products like ferric hydroxide will aid locating the source of acid generation. To characterize the existing environment, causal notes on topography and landscape, soils and erosion, flora and fauna, hydrology (catchments, streams and other water bodies) as well as local and regional climatic meteorology should also be taken.

Advanced exploration phase

At this stage, a highly mineralized area is targeted for detailed investigation. Extensive drilling and trenching may have been in progress and exploration adits may have also been constructed. With more material to work with, a field geologist can readily acquire valuable information on the nature and rate of oxidation of the subsurface materials. Detailed core logging will reveal the mineralogical content, porosity and/or permeability as well as the structural integrity of relevant lithologies. These data are essential in assessing the acid-generating/neutralizing potential of the various lithologies encountered. A thorough petrographic analysis of representative core samples will render the identity and texture of the sulphides as well as their mutual relationships with the gangue minerals. Periodic examination of rocks exposed in the trenches and adits will shed light on the relative oxidation rate of the component minerals. Likewise, periodic re-examination of drill cores rich in sulphide may reveal the formation of secondary minerals on or incipient alteration of fast reacting sulphides. For example, in the Clear Lake property, Yukon, which hosts SEDEX mineralization, incompletely recrystallized framboidal pyrite in some cores readily alters to melanterite after being exposed to the atmosphere for less than a year. Routine monitoring of water quality (pH, Eh, conductivity, etc) of discharge from exploration adits will also shed light on the chemical effects of introducing atmospheric oxygen to the previously enclosed flow system.

At this advanced exploration stage, a small number of chemical and instrumental analyses should also be conducted to confirm preliminary ARD assessments based on visual estimate of mineral abundances, textures and other pertinent parameters. In addition to continuous monitoring of pH, Eh and conductivity, water samples of adit discharge and major drainage through the property should be collected and analyzed for selected metals, sulphate, alkalinity and acidity. Prevalent sulphides should be analyzed for trace element contents. Selected rock types may be sampled for acid-base-accounting analysis. A small environmental monitoring program should also be developed to gather baseline data on water quality, aquatic biology and fauna occurrences. Moreover, in view of the strong influence of climate (which relates to rainfall, infiltration rates, the nature of runoff, temperature, and biota which catalyze sulphide oxidation) on the weathering of geologic material, a weather station should be set up early in this stage to gather local climatic data.

Feasibility study phase

At this stage, the presence of a significant ore reserve is confirmed. To aid preparing a comprehensive environmental impact statement for permitting purpose, various detailed monitoring programs and specific studies are usually developed and conducted in consultation with in-house or contracted experts. A field geologist should be actively involved in the environmental assessment process. To aid thorough ARD assessment, preliminary data collected in the early exploration phases together with any new information obtained in the detailed delineation of orebodies and various alteration zones should be communicated to relevant parties involved. In this regard, the usage of vaguely defined field terms should be avoided. Moreover, based on estimates of ARD potential of regional rock units and observations on the extent of soil profile development, a geologist should be able to make recommendations as to which occurring lithologies is best suited to host waste disposal facilities (like tailings pond and waste rock dump) so as to minimize the impact of ARD, if the mine waste is expected to be acid-generating.

A Practical Checklist for Assessing ARD Potential During Mineral Exploration

Taking into consideration various physical, chemical and biological processes that may affect the oxidation of sulphides, preliminary field assessment of ARD potential of geologic materials would benefit from field measurements and observations itemized in Table 4.

Table 4. Recommended field measurements/observations for assessing ARD potential

Object	Measurements/Observations
A. Rock	Lithology and moisture content (qualitative) Mineralogy and texture Nature and extent of weathering Fracture/joint density; foliation geometry
B. Weathering Products (gossans and soils)	Mineralogy and texture Colour and moisture Profile development Paste pH Vegetation, if any
C. Water bodies	pH, Eh and conductivity Acidity, alkalinity and sulphate, if possible Presence of secondary precipitates Evidence of microbial activity (e.g. biofilm)
D. Others	Hydrometeorology (climate) Landscape Vegetation

The recommended measurements and observations made on rock material allow estimates to be made on potential maximum acid production, buffering capacity and proportion of embedded sulphides readily susceptible to oxidation. Detailed examination of weathering products, on the other hand, sheds light on the relative reactivity and weathering rate of the prevalent primary sulphides (if they can be inferred or still occur at depth). Traditionally gossan analysis is performed to aid mineral exploration, especially in search of enriched supergene mineralization. However, the type of secondary minerals formed and their texture reflect well the pH-Eh regime under which the alteration was effected (Blain and Andrew, 1977; Andrew, 1980; Alpers and Brimhall, 1989). They can thus be extended to infer ARD potential. In-situ paste pH measurements on fine-grained material indicate whether the material contains readily available acidity or alkalinity. They are useful indicators of transient conditions associated with progressive chemical weathering. To be proficient in interpreting the varied phenomena associated with sulphide oxidation, a thorough understanding of the principles of mineral-solution equilibria (Garrels and Christ, 1965) and persistency of metastable minerals (Sato, 1992) is particularly important.

Measurements and observations recommended to be made on the water bodies (seeps, streams, ponds, lakes, etc.) in the area under exploration render information on the nature and extent of water-rock interaction occurring in the area. The occurrence of natural acid rock drainage with $pH < 4$ is indicative of fast reacting sulphides in the vicinity; the presence of biofilm in the drainage system would suggest that relevant reactions are microbially mediated. Water with mildly acidic pH (about 5) and low conductivity is probably enriched in organic acid; the acidity is not a result of sulphide oxidation. This can readily be confirmed by an analysis for dissolved sulphate.

Other recommended measurements and observations included in category D of Table 4 indicate whether the ambient environment favours deep weathering. They also have a significant effect on the transport and attenuation of products of ARD, particularly the leached metals. Furthermore, climate controls the rate of weathering of most geologic materials (Ollier, 1984), including the sulphide minerals. Consequently, for comprehensive ARD assessment, these measurements/observation cannot be ignored.

Concluding Remarks

In conclusion, inasmuch as ARD is a product of natural water-rock interaction, its prediction and prevention at a prospective mine site can benefit from a geologist's knowledge on the mineral distribution, spatial change in lithology and structural geology of the site. The involvement of a geologist in ARD assessment in every stage of a mining project may lead to a significant reduction in the cost of tackling the serious environmental problem and is thus highly recommended. However, to make field observations, especially those on mineral abundances, more useful for the purpose of ARD assessment, a geologist must strive to use precise descriptive terminology rather than vaguely defined field terms.

CHAPTER 5

DISCUSSION

ARD Prediction from A Geological And Mineralogical Perspective

Applicability and limitations

From the close relationship detected between ore deposit types and the occurrence of ARD and the detailed exposition of major factors controlling the ARD susceptibility (Chapter 2), it is evident that local geology can be utilized to predict ARD. The accuracy of the prediction depends largely on a correct identification and an accurate estimate of the abundances of both sulphide and the associated gangue minerals occurring in the prevalent rock units. Since in every stage of a mine development project, from exploration to production, detailed geological and mineralogical data are collected by the geologists, the participation of a geologist is indispensable in ARD prediction using a geological and mineralogical approach. In this regard, in describing alteration associated with mineralization, a geologist must record actual mineral proportions instead of using vaguely defined field terms.

Given the many variables that can affect the rate of oxidation of sulphide minerals (Chapter 3) and the general lack of quantitative data on the variation of the rate of weathering of both sulphide and non-sulphide minerals with pH, the proposed net acid production index (Chapter 2) is, at best, a rough indicator of the acid-generating/acid-neutralizing potential of the geologic material under examination. The parameter can be validated by firmly establishing its correlation with the predictions of the more commonly used static and kinetic tests. Before this is carried out, ARD prediction based on mineral abundances remains a rather subjective test the results of which are unlikely to be accepted by regulatory agencies. However, it is a useful and inexpensive test to conduct in the field for assessing the ARD potential of any geologic material. If applied from the earliest stage of exploration, it readily differentiates environmentally unmineable deposits from more favourable targets. This information will greatly facilitate decision-making as to where valuable resources should be allocated so that a workable mining project can be developed.

Inter-dependence of sulphide oxidation, acid generation and release of metal contaminants

In addition to acidity, the usually high dissolved metal content of ARD water is the main cause of detrimental environmental effects. Since all sulphides are thermodynamically unstable under oxygenated conditions, given sufficient time, they will be completely oxidized to form stable secondary minerals or dissolved ions as dictated by the prevalent environment. According to the modified Thornber formula (Chapter 2), the oxidative dissolution of non-iron containing sulphides with a metal/sulphur ratio greater than or equal to 1:1 (e.g., ZnS, PbS, Cu_2S, etc.) does not generate acid. However, heavy metals are released in the process. The rate of release of these metals will determine whether or not a contamination problem will occur. Since the oxidative dissolution of these sulphides can often be enhanced if galvanically coupled with pyrite, further research is warranted to determine the rate of metal release from a mixed sulphide assemblage as a result of the electrochemical process. Data collected under near neutral conditions are particularly lacking but are very useful because they facilitate the prediction of potential metal contamination even if ARD does not develop in the short-term. They will also allow an estimate of the time required to deplete the non-acid-generating sulphides before the oxidation of the acid-generating sulphides will commence. In other words, the time-lag in the occurrence of ARD associated with mixed sulphide assemblages cannot be accurately determined without such data.

In the oxidative dissolution of a sulphide mineral with a metal/sulphur atomic ratio less than 1:1 or with a high iron content (e.g. MoS_2, FeS_2, FeS, etc.), acid is generated. In addition to the release of component and included metals during the oxidative sulphide dissolution, the acid generated is capable of leaching more trace metals from the adjacent minerals, silicates included, which will otherwise remain intact under less corrosive conditions. Moreover, the development of an acidic micro-environment encourages the growth of various bacteria capable of enhancing the rate of sulphide oxidation through a combination of biogeochemical and geochemical processes. As a result, more acid is generated and more metals are released to the aqueous phase, giving rise to a classical ARD situation. To predict when this situation will occur and to devise effective schemes to prevent its occurrence, a thorough understanding of the inter-relationship of inorganic reactions, microbial mediation and electrochemical processes is required. However, research in this area is generally lacking.

Based on the results of the weathering experiment conducted during the course of this study (Chapter 3), the detailed composition of the sulphide minerals, especially their trace element content, greatly affects their weatherability. Thus, the amount of sulphate released in the experiment does not necessarily correlate with the sulphide abundance in each polished section (Table 2). Heterogeneity in the oxidizing sulphide also affects its electrochemical potential (Shuey, 1975). Furthermore, depending on the nature of the secondary minerals (and amorphous coatings) formed during the weathering process, several new electrochemical series may be established among the reacting minerals and operate for a while prior to the complete oxidation of the original sulphides. Research on microbial leaching of metal sulphides under acidic conditions (e.g., Mehta and Murr, 1983) suggested a close relationship between galvanic reactions and bacterial mediation in the oxidative dissolution of sulphide minerals. Lawrence et al. (in preparation) also presented evidence of selective colonization of sulphides by acidophilic bacteria according to the electrochemical series. Detailed mineralogical controls of the selective bacterial colonization and the associated sulphide solubilization processes are yet to be investigated. Parallel chemical and microbial weathering experiments using duplicate rock slabs or polished thin sections are promising in clarifying the inter-relationship of chemical, microbial and electrochemical processes involved in sulphide oxidation. Valuable data may also be obtained from such experiments for modelling water quality in drainage systems affected by sulphide oxidation.

Relevance of Local Mineralogy and Geology to ARD Prevention and Abatement

In addition to potential applications in ARD prediction, local mineralogy and geology are important parameters to consider in ARD prevention and abatement. It suffices here to briefly describe and discuss the ARD situation in the Macmillan Pass area, Yukon, and at Mount Washington, British Columbia, to illustrate the relevant issues involved.

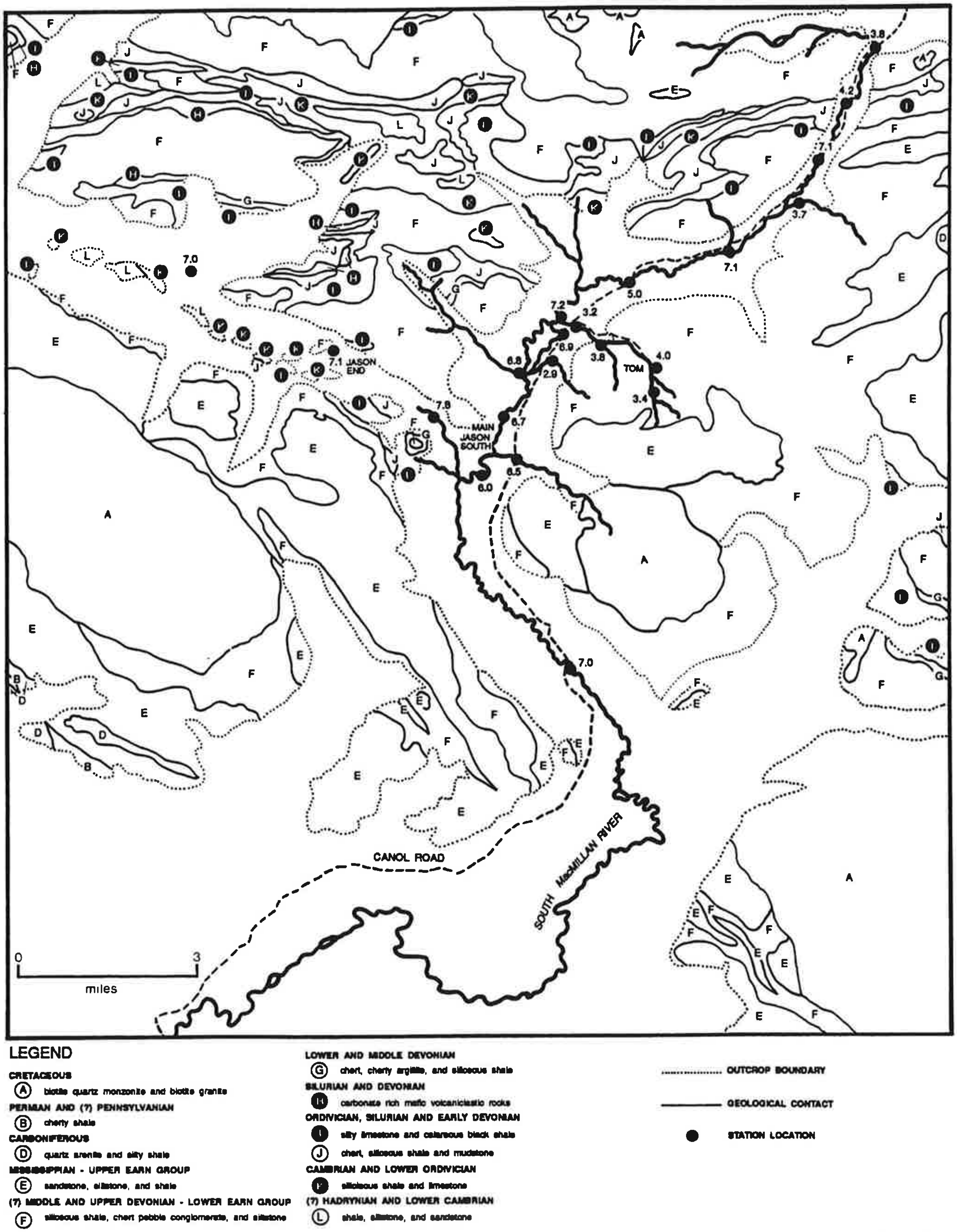


Figure 11. Correlation of water chemistry with geology in the Macmillan Pass area as evidenced by pH distribution.

Natural ARD in the Macmillan Pass area, Yukon

In the Macmillan Pass areas located in east-central Yukon near the border with the Northwest Territories, black clastic rocks of Devonian-Mississippian age host many significant concentrations of lead-zinc mineralization. Two relatively well defined deposits are the Tom Property (Goodfellow and Rhodes, 1990) and the Jason Claims (Turner, 1990). As evidenced by the widespread occurrence of naturally acidic streams, the area has a very high ARD potential (Kwong and Whitley, 1992). Upon close examination, however, it is apparent that the water chemistry of small drainage systems in the area is largely controlled by the local geology. Thus, acidic streams with elevated metal contents are mostly associated with sulphide-bearing, siliceous sediments of the Middle to Upper Devonian Lower Earn Group (Figure 11; geology after Abbot, 1983). The sediments vary from black shale to siltstone to chert pebble conglomerate; the pyrite content ranges from 2 to 8 per cent. Pyrite in the highly fissile shale units is especially susceptible to alteration. Mechanical weathering resulting from the freeze-thaw process provides new access for water and air and replenishes new mineral surfaces for chemical weathering. Once acid is generated through pyrite oxidation, there are few minerals in the siliceous matrix to effect neutralization. In contrast, on the west side of the south Macmillan River, calcareous units are rather widespread (e.g., rock units H, I and J in Figure 11). Although sulphide oxidation still occurs, any acid generated is neutralized in-situ and metal leaching is prevented from occurring.

The sizes and distribution of known concentrations of mineralization delineated to date in the Macmillan Pass area suggest that simultaneous mining of all mineralized zones located on both sides of the South Macmillan River may be the only economically viable option in exploiting the mineral reserve. Given the situation, to limit the potential occurrence of ARD or to reduce its impact, it is advisable to locate milling and major waste disposal facilities on the west side of the River to take advantage of the buffering capacity of the many prevalent rock types. Mining strategies involving the production of the least amount of waste rock and minimum disturbance to the existing landscape should be adopted in preference to those involving major treatment and reclamation schemes. Moreover, to keep abreast of the ARD situation, detailed delineation of the distribution of acid-generating and acid-neutralizing rocks and close monitoring should be incorporated at every stage of any prospective mining schemes. Provided potential ARD problems are recognized by the mine operator and provided appropriate precautionary actions are taken and treatment facilities emplaced to tackle the problems during active mining and after mine closure, exploitation of mineral resource can still be conducted in an environmentally acceptable manner. The mining of the Red Dog deposit in Alaska is a good example in this regard. However, the cost of environmental protection must be considered in determining the viability of a mining project in such an ARD-sensitive area.

ARD Abatement at The Abandoned Mount Washington Mine, British Columbia

The abandoned copper mine is located on the north slope of Mount Washington near Courtenay on Vancouver Island. The mine site consists of two remnant north-south oriented open pits, each with associated with waste rock dumps. Only the North Pit and the associated waste rock give rise to ARD enriched in copper. Relative to the South Pit, the North Pit contains more sulphide mineralization, more pervasively silicified host rocks and fewer late carbonate veins/veinlets. The sulphide mineralization is mainly fracture-controlled and is thus more readily exposed to weathering. Besides chalcopyrite, pyrite and arsenopyrite, sulphides identified in the North Pit include highly reactive pyrrhotite and marcasite which are very rare, if not absent, in the South Pit. The silica alteration affecting the host rocks has effectively nullified the acid buffering capacity of the primary minerals.

Interpreting the surface- and ground-water chemistries in conjunction with detailed mineralogical analysis of rock samples from the North Pit, it becomes clear that acid generation at the site is dominated by three processes: 1) Step-wise oxidation of pyrrhotite leading to the formation of a variety of intermediate alteration products including elemental sulphur and efflorescent iron sulphate minerals; 2) Flushing of concentrated films of water adhered to uneven rock surfaces and dissolution of efflorescent minerals with subsequent oxidation and hydrolysis reactions to sustain the acidity detected during spring freshet and heavy fall rains; and, 3) Year-round discharge of groundwater enriched in ferrous iron to a major rock dump where coupled oxidation and hydrolysis generate acidity in-situ (Kwong and Ferguson, 1990; Kwong, 1991).

The reclamation of the North Pit was started in 1988 (Galbraith, 1991). In the absence of detailed information on the local geology and mineralogy, the adopted abatement strategy focused on reducing the availability of water and oxygen to identified and suspected acid-generating materials occurring at the site. These include waste rock in a major dump adjacent to the shallow open pit and others scattered in the pit. Thus, the rehabilitation of the site commenced with collecting loose waste rock from the pit area, mixing-in with crushed limestone and spreading over the problematic waste dump, which was then recontoured and covered with compacted glacial till to a thickness of 1m. At the same time, a branched diversion ditch was constructed in the in the pit area to reduce water infiltration into the waste dump. Moreover, a portion of the open pit was later excavated to bedrock level so as to reduce the total reacting surface area. The waste gathered in the process was encapsulated with a variety of materials. However, it was soon discovered that the highly fractured bedrock in the open pit has a higher sulphur content than waste rock in the major dump (Kwong, 1991). Intense disturbance of the pit area associated with the abatement activities could have further opened up the shallow fracture system and exposed more fresh sulphides to oxidation. This could be a major reason why no significant reduction in ARD has effected at the site to date.

Both the mill site and the tailings pond are located farther downslope from the open pits and do not show any significant ARD problems. These facilities are underlain by brecciated metabasalt which provides an effective sink for moderate amount of acid generated. Consequently, ARD is less likely to develop.

The Mount Washington experience clearly demonstrates the need of a multi-disciplinary approach to abate ARD and related problems. A knowledge of the local geology and mineralogy should form the basis of any ARD control measures. For successful reclamation of old, abandoned mine sites, such information must be acquired and thoroughly reviewed before appropriate abatement schemes are executed.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

SYNOPSIS

In recapitulation, this research project on prediction and prevention of acid rock drainage from a geological and mineralogical prospective addresses three issues, namely,

- 1. Susceptibility of ore deposit types to ARD problems,
- 2. Weatherability of common sulphide minerals,
- 3. Role of a geologist in ARD assessment.

The major findings are a follows:

On the relationship of ore deposit types and ARD occurrences:- Seven common mineral deposits occurring in western Canada are ranked according to their ARD potential (Table 5) . The susceptibility of a deposit to develop ARD problems is largely determined by the net acid-generating potential of the prevalent mineral assemblages, accessibility of the reacting minerals to the weathering agents and potential mediation by iron-oxidizing bacteria. Generally, alteration mineral assemblages about an orebody reflect well the ARD potential of the relevant rock types. As exemplified by alteration zones about porphyry deposits and the differences in style and extent of alteration about epithermal and meothermal gold deposits, alteration mineral assembalges formed near the earth surface with the involvement of a large amount of meteoric water in the hydrothermal alteration process invariably lack acid buffering capacity. Therefore,

Table 5. Ranking of common ore deposit types in Western Canada according to ARD potential

Mineral Deposit Type	Examples	ARD Susceptibity
1. Sedimentary massive sulphides (SEDEX)	Sullivan, Tom (Yukon)	most prone
2. Volcanogenic massive sulphides (VMS)		
a) Kuroko-type	Westmin, Britannia	
b) Besshi-type	Windy Craggy, Ruttan	
c) Cyprus-type	Chu Chua, Anyox	
3. Calc-alkaline suite porphyry deposits	Gibraltar, Island Copper	
4. Epithermal Au-Ag deposits	Cinnola, Premier Gold	
5. Mesothermal vein Au deposits	Snip, Frasergold	
6. Alkaline suite porphyry deposits	Afton, CopperMountain	
7. Skarns	Craigmont, Nickel Plate	least prone

deeper-seated mineralization generally are less prone to ARD problems relative to their near-surface counter-parts. A conveninet way to assess ARD potential of geologic material in the field is to determine the relative abundance of acid-generating and acid-consuming minerals. A formulae of acid-base accounting based on mineral constituents (Equation 6, Chapter 2) is suggested.

On the weatherability of common sulphide minerals:- An exploratory, kinetic-type weathering simulation experiment using polished thin sections as test material has been conducted. Observations made in detailed examination of the prevalent sulphides on the sections with petrographic and scanning electron microscopes, augmented by results of electron microprobe analysis and those obtained in the determination of leachate chemistry by induction coupled plasma mass spectrometry (ICPMS), indicate the importance of trace element composition in affecting the rate of oxidation of common sulphides such as pyrite and pyrrhotite. Where different sulphides are in contact with each other, electrochemical processes are likely to be operative, further complicating the relative reactivity of the sulphides. Since the order of sulphides in an electrochemical series is pH-dependent and since the electrode potential of a sulphide mineral in an electrolyte solution varies with the solution chemistry, a general weathering sequence for the common sulphides may not exist except at a local scale. To predict the rate of acid generation and metal release associated with sulphide oxidation, further work to clarify the inter-dependence of geochemical reactions, microbial mediation and electrochemical processes involved is required.

On the role of a geologist in ARD assessment:- Well-trained to collect and interpret mineralogical and geological data, a field geologist can readily assess the ARD potential of geologic materials based on field observations. A practical checklist for field assessment of ARD potential during mineral exploration is suggested (Table 4, Chapter 4) and the tasks of a geologist in ARD assessment at various phases of a pre-mine development project are briefly described. Furthermore, inasmuch as ARD is a product of natural water-rock interaction, its prevention and, to some extent, its control rely on a thorough understanding of the local geology and mineralogy. The Mount Washington experience (Chapter 5) demonstrates the essential need to incorporate information on local geology and mineralogy into a remediation scheme; the natural acid rock drainage investigation at Macmillan Pass illustrates the relationship between geology and water chemistry. The involvement of a geologist in ARD assessment in every stage of mining project may lead to a more efficient approach to ARD prediction and prevention and thus results in a significant reduction in the cost of tackling this serious environmental problem.

RECOMMENDATIONS

Based on the findings of the current project, a few recommendations on further research and practical aspects of ARD assessment and prevention at a mine site can be made. These are outlined as follows:

From a research perspective:- To improve the accuracy of ARD prediction based on geology and mineralogy, more work is required in the following areas:

1. Confirmation and quantification of trace element control on the relative reactivity of sulphides.
2. More accurate determination of the acid buffering capacities of non-carbonate minerals.
3. Clarification of the interplay of geochemical, electrochemical and microbial mediation processes in the oxidation of sulphides.

4. Validation of field ARD assessment according to mineral abundances with established laboratory assessment techniques.
5. Detailed investigation of the influence of climate on acid generation and metal leaching, which has not been fully addressed in this project.

From a practical viewpoint:- To efficently tackle ARD-related problems requires a multi-disciplinary effort. Field ARD assessment based on geology and mineralogy is a cost-effective tools and easy to apply. To fully reap the profit of the methodology, the following are recommended:

1. Geologists should be involved in ARD assessent in every stage of a mining project.
2. The importance of ARD prevention should be conveyed to miners, who should also receive some basic training in field assessment techniques from the geologists.
3. Close co-ordination among various departments at a mine site to address environmental issues is perhaps more preferrable than assigning the sole responsiblity to one particular department.

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