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REVIEW OF MEND STUDIES ON THE SUBAQUEOUS DISPOSAL OF TAILINGS (1993-95)

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EXECUTIVE SUMMARY

A previous review of MEND studies on subaqueous disposal of tailings presented several recommendations (RAAS 1992). Proposed work in Anderson and Buttle lakes included a mass balance of selected chemicals, measurements of geochemical fluxes across the sediment interface and the application of comprehensive QA/QC procedures to ensure reliable data. A literature study of biological effects of metals was also proposed. This report reviews progress since 1992.

The literature study on biological effects demonstrated that sorption reactions on Fe, Mn oxyhydroxides and organic matter, and reactions with acid volatile sulphides allow reasonable prediction of geochemical behaviours under oxic and anoxic conditions. Biological availability of dissolved metals is reasonably well described by the free ion activity model.

Attempts to combine field data and historical records (water quality/quantity and effluent loadings) provided valuable background information but were not sufficient to detail the effects of sulphide-rich tailings on either lake, or to support an acid-base mass balance for Anderson Lake.

QA/QC protocols provided much high quality data about the diffusive flux at the sediment/water interface in both lakes. Weight of evidence indicates there can be a small loss of metals (mostly Zn) from sediment to the overlying water, and some recycling (including metals) is probably related to the natural degradation of organic matter. Tailings exposed to subaqueous oxidation react very slowly but actual rates in the lake environment are uncertain.

The diffusive flux is one of several factors that control the effect of tailings in subaqueous environments and in man-made containments it may be the dominant factor. Man-made containments and lakes with naturally anoxic bottom water are likely to be most suitable for subaqueous tailings disposal.

It is concluded that a comprehensive assessment of the advantages and disadvantages of subaqueous and subaerial disposal would be useful. A model study (with examples) could address costs, risks and potential benefits, and focus on long term stability. The need for a better understanding of the "cradle to grave" effects of tailings remains but study costs are high. New studies on such effects in complex natural environments may be non-generic and made only on a case-specific basis.

RÉSUMÉ

Un examen antérieur des études portant sur la déposition subaquatique des résidus réalisées dans le cadre du programme NEDEM a donné lieu à plusieurs recommandations (RAAS 1992). Les travaux proposés dans le cas des lacs Anderson et Buttle comprenaient le bilan massique de substances chimiques sélectionnées, la mesure des flux géochimiques à l'interface des sédiments et l'application de procédures QA/QC précises afin d'assurer la fiabilité des données. Une étude bibliographique des effets biologiques des métaux a également été proposée. Ce rapport fait état des progrès réalisés depuis 1992.

Une analyse bibliographique des effets biologiques a démontré que les réactions de sorption sur les oxyhydroxides Fe, Mn et la matière organique et les réactions avec les sulfures acides volatiles permettent de prévoir assez exactement les comportements géochimiques dans des conditions oxiques et anoxiques. La disponibilité biologique des métaux dissous est raisonnablement bien illustrée par le modèle d'activité à ion libre.

Les tentatives pour intégrer les données de terrain et le dossier historique (qualité de l'eau et apports des effluents) ont fourni des renseignements généraux précieux mais n'ont pas permis d'obtenir de détails sur les incidences des résidus riches en sulfures sur aucun des deux lacs ou à étayer le bilan massique acide-base pour le Lac Anderson.

Les protocoles QA/QC ont fourni des données de grande qualité sur le flux de diffusion à l'interface sédiment/eau des deux lacs. L'ensemble de la preuve démontre que les sédiments peuvent subir une légère perte de métaux (en grande partie du Zn) dans l'eau qui les recouvre et une certaine partie du recyclage (y compris les métaux) est probablement liée à la dégradation naturelle de la matière organique. Les résidus exposés à l'oxydation subaqueuse réagissent très lentement mais les vitesses actuelles de réaction dans le milieu lacustre sont encore incertaines.

Le flux de diffusion est un des facteurs parmi plusieurs autres qui contrôle les incidences des résidus dans le milieu subaqueux et peut constituer l'élément principal dans les lacs artificiels. Les lacs artificiels et les lacs dont l'eau de fond est naturellement anoxique sont susceptibles de se prêter davantage à la déposition subaquatique des résidus.

Par conséquent on peut conclure qu'une évaluation globale des avantages et inconvénients de la déposition subaquatique et de la déposition traditionnelle serait utile. Une étude modèle (comportant des exemples) pourrait porter sur les coûts, les risques et les avantages potentiels et être axée sur la stabilité à long terme. La nécessité de mieux comprendre les incidences «berceau au tombeau» des résidus est indéniable mais une telle étude comporte des coûts élevés. De nouvelles études de ces incidences dans des milieux naturels complexes pourraient être spécifiques et réalisées d'après les conditions particulières à chaque cas.

1. INTRODUCTION

1.1 General background

Studies under the MEND program on subaqueous disposal of tailings began in 1988, and a number of detailed reports have been completed on specific parts of the project. Two overviews have now been prepared, the first report (Phase 1) by the Rawson Academy of Aquatic Science (RAAS 1992) covered the period up to 1992. It confirmed that subaqueous disposal of tailings represented an important option for mining wastes, particularly where the potential for acid-generation is high. The second and present report (Phase 2) provides a further overview and considers, in particular, MEND studies carried out on the subaqueous disposal of tailings from 1992 to the present.

In the first overview (RAAS 1992), it was noted that:

.... *while it is appropriate to suggest geochemical evidence supports the view that subaqueous disposal of tailings results in a substantially less reactive environment than terrestrial disposal, the nature and extent of biological response in the aquatic environment is (at best) unclear. It is probable that severe physico-chemical effects occur during subaqueous disposal of tailings and although amelioration and subsequent remediation may be possible, the effectiveness of many measures is not yet predictable, with reasonable certainty.*

There is no question, on a case-by-case basis, that it will be necessary to establish the biological response to tailings disposal and, perhaps, the significance of physical processes at the sediment/water interface, and these requirements are fully recognized by MEND. The site-specific needs were, however, beyond the scope of subsequent MEND studies (1992-95) that were specifically directed to strengthen the understanding of "generic" geochemical processes which control release of metals from subaqueous tailings.

The Rawson Academy report (RAAS 1992) noted that the then current levels of scientific understanding and case history data were not sufficient to encourage industry to seek approval for subaqueous disposal as a preferred option. The 1992-95 studies were undertaken to provide a more substantial base on which to consider the appropriateness of subaqueous disposal of tailings.

The Rawson Academy report also noted:

.... *Although more detailed studies would be useful, from the perspective of* *science there is little to be gained from a wider (geographic) spread of the case-study lakes.*

As a result of this recommendation, the subsequent field studies focused on Anderson and Buttle lakes where it was felt that further field research would provide the maximum return for the funds available and where, already, there were substantial background data to be built upon.

1.2 Content of the report

Summaries of the recommendations made in the Rawson Academy report (RAAS 1992) and the project activities from 1992 are provided in Appendix 1. In relation to these, the present report generally addresses three main points of interest:

How well have the MEND studies on Anderson and Buttle lakes met the relevant recommendations and suggestions of the 1992 report by the Rawson Academy (RAAS 1992)?

What new understandings have been gained from the 1993-1995 studies?

What additional geochemical and related studies may be needed to provide the levels of certainty and credibility for advancing the subaqueous disposal of tailings as an effective and environmentally acceptable technology?

These points form a recurring theme within this report and provide the basis for its conclusions.

The present report looks at the appropriateness of subaqueous disposal of tailings, based on the results of the Anderson and Buttle lake field studies (1993-1995), and assessments of historical data and available scientific literature. Some difficulties remain in the ability to use part of the study data collected from the two lakes but there now seems little doubt that subaqueous disposal offers a viable means of long term disposal, at least for the metals associated with these tailings.

The findings are presented in three sections. Section 2 addresses the present understanding of geochemical processes which can be applied widely to different types of aquatic environments (based largely on literature reviews). Section 3 provides a summary of the understandings gained from the 1993-5 and earlier studies on Anderson and Buttle lakes, the most likely interpretations to be placed on various data sets from these two lakes, and their importance as a basis for the application of subaqueous disposal. Section 4 considers the implications arising from the studies in relation to potential options of disposal in headwater lakes, artificial structures (e.g. man-made ponds/lakes), and other forms of natural lakes.

1.3 Overview process

Following the process adopted during the Phase 1 overview by the Rawson Academy of Aquatic Science (RAAS 1992), copies of all reports, data evaluations, and advisory comments associated with the MEND project on subaqueous disposal were made available to a scientific review team (SRT). Review comments were prepared individually and later shared among the SRT members. Their comments form the basis of this Phase 2 report. Appendix 2 lists the members of the SRT, most of whom were also members of the first review by the Rawson Academy. Appendix 3 lists the documents provided to each of the members of the SRT, and a shared list of questions provided guidance and a common focus for SRT member response (Appendix 4). Subsequently, two short reports were prepared by Dr. T. Pedersen and J. McNee (documents # 19 and 20, Appendix 3). These reports addressed new data and also provided follow-up to questions raised by the SRT during the 1995 review. This additional information has been incorporated into the findings and conclusions.

2. PRESENT UNDERSTANDING OF GEOCHEMICAL EFFECTS ASSOCIATED WITH SUBAQUEOUS TAILINGS DISPOSAL

2.1 1992 Assessment

As part of the Phase 1 assessment, members of the SRT reviewed a synthesis on the *Subaqueous disposal of mine wastes: an overview* (Rescan 1991). The synthesis was aimed, in particular, at the geochemistry of common sulphide-rich materials, and included a review of information relating to subaqueous disposal and some of the environmental effects of such practices. Most of the literature on chemical reactivity was from land-based disposal studies. The SRT agreed unanimously that the synthesis, especially as it related to acid mine drainage and sediment diagenesis, was excellent and up-to-date. However, it was felt that the literature review did not adequately deal with some other aspects of environmental effect, including sediment/aquatic toxicities (references were not sufficiently up-to-date and little work on solids ingestion was cited).

The Phase 1 review provided a number of additional references to supplement this synthesis and made recommendation that a further overview be prepared to provide a greater understanding of sediment (metal) toxicity. This recommendation was supported by MEND and a report was prepared by Roy and Campbell (1993) - *Literature review report: Possible means of evaluating the biological effects of subaqueous disposal of mine tailings* (document # 8, Appendix 3).

2.2 Contents of report on means of evaluating the biological effects of sub-aqueous disposal of mine tailings

This report (Roy and Campbell 1993) discussed information specific to Cd, Cu, Ni, Pb, and Zn. These dissolved cations are toxic at low concentrations and they are of particular interest to the Anderson and Buttle Lake studies. Because the published literature on subaqueous disposal of mine wastes had not greatly increased since the Phase 1 review (RAAS 1992), the work of these authors, again, followed a generally "generic" approach (based on best available chemical process models).

Metals may affect aquatic life by direct assimilation from the aqueous phase, and by ingestion of solids and gut assimilation. Under oxic conditions, metal concentrations in porewater are largely related to sorption reactions on Fe, Mn oxyhydroxides and organic matter. Under anoxic conditions, concentrations of dissolved metals are largely controlled by precipitation-dissolution reactions with amorphous sulphides (operationally defined as acid volatile sulphides or

AVS). The report notes the reality of field conditions which are generally more complex than those occurring in controlled laboratory studies (*e.g.* although a thin layer of oxic surface sediment usually overlies anoxic material, oxic microzones often rim the burrows of benthic organisms that penetrate this anoxic layer).

Metal speciation is recognized as an important factor which influences both bioavailability and toxic effects, and bioavailability is related to the concentration of free metal ions present. Total aqueous concentrations of a metal are not a good predictor of bioavailability. Presented as the free ion activity model (FIAM), relationships apply to organisms for which assimilation from the dissolved phase is the principal means of metal uptake (i.e., they do not assimilate metals in particulate form). Dissolved organic matter is recognized as an influence on metal availability and is often present in significant quantities in the natural waters, but its effects are poorly documented.

Digestive processes and chemical conditions in the intestinal tract largely control the extent to which metals may be released (leached) from particulates and taken into the body by means of transfer across the intestinal wall. Bioavailability from a particulate is therefore generally related to the strength of metal binding in the material. Binding is both compound- and substrate- specific, and digestive process may be species-specific.

High levels of the metal-binding protein metallothionein are frequently found in aquatic organisms subjected to contamination, where it acts to sequester metals in organisms (associated with both storage and excretion processes). The effects of toxic stress may be seen at all levels from the organism to the community, with effects occurring selectively or throughout the food chain.

2.3 1995 evaluation by the SRT

The report by Roy and Campbell (1993) focuses on the key issues and avoids dissipation with uncertainties in the literature. It notes the limitations of current approaches, in particular those related to heterogeneity in natural sediments and the over-simplification of many laboratory experiments. Sorption reactions on Fe, Mn oxyhydroxides and organic matter, and reactions with acid volatile sulphides (AVS) allow reasonable prediction of geochemical behaviours under oxic and anoxic conditions, respectively.

In terms of the uptake of dissolved metals, biological availability appears to be well described by means of the free ion activity model (FIAM). Uptake of solid-phase metals following ingestion is largely controlled by pH and residence time in the intestinal tract. Uptake from the solid-phase may be confounded by host-specific microbial processes.

Although the range of metals covered in the report is limited (Cd, Cu, Ni, Pb and Zn) and most of the available research literature (at the time) was related to freshwater rather than marine systems, it was recognized that common reactivities are shared by many other metals as well (document # 17, Appendix 3). Also, since completion of the Phase 1 report (RAAS 1992), other publications have become available (*e.g.* Burton 1992, Manahan 1992). These provide a broad understanding of the geochemistry of a wider range of metals and may be considered as a valuable expansion of the report by Roy and Campbell (1993).

General information is provided but bioaccumulation is not addressed in detail by Roy and Campbell (1993). The lack of detail is in part a reflection of priority, and a reflection of inherent complexities and the amount of directly useful information that can be drawn upon. Also, it should be noted that most of the metals covered by this review do not concentrate in fish (Cd accumulates in some fish tissues, especially kidneys, but not in muscle). Bioaccumulation data may require a species-specific approach to provide the most useful results.

The report provides a clear understanding of metal toxic effects (including biochemical indicators of stress), but it provides no in-depth assessment of metal-nutrient interactions (*i.e.* links between metal effects/cycling and lake trophic status). Again, this is partly a reflection of the MEND priorities and partly a reflection of the paucity of useful information. Nutrient-organochlorine effects may be better understood than nutrient-metal effects. A greater understanding of metal-nutrient interactions in phytoplankton and benthic algae would be useful, particularly as they may influence productivity.

Because of complexities involved in many approaches (*e.g.* population and community indicators of stress), Roy and Campbell (1993) conclude that it may be most practical to focus on the more limited use of specific benthic and phytoplankton indicators as sensitive tools of rapid bioassessment rather than fish; in many cases fish would best represent the (end) effects of acute toxicity. Approaches to determine the more subtle influence of metals and metal-nutrient interactions are beyond the scope of the present MEND requirements.

The SRT (1995) considered significant and more recent studies that became available after the completion of the report by Roy and Campbell (1993). Specific reference was made only to the works of P. Welch and G. Dixon (University of Waterloo and OMEE Dorset Research Station), which build on the application of the FIAM. The application of AVS analysis remains limited. The authors have recently updated one key summary in their report (Roy and Campbell 1993) and a revised and expanded Table 3 is provided in Appendix 5.

2.4 Summary

In both geochemical and toxicological terms, the present state of knowledge should provide an adequate base on which to interpret most of the findings associated with the Anderson and Buttle lakes field work. In terms of biological impact, the state of knowledge could be applied if generally limited to gross and acute levels of effect. Understandings of some of the long term chronic and other subtle effects of metals and metal mixtures are uncertain. Together, the literature reviews prepared by Rescan (1991), and by Roy and Campbell (1993) provide a substantial level of scientific understanding which can be applied widely to assess the likely effets of subaqueous disposal of tailings. The bio-geochemistry of microbial systems was not addressed by either report and additional information on this topic may be useful.

3. UNDERSTANDINGS GAINED FROM THE 1993-95 ANDERSON AND BUTTLE LAKE STUDIES

3.1 Study activities

Most of the resources available to support additional work on the subaqueous disposal of tailings were directed to further studies on Anderson and Buttle lakes (Fig. 1), between 1993-95. Some of the background information about Anderson and Buttle lakes (previously available and included in the Phase 1 review, RAAS 1992) was reconsidered in the light of current study needs, and the most important new source of background material was a historical assessment of mine-related inputs to Anderson Lake (document # 14, Appendix 3).

This historical assessment provided an outline of mine-related activities in the area, descriptions of lake chemistry and discharge, and quantitative estimates of various discharges from the mining activities. It provides information about lime and caustic soda treatments, tailings deposition and sediment chemistry, and estimates were made of metal fluxes to the lake bed.

Field studies were focused on the need to establish a better understanding of the sediment/water interface geochemistry in both lakes, to improve initial quantitative estimates of metals release, and to gain a better appreciation of spatial and temporal variabilities. Field work was carried out during April and August (1993) in Anderson Lake, and during October (1993) in Buttle Lake. High quality cores provided the basis for a detailed analysis of sediment and porewater geochemistry. Dialysis chambers ("peepers") were used to obtain detailed samples of interstitial water and water column chemistry across the sediment/water interface. Precision sampling also provided an extremely detailed understanding of chemical structure of the winter water column in Anderson Lake.

Additional water quality and discharge data were collected from Anderson Lake from June 20 to October 2, 1995. An assessment of how the thermal regime of the water column responded to meteorological forcing (including: precipitation, temperature and wind) was supported by another data set collected from Anderson Lake between August 1993 and July 1995.

In recognition of the need to provide reliable analytical data over a wide range of metal concentrations and on extremely small volume water samples (core porewater and peeper cells), all laboratory practices were subject to demanding QA/QC protocols and statistical procedures were used to provide an extensive evaluation of the analytical results. The geochemical research laboratory of the University of British Columbia (UBC) and the service laboratory of Analytical Services Ltd (ASL), Vancouver participated fully in the QA/QC requirements (established,

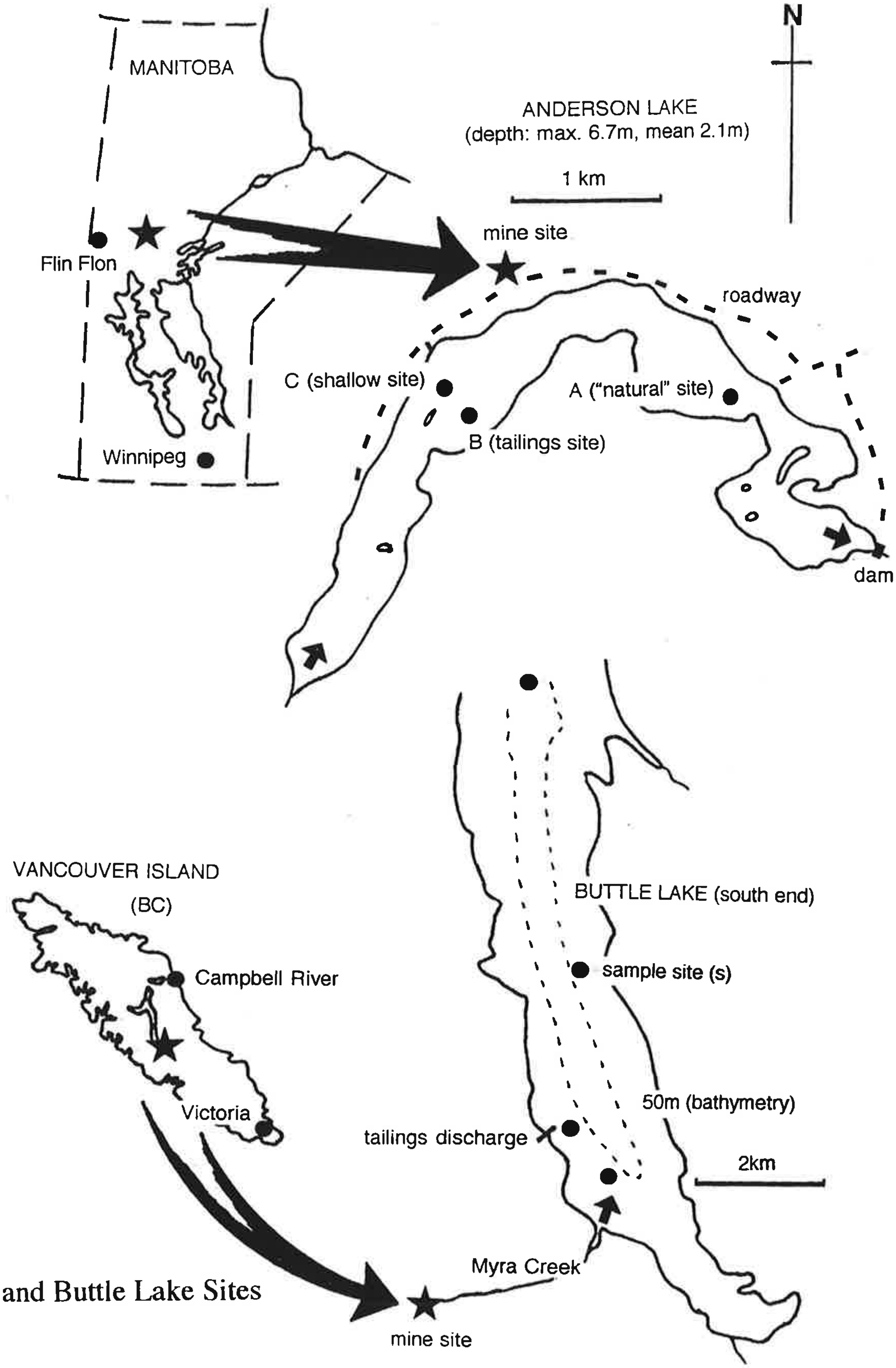

Figure 1

Anderson and Buttle Lake Sites

independently by the SRT).

The scope and work plans for field and laboratory studies on these two lakes are described in detail in documents # 6, 7, 9, 10 and 11 of Appendix 3, and the results of the 1993-95 studies are presented in documents # 13, 16. 19 and 20 (Appendix 3).

3.2 Data quality

Most of the field samples from both lakes and the laboratory analyses were of good quality. Almost all of the water column, sediment particulate and sediment porewater data from Anderson Lake are good, and about 75% of the peeper data (dialysis chambers) are also good (Table 1, Appendix 6).

The data return from Buttle Lake is of slightly lower quality. Again, almost all of the water column, sediment particulate and sediment porewater data are good-excellent. More than 80% of the peeper data are moderate-good and variabilities relate, mostly, to Fe and some trace metal data (Table 2, Appendix 6).

Where problems occurred in the field sampling, they were almost always associated the peepers. The most common problem appears to have been unexpected movement of the sampler after it was placed into the sediment and during the period of equilibration with ambient conditions. Movements are thought to have been caused by strong water motions (probably, wave action in Anderson Lake and bottom currents in Buttle Lake).

Generally, the QA/QC was very effective; blanks, spikes, duplicates and certified reference materials (CRMs) etc. were all used, and the potential for delivery of reliable data was excellent. Almost all metal data from the water column samples from both ASL and UBC laboratories fall well within the envelopes of expected error, the range of variabilities being greater in core porewater and peeper data which were derived from very small samples. In inter-laboratory comparisons, most inconsistencies were identified in laboratory analyses of Fe, Mn, and Zn, and variabilities in the Fe data might also have some influence interpretations related to the As data. Method detection limits for Cd, Hg and Pb may have been too high for some samples.

Because Hg in solutions with different matrices appears to be stable to differing degrees (Pedersen 1996), it is possible that use of nitric acid for storage and preparation of samples may have caused some loss of Hg prior to analysis. However, for many samples of natural water, nitric acid significantly reduces the loss of Hg although it may not eliminate the problem. The very small samples of pore water from Buttle Lake limited the extent to which different preservation techniques could be applied to subsamples. The resulting Hg analyses may underestimate the amount of Hg actually present (Pedersen 1996).

Between-laboratory comparisons were run on a wide range of sample materials. Specifically, anomalies from Anderson Lake winter water column samples decrease in the order Fe > Mn > trace metals, and there may be a slight bias in the Fe concentration data (UBC > ASL). Comparative anomalies in the Anderson Lake summer peeper and porewater samples decrease in the order Fe > Mn > Zn > Cu, and there may be a slight bias towards generally higher values (ASL > UBC). Comparative anomalies in Buttle Lake peeper and porewater samples decrease in the order Fe > Mn > Pb > Zn > Cu. There is no overall tendency for one laboratory to have higher or lower values than the other but there are several sample pairs in which both Fe and Mn share the same bias.

Differences in the paired data do not appear to be specifically related to high/low sample concentrations. If differences were related to redox sensitivity and all sample storage/preparation/ analysis techniques remained consistent, Fe, Mn and Zn anomalies might be expected to show similar patterns throughout the series of comparative data. There are similarities but the patterns are not consistent.

The Fe and Mn data were derived from GF-AAS analyses (ASL and UBC). Analyses of Cd, Cu, Pb, and Zn were made by GF-AAS at ASL but by ICP-MS at UBC. If differences were related to analytical techniques, greatest variability might be expected in the trace metal data but this is not the case. If differences were caused by "errors" in dilution or pH control, ASL:UBC anomalies might tend to occur as all high/low for each element in the same sample. No such consistencies occur.

Subsequently, tests of the UBC and ASL laboratories have indicated that dilution may indeed be a factor. At the same dilution, UBC results were generally somewhat higher than those from ASL but this is not the only explanation for the variance (Pedersen 1996). Operational differences could account for inconsistent variabilities in the data comparisons and might be a significant factor at very small sample volumes. Anomalies likely reflect a number of factors in the preparation, storage and analysis of the samples.

While between-laboratory comparability is not quite as good as originally hoped for, internal consistencies are high, as is the quality of data used to construct chemical profiles.

Overall, the QA/QC program applied to the 1993-95 studies in Anderson and Buttle lakes is considered to have been extremely successful. It ensured good quality data from most samples, over a considerable range of concentrations (*e.g.* trace metal concentrations range over 6 orders of magnitude in core porewater and peeper samples), and in a variety of different media (sediment, porewater, and lake water). It has also provided valuable sources of information which have been used to identify and explain potential problems in the laboratory work. Replicate samples are available for further analyses, if required. Questionable data were rejected in the discussions of results from the Anderson and Buttle lakes studies.

3.3 Results and interpretations

The results and interpretations of the Anderson and Buttle lakes field studies are contained in documents # 13, 16, 19 and 20 (Appendix 3). Similar approaches to data collection were used in both lakes and represent a significant advance over the studies reviewed by the Rawson Academy (RAAS 1992). Precision sampling of the water column was completed only for the April field program at Anderson Lake. The most important new approach was the use of peepers to measure concentrations of dissolved chemicals across the sediment/water interface. Trends and patterns in these concentration profiles, and those of the sediment core porewaters and the water column were used to describe geochemical processes across this interface. They were also used as a means of estimating the diffusive flux of metals.

Peeper data provide high resolution, and all cells of the same peeper (both in the water and in the sediment) were allowed to equilibrate with ambient conditions over the same period of time. Separate core porewater and water column samples provide less vertical resolution and lack common temporal integration. Spatial variability, particularly at shallow water sites or at those within the influence of the dispersal plume of tailings discharge, was sufficient to cause differences in the profiles of some peeper and core samples recovered only a few metres apart. Core profile and peeper data therefore describe essentially the same bed and sub-surface materials at some sites, but different sub-surface materials or structures at others.

Direct comparison has been possible between some core porewater and peeper data, and has maintained confidence in these techniques which can result in not only closely similar within-sediment concentration trends but, also, closely similar concentrations. Consistent trends within individual profiles, even where cores and peepers penetrate different subsurface materials, also provide confidence in both data sets and broaden the base of interpretation, particularly where diver observations or other supplementary information give independent support to the interpretations. The weight of evidence gained from the studies in both lakes provides confidence in the ability to correctly interpret the data. This is important because the studies were undertaken under existing environmental conditions in which there were confounding effects, and not in a laboratory.

In Anderson Lake, acid-generating waste rock was spread along part of the shoreline (beginning in 1987) and some mine wastes were also discharged directly into the lake with the tailings. Although the oxidising waste rock was removed during 1994, its earlier presence and that of other discharges (including acid wastes and dissolved metals) has made it difficult to clearly define sediment/water interface conditions at and near the site of tailings deposition.

Around Buttle Lake, mine wastes still affect the surface drainage although additions of tailings material have ceased, and it has been difficult to assess the extent to which elevated concentrations of metals (*e.g.* Zn) in the water column of the lake may be related to release from the tailings. A reassessment of Myra Creek data (Pedersen 1996) clearly shows that dissolved metal and sulphate concentrations rise in winter (precipitation as snow) and drop during the spring freshet. Depending on the seasonal buoyancy of the Myra Creek plume relative to Buttle Lake water, dissolved species will be added mostly to the thermocline or sub-thermocline waters. The plume is unlikely to exist in the surface waters of the lake during the summer or near the bottom (south basin) during the winter. Concentrations of Zn recorded by the water column samples may well reflect the influence of the Myra Creek input.

Some members of the SRT have suggested that the surface of the tailings may be reactive in both Anderson and Buttle lakes, but the reactivities are likely to be small. Anderson Lake data demonstrate the occurrence of transients in pH and O_2 conditions at the sediment/water interface (anoxia may develop under the winter ice cover and a thin oxidized layer during the open-water period). More frequent sampling would have been required to quantify annual cycles in both lakes.

Some metal cycling may occur between the tailings and natural sediment sites in both lakes but, probably, much of this could be related to the natural breakdown of organic matter at or near the lake bed. Small releases of Fe and As may accompany seasonal changes in the state of oxidation at the tailings/water interface in both lakes. The fluxes of Cd, Pb and Zn are mostly from the water column into the sediment but small releases may also occur at the tailings sites in both lakes. In the porewater from sediment cores or parts of the peepers in sediment-contact, most of the trace metals present in dissolved form were at very low concentrations and often near study detection limits (*e.g.* Cd, Hg, and Pb). In Buttle Lake, the apparent decline of metal levels in the lake water over 20 years (particularly Zn) may include artifacts in sample processing and analytical methods over this period (Coale and Flegal 1989).

In summary, members of the SRT concluded that treatment of the geochemical data has been objective and the conclusions reached are reasonable and generally supported. The 1993-95 data further substantiate that the near-ubiquitous within-sediment sulphide production blocks the upward loss of most metals. Under oxic conditions, Fe and Mn oxides occur as solids in surface and near-surface sediments and have the ability to scavenge other metals present as dissolved species, this oxide-blocking (documents # 4, 5, and 17, Appendix 3) also greatly limits the release of metals. On a lakewide basis and in both lakes, the weight of evidence indicates that the diffusive loss of metals from the sediment to the overlying lake water is very small.

Where rates of burial have been based only on sediment accumulation (Buttle Lake), they are likely to underestimate time required for the exclusion of tailings from processes of metal cycling between sediments and lake water. This is because biological and physical processes which disturb sediments or transfer metal through the food chain may considerably extend the potential "contact" time.

3.4 Tailings reactivity

Although tailings could be slightly reactive in both lakes, Anderson Lake may provide the best opportunity to understand what processes are occurring and their rate and extent.

3.4.1 Interpretations based on the SRT review (1995)

Periodically, it has been found necessary to add base (sodium hydroxide) to Anderson Lake to maintain its pH balance, but the need for this is almost certainly related more to external than internal sources of acidification. However, without an adequate acid-base balance, the conclusion that removal of acid-generating material from the lakeshore (and/or tailings discharge) will ensure high pH and favour little or no metal release remains somewhat uncertain. Some acid-generation and metal recycling might still occur as a result of in-lake oxidation over the surface/near-surface tailings.

The SRT agreed, from the studies completed in Anderson Lake (to June 1995), that there is no clear evidence of tailings oxidation. On the other hand, the SRT felt that the case for no oxidation also remained to be proven. It was possible only to suggest that the presence of dissolved sulphate in the deposited tailings at site B might indicate oxidation and that gradients of ammonium might be a bio-geochemical indicator of acid production. It was noted that sulphate produced in the milling process would be discharged with the mine effluent and could be retained in the entrained tailings.

Based on results reported to June 1995, there is a large difference in the sediment content of organic carbon (OC) at sites A ("natural") and B (tailings), in Anderson Lake. Some of this may be due to "dilution" associated with the input of tailings and some to wind drifted organic matter. The composition of OC and its degradability may also differ at the two sites (e.g. lake organic matter v.s. terrestrial plant material). According to this explanation, microbial degradation at site A decreases the OC content by about one-quarter to one-third, but almost all of the OC is degraded in the near-surface sediment at site B.

The April (1993) interface profiles suggest upward diffusion of ammonium-N from the tailings at site B but not at site A. Also by April, DO depletion affected much of Anderson Lake but there was a little more DO near the base of the water column at site A than B. If, as suggested by the SRT, the DO at site A is in a relict water mass which has been protected from displacement by the irregular bed form (of tailings material), this would also imply that there is greater over-winter reactivity of the sediment/water interface at site B than A. With DO depleted, nitrate would be used next as an oxidant in microbial processes.

In summer, under well oxygenated conditions, DO saturation remains depressed in Anderson Lake. This could indicate that August O_2 consumption is high due to biological processes in the water column, and/or that O_2 is being consumed at the sediment/water interface, and/or by suspended tailings in the water.

Site A appears to be a sink for sulphate which becomes progressively reduced at depth in the sediment but there is no indication of a similar process at site B. At site B, summer and winter core profile data look similar. This could mean that some sulphate release from deposited tailings continues throughout the year at site B. Concentrations of dissolved sulphate increase with sediment depth and H_2S appears to be absent at all depths at site B.

Covariance of sulphate and calcium in profile data may indicate that gypsum is present in the tailings (T. Pedersen, pers. comm.) but it has not been detected by microscopic analysis. The lack of macro-crystal forms implies that post-depositional formation is unlikely. Mine effluent is limed and the discharge is alkaline and, presumably, if gypsum was formed it might be preserved by rapid burial.

3.4.2 Additional considerations (1996)

Based on the results of additional studies reported by McNee in 1996 (document # 20, Appendix 3), it has become possible to add emphasis to the factors that are most likely to influence water quality in Anderson Lake. The tailings discharge to the lake ceased in early 1994 and acid-generating materials were removed from areas adjacent to the lake shortly afterwards. Tailings discharge began, again, in mid-August 1995. Water quality improved in the lake between the time of the last surveys in 1993 and the new surveys in 1995 and, in particular, Zn concentrations declined significantly. Concentrations of Zn, however, increased in 1995 but this change began before the discharge of tailings resumed. There is no evidence that this increase was related to tailings or sediment/water interactions within the lake but it was coincident with the beginning of strong precipitation after a dry summer. It is thought likely that runoff over areas disturbed by the removal of acid-generating material contributed most of the increased load of Zn (and slight increase in Cu). A strong decline in the lake water concentration of major ions also coincided with the onset of precipitation, and parts of the lake most affected by the input of Zn were adjacent to areas where surface remediation had occurred. Mass balance calculations suggest that the subsequent discharge of tailings and mine water would have contributed less than 10% of the additional load of dissolved Zn. If it is assumed that Zn is derived only from dissolution of solid phase detrital material, the amount released would be negligible (McNee 1996). If, however, Zn was also associated with amorphous solids formed in the effluent stream, desorption or dissolution could occur more rapidly and with greater rates of release (P. Campbell, pers. comm.). The use of data to show temporal changes in pH, suspended solids and sulphate in lake and effluent waters might have helped to strengthen this interpretation (e.g., to be expected that levels of dissolved Zn increased without an increase in suspended solids or acidity of lake water).

Meteorological data and lake water and sediment temperature data were also assessed. During the open-water season, lake temperatures reach a maximum in August and minimum in November. The lake is usually well mixed but strong diurnal cooling in the fall can produce conditions where sediment cooling lags that of the water column. Surface sediment temperatures usually closely track those of the overlying water but, after a few days of rapid cooling, reverse thermal gradients may exist in near-surface sediments. Diffusive transfer of chemical species, therefore, remains dominant except in areas subject to erosional scour (caused by wind-wave action).

Collectively, the 1993 to 1995 observations demonstrate the overriding impact of changes in the environment external to the lake. These include the roadway and shoreline areas of acid-generating material (and subsequent site remediation), and the discharge of tailings and mine water. The collective data do not eliminate within lake processes as a source of metals but, almost certainly, the extent of tailings oxidation and metals release is very small. Both the data reviewed by the SRT and the most recent data reported by J. McNee (1996) appear consistent with this interpretation.

4. IMPLICATIONS FOR SUBAQUEOUS DISPOSAL

4.1 Concepts

Document # 17 (Appendix 3) provides an overview of the reactivity of subaqueous tailings deposits based largely on the collective experience gained from the Anderson and Buttle lake studies. It uses "model" sediment porewater profiles to explain the significance of concentration gradients in terms of the potential movements of metals within sediments and across the sediment/water interface. The overview concludes that sulphide-rich mine tailings are largely unreactive when stored in the subaqueous environment. It also concludes that minimal recycling of metals will occur from buried tailings (assuming that the tailings are covered by natural sediment or an artificial "blanket" of material, that they remain stable and are not subject to reworking). Members of the SRT generally agreed with both of these conclusions.

Document # 17 (Appendix 3) raises the possibility of reactions at the sediment surface, largely as a result of the degradation of organic matter, and some members of the SRT have suggested that exposed tailings could be oxidising to a certain extent in both of the study lakes (influencing both acidity and release of metals). Some metal concentrations in the water column of both lakes are higher than in many "natural" lakes but it is not known to what extent these reflect in-lake release from organic matter or underwater tailings, external contributions, or naturally high background conditions. Weight of evidence suggests that external sources are likely the most important. Some release of metals during the breakdown of organic matter may also occur.

From the studies at Anderson and Buttle lakes, subaqueous disposal offers a long term stable and reliable storage technique, once the tailings have become buried and decoupled from biological and physical processes that affect the surface and near-surface sediment layer. In addition, many of these sediment/water and near interface effects would be minimized under conditions in which bottom water remains continually anoxic.

4.2 Implications

The Rawson Academy report (RAAS 1992) considered the potential for tailings disposal in different subaqueous environments (*e.g.* artificial ponds/lakes, headwater lakes, and deep lakes). Many environmental concerns are associated with such practices, especially the potential for major biological impacts during the process of introduction. However, concerns for long term or indefinite security and stability of tailings are increasing, and it seems useful to reconsider some of the advantages and disadvantages associated with subaqueous disposal. The following matrix provides a summary of some of the points to be considered when assessing options for dry land

and subaqueous disposal. Positive aspects are generally rated as high (H), medium (M) or low (L) and underlines are used to focus attention on selected attributes .

	Dry land	Subaqueous disposal				
	Land surface	Artificial pond	Headwater lake	Other natural lakes		
				Anoxic	Deep	Shallow
Opportunity for optimal design	M	H	H-M	M	L	M-L
Need to control inflow (*exposure)	L	M	M	M	H	M-L
Control of physical/chemical conditions	L	H	H-M	H	H-M	M
Control of outflow water quality	L	H	M-L	M	M	M
Control of access and use	M-L	H	H-M	M	M	M
Short term physical stability of tailings	M	H	H-M	H	H	M-L
Long term maintenance of containment	L	M-L	M	H-M	H	H-M
Long term physical stability of tailings	L	M-L	H-M	H	H	M-L
Need to entrain tailings input	M	H	M	M-L	L	M-L
Ability to entrain tailings	H	H	H-M	H-M	L	H-M

The above terms have very general meanings:

Artificial ponds can use existing landforms to create shallow or deep impoundments. Headwater lakes are usually small and isolated in the upper part of a drainage basin. A unique group of lakes have naturally anoxic bottom water due to a special combination of physical and chemical conditions. Most bottom sediments are not affected by wave action in deep lakes, but can be moved by strong wave action in shallow lakes.

4.2.1 Land surface

Storage must attempt to seal the tailings so that they are not exposed to the air and thereby to impede reactions. This is because processes of oxidation, acid-generation and metal release can occur at rates thousands of times faster in the air than under water. Containment also facilitates application of chemical procedures to neutralize tailings. The cost and long term stability of storage structures designed to accomplish this are of particular concern.

4.2.2 Artificial ponds

Obviously there are many advantages to the use of artificial ponds for the subaqueous storage of tailings, particularly over time periods ranging from decades to a century or so. Tailings stability, however, needs to be maintained indefinitely and, over the long term, significant problems could arise with both maintenance and integrity of the containment structures.

4.2.3 Headwater lakes

Where headwater lakes are potentially available for the storage of tailings they may offer many of the same advantages as artificial ponds. Some drainage modification might be needed to maintain suitable inflow and outflow but, for the most part, natural landform would provide secure long term containment. However, depending on the size of lake and volume of tailings, this type of storage could radically change an existing environment.

4.2.4 Anoxic lakes

Some temperate lakes which, due to size and depth, have little mixing of the water column but which due to nutrient availability also have high biological productivity in their surface waters, may have bottom waters that remain anoxic due to the degradation of organic matter. Such lakes may offer near-ideal storage conditions for tailings and present minimal concern from the point of view of biological impact. To make an effective proposal for such use, however, it would be essential for the tailing to be introduced under entrained conditions so that they would not affect biological processes in upper parts of the water column; also, to ensure that the depth of fill would not destabilise stability of the water column.

4.2.5 Deep lakes

Unconfined disposal in deep lakes is not an environmentally acceptable procedure (RAAS 1992) but technologies which could ensure entrainment do exist, or could be developed. If used, such introductions would not likely be without some short term detriment but, conceivably, remediation and or compensation might be used to ameliorate most negative effects. Deep lake disposal, however, has the potential to provide two extremely valuable requirements of storage. Large volumes could be contained without significantly altering water column stability (and thus the physical and chemical integrity of the lake could be largely retained), and the stability of the tailings could be maintained over geologic time.

4.2.6 Shallow lakes

Unconfined disposal in a shallow lake may result in large scale dispersal of tailings and could dramatically alter the physical form of a lake. If it occurs, frequent reworking of tailings is also likely to provide the maximum potential for surface reactivities and the recycling of metals. Entrained deposition may be used to infill part of a lake, thus keeping part of it in a near-natural state and part as a controlled environment (much like an artificial pond). Confined disposal in a shallow lake could provide good conditions for both short and long term storage of tailings.

4.2.7 General

Collectively, these observations suggest that, although short term effects of introductions into many different types of lakes are likely to be undesirable, the significance of short term negative impacts in relation to the long term benefits of stability/security associated with many natural lakes should receive careful and full reevaluation (including technical, environmental, and social and economic aspects). Few environments remain in a pristine state and while this should not be seen as an excuse for further degradation, it is possible to carry out remedial work and the potential for beneficial modifications (enhancement) also exists.

4.3 Benthic flux

So far, the studies on subaqueous disposal of tailings have largely addressed the diffusive flux within bed materials. This is driven by geochemical potentials and largely defines the reactivity of the buried tailings. However, the diffusive flux is only one of several factors influencing metals release in the active zone of surface and near-surface sediments. In artificial ponds, physical factors (*e.g.* wave effects) and diffusion are most important. In lakes, biological processes must be addressed, as well (*e.g.* ingestion/assimilation and transport through the food web, and bioturbation). The benthic flux refers to the process integration of chemical diffusion, biological transfers through the food web, and physical or biological movements at the sediment/water interface.

The Anderson and Buttle lake studies address many of the concerns about placement of tailings in artificial ponds and headwater and naturally anoxic lakes. Although much information is now available, some uncertainty remains about the small surface reaction rates of tailings in Anderson and Buttle lakes and how long will it take for these materials to be buried under natural sediment.

A more comprehensive understanding of the effects of tailings disposal in lakes would probably require case-specific research and literature studies to address biological processes as a major pathway for metals; the scavenging effects of suspended sediment or release of porewater due to sediment disruption; toxic effects; and whole-lake mass balance measurements to provide an independent check on in-lake metal fluxes.

5. CONCLUSIONS AND RECOMMENDATIONS

The results of studies carried out in Anderson and Buttle lakes between 1993 and 1995, the literature review on biological effects and the assessment of historical data (Anderson Lake) strongly support the earlier, general conclusions of the Phase 1 report (RAAS 1992). Namely, that subaqueous disposal of sulphide-rich tailings would result in negligible rates of oxidation and a minimal loss of metals to overlying waters (including: Cu, Fe, Mn, Pb and Zn and others of similar chemical behaviour). Despite the confounding effects of working in real lakes, the influence of variable loadings from multiple sources, and the complexities of working with extremely small volume samples, a remarkably consistent picture has emerged from the studies of this MEND project. The quantification of flux rates across the sediment/water interface proved more difficult to establish than originally hoped but, nevertheless, the relative importance of the diffusive flux is now known. Given the intent to establish the significance of geochemical processes at a generic level, it is reasonable to conclude that the objective has been essentially met.

Although subaqueous disposal appears to offer a practical means of dealing with many sulphide-rich tailings, present levels of information and understanding are not sufficient to provide a comprehensive prediction of environmental response. The cradle-to-grave effects of tailings introduction to natural aquatic environments requires site-specific assessments of physical, chemical and biological effects. Much is known about the physical and chemical processes at a generic level, but biological understandings are not so well established. As a next step, therefore, it is probably most appropriate to develop site-specific model assessments in aquatic systems which link physical and chemical factors, but in which biota represent a minor component (*e.g.* man-made storage ponds). A move to more complex aquatic systems which include biota may be appropriate, later. Because of the need to consider environmental effects from the time that tailings are first introduced into such an environment to the time that they finally become buried, detailed assessments are not likely to be applied unless site-specific.

Referring to the matrix on the advantages and disadvantages of subaerial and subaqueous disposal (Section 4), it seems useful to develop a model assessment for comparison of the risks, costs, and benefits of different means of disposal. The approach needs to give particular attention to long term stability and security of disposal systems. Further, habitat modification, compensation or no net loss of habitat, and treatment options need to be incorporated in ways that provide opportunities for beneficial outcomes (from subaqueous disposal) rather than just minimizing negative effects. Bearing in mind problems associated with many existing surface-exposed tailings, the assessment might consider not only new mining operations but, also, remediation of past disposal.

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Roy, R. and P. G. C. Campbell, 1993. Literature review report: Possible means of evaluating the biological effects of subaqueous disposal of mine tailings. Report prepared on behalf of the RAAS, for Placer Dome Inc. MEND Project 2.11.2 (a); 57 p., and attachments.

Communications

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APPENDIX 1

A1. 1992 recommendations and subsequent activities to 1995

A1.1 Recommendations

In summary, recommendations made by the Rawson Academy of Aquatic Science (RAAS 1992) for new work included:

- Additional and high quality field and laboratory data

  Estimates of mass balance for selected chemicals (*e.g.* metals and sulphates), and spatially and seasonally representative measurements in the water column and at the sediment/water interface.

  Better equipment for sampling and *in situ* measurements (*e.g.* pH and O_2 sediment profiles, dialysis array (peeper) profiles in water and sediment, thermal profiling of the water column).

  Replicate samples at representative sites in each study lake, and improved QA/QC in the field, and the handling and processing of laboratory analyses.

- Further evaluations of selected historical data

  Reassessment of the records of tailings loading and associated water chemistry to define historical trends.

- Additional literature review

  Biological uptake and bioaccumulation of metals, and their toxic effects.

A1.2 Project activities since 1992

To provide continuing advice after 1992, some members of the Phase 1 SRT and additional experts were invited to contribute to the development of the new studies. These advisors assisted MEND by providing independent views on both the planning and the interpretive stages of the field and analytical work.

It was not possible to support all of the recommendations from Phase 1 (RAAS 1992). Rather, MEND decided to focus on aspects of broad geochemical concern and to limit field activities to two different lakes. Since tailings disposal from the Snow Lake mill were expected to cease during 1994 in Anderson Lake (small shallow lake), it was decided to carry out field work in that lake, as soon as possible, and to study the effects of fresh tailings. This was carried out between June 20 and October 2, 1995. Also, as a follow-up to suggestions from the SRT in 1992 and the process of on-going review of the 1993 field work, Meteorological data was collected at Anderson Lake and detailed water temperature profiles were recorded between August 1993 and July 1995. The data were selectively analysed.

A substantial body of information about water quality and mining practices was also available for Buttle Lake (deep, long and narrow lake) which could be used to provide valuable comparative and contrasting information about the effects of subaqueous tailing disposal. By 1992, it had become known that both lakes might be affected by external factors which included an acid-generating roadway (Anderson Lake) and surface drainage from Myra Creek (Buttle Lake), but the extent of these influences was not fully appreciated until completion of the 1993 field studies. Comments by the SRT in 1995 also led to further consideration of the Myra Creek discharge data relative to seasonal conditions and the receiving waters of Buttle Lake.

In recognition of the need for high quality chemical analyses, often on very small sample volumes and at concentrations near the limits of method sensitivity, an extensive QA/QC program was designed to provide between laboratory and within sample set control. This QA/QC program was applied to the samples from both Anderson and Buttle lake studies. Following comments from the SRT in 1995, further assessments were made of the inter-laboratory QA/QC data and preparatory treatments for Hg.

In addition, a literature review was commissioned by MEND (supported by Placer Dome Inc.). This review was designed to complement an earlier review of geochemical literature (Pedersen 1991), and to cover the biological effects of availability of selected metals. In particular, it addressed bioavailability and ecotoxicology (document # 8, Appendix 3). This review was prepared by R. Roy and P. G. C. Campbell of the University of Quebec (INRS-Eau, at Ste-Foy).

MEND also commissioned a historical assessment of mine-related inputs to Anderson Lake (supported by CANMET throught the Canada/Manitoba Mineral Development Agreement and Hudson Bay Mining and Smelting Co. Ltd). The assessment was to provide a better understanding of the various factors that had affected the lake in recent years and background information against which it might be possible to compare *in situ* data from the field studies in the lake.

APPENDIX 2

A2. Members of the 1995 scientific review team (SRT)

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APPENDIX 3

A3. Documents provided to the scientific review team

Copies of the following information were provided to each of the expert reviewers for the second review of studies on the subaqueous disposal of tailings. Titles in bold face are of principal interest.

1) Rescan, March 1990. A preliminary assessment of subaqueous tailings disposal in Anderson Lake, Manitoba. MEND Project 2.11.1b.

2) Rescan, March 1990. Geochemical assessment of subaqueous tailings disposal in Buttle Lake, British Columbia. MEND Project 2.11.1b.

3) Rescan, September 1990. Geochemical assessment of subaqueous tailings disposal in Anderson Lake, Snow Lake Area, Manitoba. Mend Project 2.11.1b.

4) **Rawson Academy of Aquatic Science, July 1992. A critical review of MEND studies conducted to 1991 on subaqueous disposal of tailings. MEND Project 2.11.1 (d); 20 p., and attachments.**

5) Rawson Academy of Aquatic Science, July 1992. A critical review of MEND studies conducted to 1991 on subaqueous disposal of tailings. Final report: Stage 1 and stage 2 reviews. MEND Project 2.11.1d; 38 p.

6) Rescan, February 1993. Scope of work for Anderson Lake winter survey (1993). MEND Project 2.11.3a.

7) Analytical Service Laboratories Ltd (ASL), March 1993. Laboratory analysis and QA/QC for MEND project 2.11, Anderson Lake winter survey. MEND Project 2.11.3a.

8) **R. Roy and Campbell, P. G. C., March 1993. Literature review report: Possible means of evaluating the biological effects of subaqueous disposal of mine tailings. Report prepared on behalf of the Rawson Academy of Aquatic Science, for Placer Dome Inc. MEND Project 2.11.2 (a); 57 p., and attachments.**

9) Rescan, July 1993. Scope of work for Anderson Lake summer survey (1993). MEND

Project 2.11.3b.

10) ASL, July 1993. Workplan: Laboratory analysis and QA/QC for the MEND project 2.11, Buttle Lake summer survey. MEND Project 2.11.4.

11) Rescan, October 1993. Scope of work for Buttle Lake summer survey (1993). MEND Project 2.11.4.

12) Aspila, K. I., and M. Alkema, June 1994. On the comparability of laboratory data for water samples exchanged between UBC and ASL. Anderson Lake (winter and summer surveys) MEND project 2.11.3 NWRI, Burlington; 14 p., and attachments.

13) Rescan, July 1994. Geochemical assessment of subaqueous tailings disposal in Anderson Lake, Manitoba. 1993 study program. MEND Project 2.11.3.

14) Martin, A. J., and T. F. Pedersen, 1994. Historical assessment of the mine-related inputs to Anderson Lake, Manitoba. MEND Project 2.11.3c; 38p.

15) Aspila, K. I., and E. Koktich, December 1994. On the comparability of laboratory data for water samples exchanged between UBC and ASL. Buttle Lake (fall survey) MEND project 2.11.4. NWRI, Burlington,1994; 8 p., and attachments.

16) Rescan, February 1995. Geochemical assessment of subaqueous tailings disposal in Buttle Lake, BC. MEND Project 2.11.4.

17) Rescan, February 1995. Subaqueous tailings geochemistry: An overview of the reactivity of subaqueous mine tailings deposits. Prepared for Placer Dome Inc., 8 p.

18) Copies of some previous comments on proposed work plans and study reports.

19) T. Pedersen, January 1996. Revision of the Buttle Lake report: DRAFT comments for insertion at the appropriate point in the report.

20) J. McNee, March 1996. Anderson Lake Studies (from August, 1993), MEND Project 2.11.3d.

APPENDIX 4

A4. Summary of guidance to members of the scientific review team

A4.1 New literature review (numbers refer to Appendix 3)

Does report (8) represent the best understanding of biological uptake and bioaccumulation of metals, and toxic effects of metals and metal-nutrient interactions?

Are there more recent contributions which significantly advance our knowledge beyond this report (8)?

Does the present state of knowledge provide an adequate base on which to interpret findings from the Anderson and Buttle lakes field work?

A4.2 Anderson and Buttle lakes field work

Is the background information (1, 2, 3, & 14) adequate for interpreting the trends in sediment/water interface geochemistry caused by the introduction of tailings into Anderson and Buttle lakes?

Do the field measurements (13 & 16) provide a reliable basis for quantitative estimates of flux at the sediment/water interface?

Did the field work meet general objectives (4, 6, 9 & 11) and are changes necessary for future work?

Are the overall conclusions reached (1, 2, 3, 13, 14, & 16) reasonable (suggest alternatives if appropriate)?

A4.3 All aspects of quality assurance and quality control (QA/QC)

Did QA/QC protocols provide reliable data (12 and 15)?

Where anomalies exist in data sets, is it possible to define their source?

Did the field sampling provide sufficient redundancy (12, 13, 15, 16)?

What are the main problems affecting QA/QC and data interpretation (12, 13, 15 & 16)?

A4.4 Suggestions, conclusions, concerns

Are you sufficiently confident in the field, laboratory and literature data to support the suggestions and conclusions of (17)?

Do you agree that subaqueous disposal of tailings offers a stable and reliable storage technique?

Document (4) raised concerns about the influence of other processes on the movement and behaviour of metals at the sediment/water interface. To what extent does this remain an issue of concern?

APPENDIX 5

Revised Table 3 for report by Roy and Campbell (1993)

Table 3: Metal sulphide solubility products.

Metal sulphide	log K_{sp}[a]	$\log(K_{ms}/K_{FeS\ am})$[b]	Reference
FeS (s, am)	+4.1		Davison 1991
(s, mackinawite)	+3.4		Davison 1991
(s, greigite)	+2.6		Davison 1991
NiS (s, a)	+1.5	-2.6	NIST 1993
(s, b)	-4.0	-8.1	NIST 1993
(s, g)	-5.7	-9.8	NIST 1993
ZnS (s, sphalerite)	-4.5	-8.6	Daskalakis & Helz 1993
CdS (s, greenockite)	-7.3	-11.4	Daskalakis & Helz 1992
PbS (s)	-7.9	-12.0	NIST 1993
CuS (s, am)	-11.9	-16.0	Shea & Helz 1989
(s, covellite)	-15.3	-19.4	Shea & Helz 1989
HgS (s, black)	-31.7	-35.8	NIST 1993
(s, red)	-32.1	-36.2	NIST 1993

Notes: (a) K_{sp} given for the reactions $MS + 2H^+ \quad M^{2+} + H_2S$; multiple values are given when different sulphide solid phases exist.

(b) Ratio log (K_{MS}/K_{FeS}) calculated for amorphous FeS.

Daskalakis, K. D. and G. R. Helz, 1992. Solubility of CdS (greenockite) in sulfidic waters at 25°C. Environ. Sci. Technol. 26: 2462-2468.

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Shea, D. and G. R. Helz, 1989. Solubility product constants of covellite and a poorly crystalline copper sulphide precipitate at 298°K. Geochim. Cosmochim. Acta. 53: 229-236.

APPENDIX 6

Table 1. SUMMARY OF DATA QUALITY BASED ON WITHIN OR BETWEEN-SAMPLE CONSISTENCIES (ANDERSON LAKE)

Study - sample series		Within-Consist.	Between-Consist.	Other
Anderson Lake (winter - April 1993)				
Water column		good		
Core particulates		good		
Core porewater		good		
Anderson Lake (summer - August 1993)				
Water column		good		
Core particulates		good		
Core porewater		good		
Peepers: Rescan	10		poor (core 1)	U (movement)
	11	good	good (Res.15)	*
	12	good	good (Res. 13)	**
	13	good	good (Res. 12)	**
	14		poor (core 1)	U (movement)
	15	good	good (Res.11)	*
NWRI (tailings)		good	good (core 2)	
NWRI (natural)		good	good (core 1)	

General notes:

Some porewater and peeper sample data may be subject to Fe, Mn, and Zn analytical variabilities detected by QA/QC, and some concentrations below MDL occur in the trace metal data.

Within-consistency means that well defined trends exist and where applicable (tandem peepers or close-spaced cores) similar trends and concentrations exist in the paired data.

U .... Uncertain (caused by?)
* .... Shallow tailings site (no core for comparison)
** .... The interface chemistry of peeper and core data at the tailings site is similar but the Rescan peepers define a different sub-surface profile.

Table 2. SUMMARY OF DATA QUALITY BASED ON WITHIN OR BETWEEN-SAMPLE CONSISTENCIES (BUTTLE LAKE)

Study - sample series	Within-Consist.	Between-Consist.	Other
Buttle Lake (summer/fall - October 1993)			
Water Column	good		
Core particulates	good		
Core porewater	mostly good		*
Peepers (natural sed. site)			**
Rescan 13	moderate	moderate (core 7a) incon. (SO_4, Fe, Mn, Cu & Pb)	
NWRI 7	poor	poor (core 7a) incon. (Fe and Mn) nil (trace metals)	
Peepers (distal site)			
Rescan 14	good	good (cores 4a/b)	
NWRI 4	moderate	nil (cores 4a/b)	U (movement)
Peepers (outfall)			
Rescan 15	moderate	incon. (Fe,Cu and Pb)	
NWRI 6	moderate	incon. (Fe,Mn, trace metals)	

General note:

Some porewater and peeper sample data may be subject to Fe, Mn, and Zn analytical variabilities detected by QA/QC, and some concentrations below MDL occur in the trace metal data.

Within-consistency means that well defined trends exist and where applicable (tandem peepers or close-spaced cores) similar trends and concentrations exist in the paired data. Inconsistencies (incon.) include data sets where the sediment/water interface appears to be shifted.

U .... Uncertain (caused by?)

* .... Inconsistencies exist between paired data for Cu, Pb and Zn (mostly at depth within the cores).

** .... Data show well defined trends within in each data set (core porewater and peepers) but trends differ between sets.