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Acid Mine and Metalliferous Drainage (AMD); Sample Selection an Intricate Task

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ABSTRACT

Although acid rock drainage (ARD) exists in nature, acid mine and metalliferous drainage (AMD) as a consequence of mining remains one of the most difficult environmental problems to deal with. AMD has the potential to persist long after closure, requiring extensive and expensive on-going remediation and monitoring of local and surrounding downstream environments.

AMD characterization requires in-depth investigations to understand the key processes involved in the oxidation of sulfides and the subsequent release and transport of solutes. Approaches and solutions to mine-waste characterization and management during resource exploitation require accuracy but is site specific. Regulators, miners and scientists have different views on the numbers and types of sample specimens; these differences should be recognised and considered as they play an important role in the overall decision making process. Over time, many different approaches and methodologies to ascertain the number of samples have been developed. These range from a dominant geo-statistical approach, such as the theory of sampling (ToS), to methods inclusive of a combination of statistical, mineralogical, geochemical, environmental and economic analyses.

Despite which approach is followed, sample types and numbers are often subject to unwarranted critique. Regulation may further complicate matters, particularly where decision makers are risk averse. An innovative approach that centres around a risk-based approach and combines geological, mineralogical, geochemical and hydrogeological characteristics of the mine site into a conceptual model, from which the AMD investigator is able to define the type and number of samples and relative amount of material, appears the most appropriate approach to extricate this fundamental problem in investigating and assessing AMD. This global yet site specific approach, will assist during the various stages of mining and will provide assurance that subsequent rehabilitation and closure are achieved with little difficulty and expense.

Keywords: AMD, characterization, sample, selection, number.

INTRODUCTION

Although acid rock drainage (ARD) exists widely in nature, acid mine/metalliferous drainage (AMD) is a significant environmental concern for the mining industry and one that may persist long after closure, often requiring extensive and expensive remediation.

ARD/AMD is caused by the exposure of sulfide minerals to oxygen and water which produces acidity and triggers the dissolution of metals and metalloids, which are harmful to site and neighbouring downstream environments (Alarcón and Anstiss 2002). Owing to the complex physical, chemical and biological processes occurring during the weathering of sulfides, the production of AMD can be severe, or may not occur if the media remains in a reducing condition. This uncertainty adds further complexity to the assessment of a mining project and thus, the characterization of mine wastes becomes fundamental to develop cost effective management approaches including preventive and containment measures.

Regulators, miners and scientists have differing views on the types, number and origins of samples that would fully characterize mine waste. These differences within the various stages of mine development create a complicated paradigm and impact adequate mine-waste identification and management. Responses to these complexities include numerous research investigations and publications that incorporate an all-inclusive approach of statistical, mineralogical, geochemical, environmental and economic analyses. However, these approaches have not fully addressed the intricacies of defining *adequate sampling quality and population,* which remains a paradigm.

With reference to AMD, there are several questions that need to be answered over the life of a mining project, these including but are not limited to:

- Should samples be profiled for AMD characteristics during the exploration stages?
- What constitutes a sample for AMD assessment?
- How many, which kind and what sizes of samples are sufficient to hydrogeochemically characterize the proposed new mine?
- How are we dealing with heterogeneity and how might lithological samples express this complexity?
- How much analysis is required and what parameters need to be investigated?
- How may laboratory analyses be extrapolated to real mine conditions?

SAMPLING PARADIGM

It is accepted that samples for AMD investigations should be *site-specific and depend on the phase of the project, but must be sufficient to adequately represent the variability/heterogeneity within each geological unit and waste type* (DITR 2007). Certain key parameters including the extent of mineral variability, mineralogical alterations and sulfide types/concentrations are often omitted from AMD assessments. These parameters are required to reveal baseline conditions of the overburden/waste rock and ore (high and low grades), and assess the risks that a mining project imposes on the environment.

Whilst numerous sample selection methodologies are used worldwide, the general theory of sampling (ToS, Francis Pitard, 1989) takes into account both technical and statistical aspects of sampling. ToS was developed by the French academic Pierry Gy and addresses all facets of sampling. The main contribution attributed to this theory is the proposition of a mathematical definition of heterogeneity (Rossi *et al,* 2010).

In nature, this concept is paramount as we need to know the lithology, mineralogy, alterations and the variability of the physical, mechanical, hydraulic and chemical properties of the rocks. Alternate sampling strategies range from purely statistical to fixed-frequency approaches. The British Columbia AMD Task Force (1989) proposed that samples be collected in a fixed-frequency approach, based on the mass/volume of waste, and recommends a minimum number of samples expressed as:

$$N = 0.0026M^{0.5}$$

where N is the number of required samples and M is the mass of the geologic unit in tons (M should be > 6×10^3 tons). Based on this approach, a minimum number of 25 samples are required per 1 million tons geologic unit, or one sample for every 40,000 tons (Figure 1). However, as the waste volume increases beyond 1.5E+8 tons, the number of samples decreases. Gene Farmer of the U.S. Forest Service suggested collecting 50 samples for each 1 million tons of waste (USDA Forest Service, 1992). The specifics of Gene Farmers' approach indicate that for each 1 million tons of waste rock, eight to twelve samples of each significant rock type (as a minimum) should be collected (Schafer 1993). Brady and Hornberger (1989) proposed a minimum number of samples per coal seam based solely on acreage, calculated as [acres/(100acres)]+2. A similar approach was suggested by Freeman *et al* (1987), which allowed the areal extent of a coal mine to be used as the basis for determining the number of samples.

In general, fixed-frequency sampling methods imply that each individual sample used to test and classify larger volumes of waste, would allow lithological stratification mixing and sample chemistry blend. Consequences of this approach may be far reaching as information about sample variability could be lost, imposing a degree of liability (British Columbia AMD Task Force, 1990). In addition, sample lithotype mixture may not necessarily be applicable in highly heterogeneous conditions such as at base metal mines (SENES, 1994).

Although the scheme is not specific for AMD, a prominent code on statistical sampling theory and practice has been developed by the Joint Ore Reserve Committee for the mining industry (JORC 2012). Reporting standards on sampling methods, measurements of sampling error and correctness and Public Report transparency regarding exploration results (JORC 2012), are included in this code. The proposed method of sample selection is similar to those used to evaluate recoverable mineral resources (assay samples), which employ estimation variance (ANOVA and variant method) to determine the optimum threshold of parameters (such as total sulfur), as a function of sample density and characterization (Modis and Komnitsas 2007; Kentwell *et al* 2012; Servida *et al* 2013). If the parameter of interest is either well above or below the threshold of interest, the total unit or volume of a rock type can be classified as either potential acid forming (PAF) or non-acid forming (NAF) and managed accordingly. However, the spatial distribution of the element within a rock category may not necessarily be homogeneous across the entire volume of each rock type; this may raise questions pertaining to heterogeneity, sampling intensity and sample density.

CHARACTERIZATION AND ASSESSMENT METHOD

The methodologies used in several AMD studies (Table 1) are inclusive of a global ARD and AMD knowledge base, and experiences gained in different climatic and geological-hydrogeological settings. However, the methodology the authors practice differs slightly as it incorporates the development of a mine hydrogeochemical conceptual model as a first step in the assessment of AMD (Table 2). The conceptual model is developed to account for the potential of overburden, waste rock, and the ore body (all grades) to possess either acid or base characteristics. Studies incorporated for this assessment include geological, hydrogeochemical, hydrological and hydrogeological data gathered during exploration activities. These parameters are assessed on merits of their natural occurrences and interactions and are subsequently risk assessed with regard to potential short- to long-term social, economic and environmental impacts.

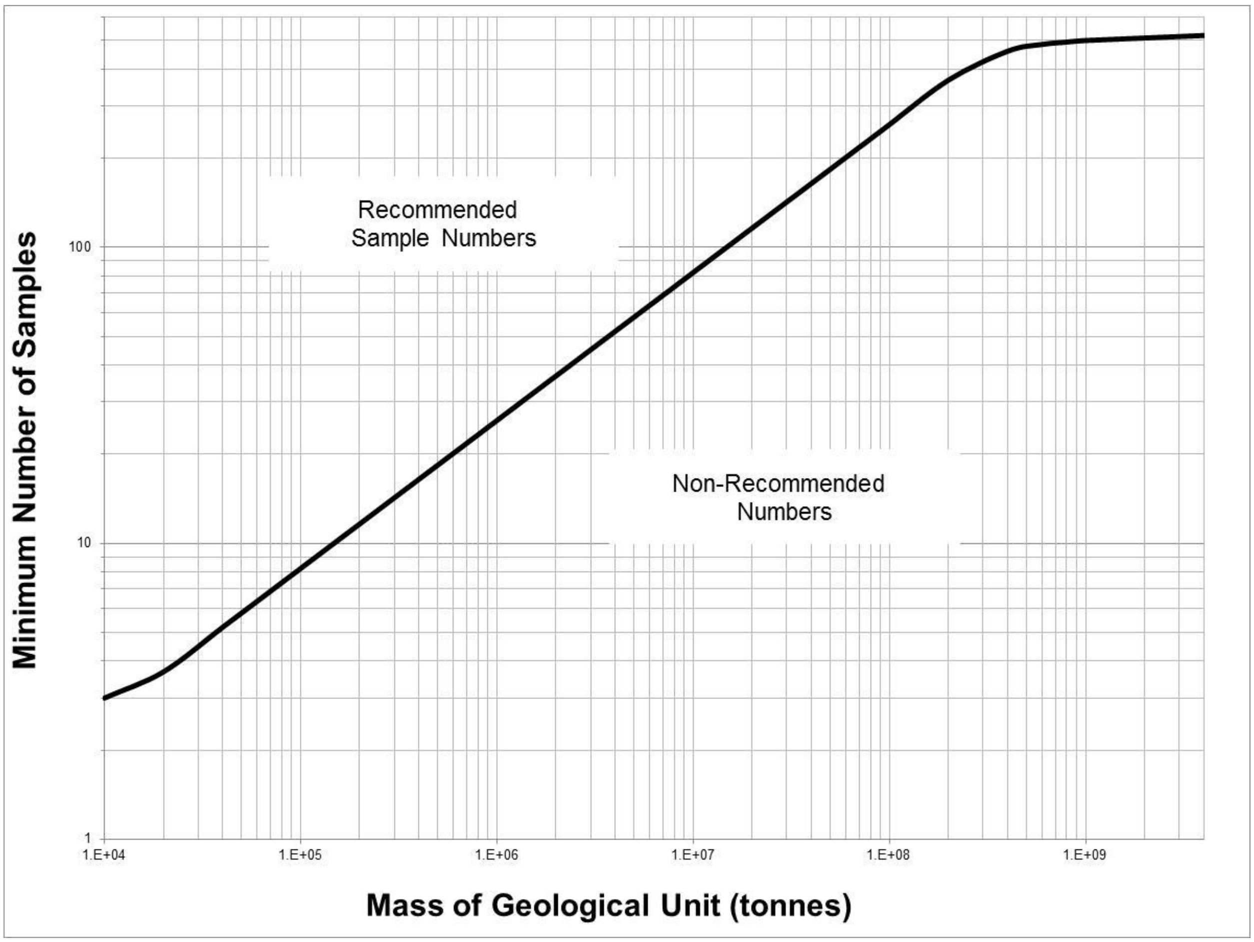

Figure 1 Recommended Minimum Number of Samples as a function of Mass of Each Geologic Unit

The conceptual model becomes a key interpretive AMD framework which provides a basis for the prediction of chemical processes that may develop during operations and post-mining. The derived framework is then tested by limited sampling and analysis which incorporates additional geochemical testing in the form of acid base accounting (ABA) and kinetic testing if required. Although the question of up scaling remains, field kinetic testing is recommended as it fosters the resemblance of actual climatic conditions and can be adapted to investigate new findings arising during the subsequent stages of mining.

Table 1 Selected AMD Investigations

Project Name	Project Location	Client	Characteristic
Area C Iron Project	NT, Australia	Sherwin Iron Pty Ltd.	EIS component
Beatons Creek	Western Australia	Novo Resources Corp.	EIS Component
Frances Creek	NT, Australia	Territory Iron Pty Ltd.	Rehabilitation
Goldsworthy Mine	Western Australia	BHP Billiton	Remediation and Closure
Kapulo Copper Project	Congo	Mawson West Ltd.	EIS component
Old Pirate Mine	NT, Australia	ABM Resources NL	MMP Component
Railway Project, Yandi	Western Australia	United Mineral Corporation	EIS component
RedbankMine Site	NT, Australia	Redbank Cooper Ltd.	EIS component
Western Desert Iron Ore Project	NT, Australia	Western Desert Resources Ltd.	EIS component
Westgold Project	NT, Australia	Westgold Resources Ltd.	EIS component

An example of conclusions reached during the conceptual model stage at one of the projects (Table 1) is presented below.

- Deposit C, due to its mineralogical characteristics and low sulfide concentrations, has a low likelihood of producing acid mine and metalliferous drainage.
- Low sulfur concentrations (<0.25%S) in more than 99% of the samples (Table 2) indicate that potential acid forming (PAF) materials occur sporadically, are highly localised and are confined to about nine locations (RC bores). Four locations (RC bores) contain samples located beneath the direct shipping ore (DSO) body.
- Most PAF materials (84% of samples) occur outside the perimeters of the proposed open pit and/or are beneath the base thereof.
- The ground water level is likely to remain below the base of the open pit. Localised perched waters in shallow highly weathered and/or fracture systems are not a cause for concern.
- Deep ground water may be impacted by infiltrating rain from the open pit (partially backfilled with a large void remaining after closure) migrating through the underlying undisturbed PAF bodies. However, PAF bodies are small and isolated and evaporation exceeds rainfall by several orders of magnitude, which limit the quantity of water that may infiltrate through the base of the open pit. Rain falling into the open pit may also be diverted away from areas where PAF bodies are known to exist.

This preliminary assessment indicated no need for a rigorous AMD evaluation but to comply with regulatory requirements, further assessments were undertaken. Using the fixed-frequency sampling approach a minimum of 404 samples across the different sandstone (Sst), siltstone (Slt), shale (Shl), ferruginous sandstone (Fst) and other layers would have been required. However, a total-S global statistical approach indicated that at a 95% confidence level, a maximum of 50 samples would yield a low global 1.41% margin of error (Table 3).

Table 2 Mine Geochemical Conceptual Models

Project Name	Exploration Geochemistry, Mineralogy and Geology								Conceptual Model							
	XRF (No samples; %)				XRD					Perceived Risks:						
	No Samples	<0.25%	0.25% - 0.3%	>0.3%	No Samples	Sulfides	Petrography	SEM	Interactions	Issue / Cause	Insignificant	Minor	Moderate	Major	Catastrophic	AMD Potential
Redbank Cooper Project	140	*50*	*6*	*44*	40	Yes			Surface / Ground water	Acidic seepages from waste rock dumps (WRD), tailing storage facilities (TSF) and pits.				X		Likely
Sherwin Iron Ore Project	2541	*99*	*0.3*	*0.7*	21	Yes	6		Surface / Ground water	Acidic seepages from waste rock dumps (WRD), tailing storage facilities (TSF) and pits.		X				Unlikely
Old Pirate, ABM Resources	1743	*99.8*		*0.2*		Yes			Surface / Ground water	Acidic seepages from waste rock dumps (WRD), tailing storage facilities (TSF) and pits.	X					Unlikely
Western Desert Iron Ore Project	5286	*72*	*7*	*21*	50	Yes		46	Surface / Ground water	Acidic seepages from waste rock dumps (WRD), tailing storage facilities (TSF) and pits.			X			Likely
Westgold Project	500	*99.5*		*0.5*	150	Yes		15	Surface / Ground water	Acidic seepages from waste rock dumps (WRD), tailing storage facilities (TSF) and pits.	X					Unlikely
Frances Creek	1747	*83*	*1*	*16*		Yes			Surface / Ground water	Acidic seepages from waste rock dumps (WRD), tailing storage facilities (TSF) and pits.				X		Likely

Table 3 Number of Samples Required and Analytically Assessed for AMD Investigations

Project Name	Required number of samples by fixed-frequency analysis (refer Figure 1)	Confidence level 95% with pre-established margin error (±20%)		Number of samples selected for analytical assessment		
		Sample No.	Margin Error (%)	ABA Test	NAG Test	Leaching Test
Redbank Cooper Project	354	40	7.5	42	42	23
Kapulo Cooper Project*	142	50	2.2	50	50	20
Sherwin Iron Ore Project	404	50	1.41	54	54	27
Western Desert Iron Ore Project	1491	250	2.7	204	204	204
Westgold Project	115	30	1.2	17	17	17

*Iron and cooper concentrations used for the statistical assessment.

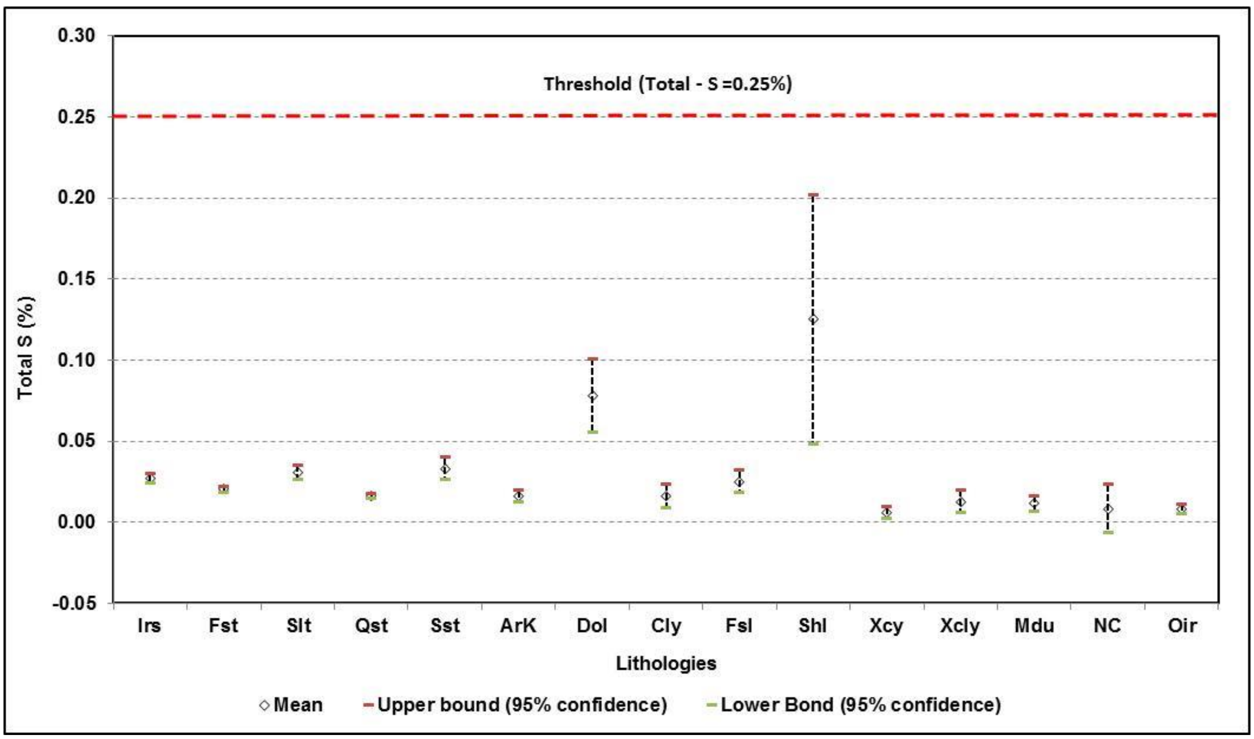

Figure 2 95% Confidence Intervals for Waste Lithologies at Deposit C

A further statistical assessment of the sample population in relation to global lithological distribution based also on total-S concentration (Figure 2) indicated that the threshold sulfur value of 0.25% is well above of the highest mean of 0.13% of the shale (Shl). The 95% confidence level of this highest mean ranges from 0.05% to 0.20% and all rocks may be classified as non-acid forming (NAF) materials.

In summary, the development of the conceptual model assisted with defining the degree of rigour with which the exploration data needed to be assessed, as a first step of sample number definition and quantification. The statistical assessment, to comply with regulatory requirements, allowed verification of the optimum number of samples (Table 3) submitted for analytical assessment. The highest confidence levels tolerated indicated that the sample population selected would produce high confidence levels and contain the true sample population value which, provided confidence to verify the assumptions made during the development of the geochemical conceptual model.

The conceptual model approach with clearly defined objectives abridged the premise that *samples must be selected to characterize both the type and volume of rock materials and also to account for the variability of materials that will be exposed during the life of the mine* (DITR 2007; DMP 2009). In addition, it assisted with determining the extent of the mine AMD management plan (including sampling methodologies and monitoring requirements) and a site specific standard operation procedure (SoP) for the daily management of PAF/NAF waste materials.

AMD ASSESSMENT APPROACH

Sample qualification and quantification are generally regulated by various authorities and approval agencies, and supplemented by a series of guidelines which despite postulating sample location, quantity and type, are seldom specific in regard to analytical assessment methodology. The use of these guidelines in distinguishing an approach to sampling should not be regarded as a stringent *step-by-step,* but instead be considered in conjunction with a risk-based approach, incorporating interpretation of the wider interactions of site conditions with current ARD and AMD scientific knowledge, and adjusted accordingly. Guidelines, rather than being prescriptive, should aid stakeholders to factor internal and external influences of and for the project. This in essence should set a framework that integrates the processes for identifying and managing risks, strategies and planning for the management of potential acid forming materials.

Included in the development of the hydrogeochemical conceptual model are the environmental risk assessment of AMD and an overall evaluation of social, economic and environmental impacts of the project. The analysis of these parameters primarily assists with defining the potential extent of impacts and perceived value of onsite and offsite environments. These are also considered to ascertain the degree of rigour required by further sampling and help in setting adequate analysis to characterize sources, pathways and receptors. For example, if the mine is located within a sensitive environment with likely downstream impacts by AMD formation, the sample number and sampling frequency are likely to increase as a consequence of the risks coupled with a stricter more detailed assessment by the regulator. However, if the site has no significant potential for AMD and is located in a remote locality with little or no predicted downstream environmental impacts, the AMD assessment may be concluded after finalising the conceptual model, with limited confirmatory sampling and analysis.

In summary, if the analysis of key parameters incorporates a quantifiable risk of the local and regional site conditions, the wider geological and geochemical analysis, qualification and quantification of wastes and a hydrogeochemical assessment, a site specific investigation should provide a good base to evaluate AMD and their implications for mining development (Figure 3).

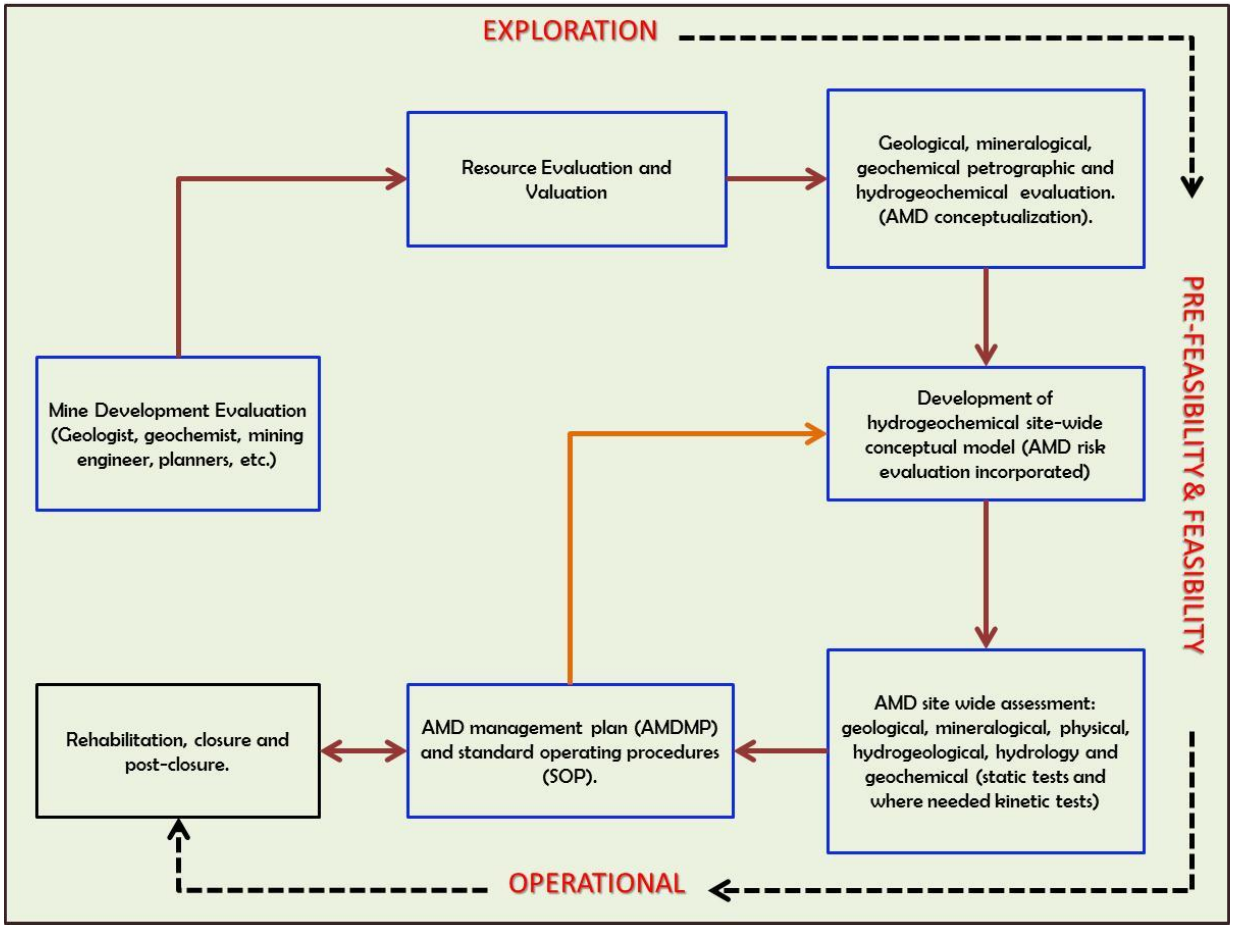

Figure 3 Flow Diagram to be adopted at the Exploration Stage

However, this approach needs to be incorporated at the exploration stage and continued through to the pre-feasibility, feasibility and operation phases. A good opportunity to further AMD studies is also presented by the grade control drilling program during feasibility studies and subsequent mining. This drilling program is developed to better understand grade distribution and variability of recoverable resources. Thus the development of a site wide hydrogeochemical conceptual model during the early stages of the exploration program should be used as a forum to:

- Analyse the potential for AMD formation.
- Assess the environmental sensitivity of the site and potential risks than this may pose.
- Assess the potential short- to long-term social, economic and environmental consequences.
- Define sample quality and number.
- Define methodologies to be used for AMD investigations and assessments.

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