MOLY MINES LIMITED

SPINIFEX RIDGE PROJECT

GEOCHEMICAL CHARACTERISATION OF PROCESS-TAILINGS-SLURRY SAMPLES

Implications for Process-Tailings Management

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SUMMARY OF TECHNICAL TERMS EMPLOYED IN THIS REPORT

ACRONYM	PARAMETER	DEFINITION/DETERMINATION	UNIT
AFP	Acid-Formation Potential		
ARD	Acid-Rock Drainage		
Total-S	Total Sulphur	Analysis Result	% (w/w)
Sulphide-S	Sulphide Sulphur	Testwork Result [i.e. Sulphide-S = Total-S - Sulphate-S]	% (w/w)
ANC	Acid-Neutralisation Capacity	Testwork Result	kg H_2SO_4/tonne
MPA	Maximum-Potential Acidity	Calculation	kg H_2SO_4/tonne
NAPP	Net-Acid-Producing Potential	Calculation	kg H_2SO_4/tonne
NAG	Net-Acid Generation	Testwork Result	kg H_2SO_4/tonne
NAF	Non-Acid Forming	Calculation: • Sulphide-S < 0.3 % • Sulphide-S ≥ 0.3 %, and negative-NAPP value with ANC/MPA ≥ 2.0	kg H_2SO_4/tonne
PAF	Potentially-Acid Forming	Calculation: • Sulphide-S ≥ 0.3 %, and any positive-NAPP value • Sulphide-S ≥ 0.3 %, and a negative-NAPP value with ANC/MPA < 2.0	kg H_2SO_4/tonne
PAF-[SL]	PAF-[Short-Lag]	Estimation [e.g. inferred from 'kinetic' testing]	
PAF-[LL]	PAF-[Long-Lag]	Estimation [e.g. inferred from 'kinetic' testing]	
SOR	Sulphide-Oxidation Rate	Testwork Result [e.g. obtained from 'kinetic' testing]	mg SO_4/kg/week,

Notes:

The **PAF-[SL**] classification applies to PAF-materials (e.g. mine-wastes, and/or process-tailings) that are initially circum-neutral, but acidify (viz. pH less than 5) within weeks-to-months when exposed, and subjected to an "aggressive-weathering" regime typical of well-watered environments (e.g. where unsaturated-conditions prevail for at least a few days [via drainage/evaporation processes] between successive infiltration/flushing episodes that, in turn, occur regularly [e.g. monthly rainfall patterns comprising 1-2+ major-raindays of 10+ mm "on-average" during most of the annual hydrological-cycle]). The occurrence of thin, dilute films of pore-fluids on sulphide-grain surfaces which are regularly flushed constitutes an aeration/moisture regime that is near-optimal for sulphide-oxidation. In such well-watered settings, surface-zones of exposed mine-wastes/process-tailings seldom experience total-suctions in excess of 1+ bars (i.e. 0.1+ MPa).

The **PAF-[LL]** classification applies to PAF-materials where exposure for years (even decades+) may be needed before acidification develops. Circum-neutral-pH during "lag-phase" weathering is chiefly due to "at-source" buffering by carbonate-minerals.

Climate directly influences "lag-phase" duration, and a sulphide-gangue assemblage classified as PAF-[SL] in well-watered settings where the SOR is controlled by **O_2-supply**, may instead be classified as PAF-[LL] in water-limited settings where the SOR is controlled by **H_2O-supply** in terms of both total-suction, and infrequency of "flushing-episodes" (Campbell 2004, 2006). The formation of "secondary-oxidation-products" (e.g. Fe-oxyhydroxides) as indurated, and tightly adhering/cohering deposits, is typically enhanced during "lag-phase" weathering in water-limited settings, and is a further mechanism by with sulphide-oxidation is stifled under the ensuing "mild" weathering-regime. Surface-zones of exposed mine-wastes/process-tailings in such environments are typically characterised by total-suctions well in excess of 1 bar for most of the year. At high total-suctions, even the physical meaning of pore-fluid "films" becomes tenuous.

1.0 INTRODUCTION

Moly Mines Limited is developing the Spinifex Ridge Project located *c.* 50 kms to the north-east of Marble Bar, Western Australia.

Ore will be treated for molybdenite recovery, and the resulting stream of process-tailings (in the form of a slurry) discharged to an engineered, tailings-storage facility (TSF).

Graeme Campbell & Associates Pty Ltd (GCA) was commissioned to carry out geochemical testwork on process-tailings-slurry samples derived from a pilot-plant-metallurgical investigation.

The 'Static-Testwork' Programme focused on the Acid-Formation Potential (AFP), Multi-Element Composition, and Mineralogy of the tailings-solids samples.[1] In addition, the quality (viz. major/minor-ion chemistry) of the tailings-slurry-water samples was determined.

The testwork results are presented and discussed in this report, and implications for process-tailings management highlighted.[2]

The present study supplements the engineering investigations on process-tailings management being carried out by DE Cooper & Associates Pty Ltd for the Spinifex Ridge Project.

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[1] A 'Static-Testwork' Programme comprises "whole-rock" analyses and tests.

[2] Related geochemical testing of a process-tailings sample forms the subject of the GCA (2006) report. The present study extends the GCA (2006) study.

2.0 STUDY APPROACH

Details of the sampling and testwork programmes, and the calculations and criteria employed for classifying the tailings-solids samples into AFP categories, are presented and discussed in the following sections.

2.1 Testwork Programme

2.1.1 Samples

Details of the process-tailings-slurry samples submitted for testing by GCA are presented in Appendix A.

The **Composite-A-Tailings** sample corresponds to the milling of ore-blends in the early years of the Project, whereas the **Composite-B-Tailings** sample corresponds to treating ore-blends during the later years of the Project when Granodiorite-ores make an increasing contribution to the ore-blends.

Each tailings-slurry sample was submitted in a 20-L, opaque-plastic-pail that was filled-to-the-brim with tailings-slurry. The heights of the tailings-solids was approximately one-half of the total-slurry heights. The supernatants (viz. tailings-slurry-waters) overlying the tailings-solids were decanted via siphoning, vacuum-filtered (0.45-µm-membrane), and preserved for specific analyses.[3]

The 'sludges' of tailings-solids in the plastic-pails had a "sloppy" consistency, and were oven-dried at 45 °C, followed by pulverising to nominal 75 µm. The tailings-solids were not washed prior to testing.

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[3] Sub-sample of the 'raw-filtrates' were employed for the analysis of major-parameters, whereas HNO_3-dosed filtrates were used for the multi-element analyses. The determination of NO_3-N and NH_3-N was performed on H_2SO_4-dosed filtrates.

2.1.2 Testwork

The testwork methods employed in this study are based on recognised procedures for the geochemical characterisation of mine-waste materials, process-liquors and natural-waters (e.g. AMIRA 2002; Morin and Hutt 1997; Smith 1992; Coastech Research 1991; BC AMD Task Force 1989; APHA 1992).

Details of the testwork methods are presented in Appendix B.

Part of the testwork was carried out by Genalysis Laboratory Services [GLS] (Maddington), and SGS Environmental Services [SGS] (Welshpool). The analyses performed by GLS and SGS have NATA endorsement.[4]

Specialised testing (viz. auto-titrations and Net-Acid-Generation [NAG] Tests) was undertaken by Dr. Graeme Campbell in the GCA Testing-Laboratory (Bridgetown).

The mineralogical work was performed by Dr. Roger Townend of Roger Townend & Associates (Malaga).

Copies of the laboratory and mineralogical reports are presented in Appendix C.

2.2 Calculated Parameters

The Maximum-Potential-Acidity (MPA) values (in kg H_2SO_4/tonne) of the tailings-samples were calculated by multiplying the Sulphide-S values (in %) by 30.6. The multiplication-factor of 30.6 reflects both the reaction stoichiometry for the complete-oxidation of pyrite, and/or pyrrhotite, by O_2 to "$Fe(OH)_3$" and H_2SO_4, and the different weight-based units of % and kg H_2SO_4/tonne. The stoichiometry of pyrite/pyrrhotite-oxidation is discussed further in Appendix B.

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[4] NATA = National Association of Testing Authorities.

The Net-Acid-Producing-Potential (NAPP) values (in kg H_2SO_4/tonne) of the tailings-solids samples were calculated from the corresponding MPA and Acid-Neutralisation-Capacity(ANC) values (i.e. NAPP = MPA - ANC).

2.3 Classification Criteria

In terms of AFP, mine-waste materials may be classified into one of the following categories, viz.

- Non-Acid Forming (NAF).
- Potentially-Acid Forming (PAF).

There are **no** unifying, "standard" criteria for classifying the AFP of mine-waste materials (Campbell 2002a,b; Smith 1992), and reflects the diversity of sulphide and gangue-mineral assemblages within (un)mineralised-lithotypes of varying weathering- and alteration-status. Rather, criteria for classifying AFP may need to be tailored to deposit-specific geochemistry, and mineralogy.

The AFP-classification criteria often employed at mining-operations worldwide are:

- **NAF**: Sulphide-S < 0.3 %. For Sulphide-S ≥ 0.3 %, both a negative NAPP value, and an ANC/MPA ratio ≥ 2.0.
- **PAF**: For Sulphide-S ≥ 0.3 %, any positive-NAPP value; negative-NAPP value with an ANC/MPA ratio < 2.0.

In assessing the AFP of mine-waste materials, there is general consensus that lithotypes with Sulphide-S contents less than 0.3 % are unlikely to oxidise at rates fast enough to result in acidification (e.g. pH less than 4-5) [Soregaroli and Lawrence 1997]. This position assumes that the groundmass hosting such "trace-sulphides" is not simply quartz, and/or clays (Price *et al.* 1997), and that for a carbonate-deficient gangue, the sulphides are not unusually reactive (e.g. sulphide-oxidation rates [SORs] less than *c.* 20-40 mg SO_4/kg/week) [= *c.* 1-2 kg SO_4/tonne/year].[5] A "cut-off" of 0.3 % for Sulphide-S also accords with the findings of 'kinetic' testing conducted, since the late-1980s, by Dr. Graeme Campbell for mine-waste samples of diverse mineralogy in terms of AFP.

The ANC/MPA criteria for the NAF category reflects the need to compensate for "less-than-perfect" availability of alkalinity-forms (e.g. carbonates) for neutralisation of acid produced through pyrite-oxidation. A "less-than-perfect" availability of alkalinity-forms may arise from:

(a) Restricted accessibility of acid to carbonate-grains.

(b) Rate-limiting dissolution of carbonates-grains near pH=7.

(c) Depletion of carbonate-minerals through rainfall-fed leaching within waste-dumps.[6]

Restricted accessibility of acid to the surfaces of carbonate-grains may occur at different spatial-scales (viz. at the "whole-rock-scale" in which Acid-Rock Drainage [ARD] "by-passes" carbonate-bearing materials via preferential-flow pathways within a waste-dump, and at the "pore/grain-scale" in which the surfaces of individual carbonate-grains are "blinded/rimmed" by precipitates of Fe(III)-oxyhydroxides [e.g. ferrihydrite-type phases]). As shown by Li (1997), ferroan-carbonates (especially "Fe-rich" varieties) are prone to "surface-armouring/rimming" during dissolution: weathering of tailings-solids containing pyrite, ankerites and Mg-siderites produced acidic leachates when less than one-third of the carbonate-grains had dissolved.

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[5] Although 'steady-state' SORs (at circum-neutral-pH) for Sulphide-S contents less than 0.3 % may indeed exceed 1-2 kg SO_4/tonne/year, such rates are generally restricted to either sedimentary forms (e.g. framboidal-pyrite), or hydrothermal-sulphides that are atypically reactive.

[6] Depletion of carbonate-minerals through dissolution in meteoric-waters is minimal in semi-arid settings, especially within the "hydrologically-active-zone" (e.g. top 2-3 m) of a waste-dump, since re-precipitation occurs during evapo-concentration when desiccating conditions return after "wet-spells".

To compensate for the effects of (a) to (c) above, some authors advocate that, for a mine-waste sample to be classified as NAF, it must have an ANC/MPA ratio of at least 3.0 (see review of earlier literature by Smith [1992]). In recent years, fundamental-research (especially estimation of reaction-rates for diverse sulphide/gangue-mineral assemblages), and field-experience at mining operations world-wide, have shown that the potential for ARD production is very low for mine-waste materials with ANC/MPA ratios greater than 2.0 (AMIRA 2002; Price *et al.* 1997, Currey *et al.* 1997, and Murray *et al.* 1995).[7] This ANC/MPA ratio is employed in the present work.[8]

The risk posed by handling PAF-lithotypes during the working of a deposit is governed primarily by the duration of the "lag-phase" (i.e. the period during which sulphide-oxidation occurs, but acidification does not develop, due to buffering near pH=7 by gangue-phases).[9] Although the "lag-phase" applicable to exposed mine-wastes at "field-scale" cannot be accurately predicted *a priori*, estimates (albeit approximate) are still needed to identify the exposure-times for the safe handling of PAF-lithotypes, and so reduce the risk for ARD production. Estimates of the "lag-phase" are invariably obtained through programmes of 'kinetic' testing (viz. Weathering-Columns). However, based on experience, "first-pass" estimates of the "lag-phase" may be made, and thereby used to further classify PAF-lithotypes into **PAF-[Short-Lag]** and **PAF-[Long-Lag]** sub-categories. Such "first-pass" estimates are necessarily provisional, and subject to revision, in the light of the outcomes of 'kinetic' testing, and field observations.

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[7] Such ANC/MPA ratios are consistent with those indicated from SORs, and carbonate-depletion rates, as reported in the International-Kinetic Database for mine-waste materials from around the world (Morin and Hutt 1997).

[8] It should be noted that mining-regulators in Nevada (USA) classify a mine-waste sample as NAF, if it is characterised by an ANC/MPA ratio greater than 1.2 (US EPA 1994). This lower ANC/MPA ratio reflects the semi-arid conditions typically encountered at mine-sites in Nevada. Although utilised in the early-1990s, it is understood that an ANC/MPA ratio of 1.2 is still entertained by regulators in Nevada for "screening" PAF and NAF varieties of mine-wastes in semi-arid settings.

[9] SO_4 is still produced by sulphide-oxidation during the "lag-phase", and soluble-forms of minor-elements (e.g. As) may be released at circum-neutral-pH during the "lag-phase-stage" of mine-waste weathering.

3.0 ACID-BASE CHEMISTRY OF TAILINGS-SOLIDS SAMPLES

The testwork results on the acid-base chemistry of the tailings-solids samples are presented in Table 3.1, and shown on Figure 1.

The tailings-solids samples were characterised by (Table 3.1):

- Sulphide-S values of 0.29-0.43 %;
- ANC and CO_3-C values of 40-48 kg H_2SO_4/tonne, and 0.28-0.30 %, respectively;
- negative-NAPP values; and,
- NAG-pH values of 8.1, and NAG values less than 0.5 kg H_2SO_4/tonne.

The pH-buffering properties of the tailings-solids samples were determined via auto-titration, and 0.05 M-H_2SO_4. The H_2SO_4-addition rates employed during the auto-titrations were *c.* 10^4 kg H_2SO_4/tonne/year, and correspond to SORs up to 10^4-10^5 faster than those typically observed for the weathering (at circum-neutral-pH) of "trace-sulphides". The pH-buffering curves (Figure 1) exhibited well-defined "inflection-points" near pH=7, associated with the dissolution of calcite (Table 4.2).

The testwork results indicate that the tailings-solids samples are both classified as NAF, and reflects "trace-sulphides" (chiefly pyrite and pyrrhotite) in a gangue that contains "accessory-calcites".

4.0 MULTI-ELEMENT COMPOSITION AND MINERALOGY OF TAILINGS-SOLIDS SAMPLES

The multi-element composition and mineralogy of the tailings-solids samples are indicated by the data presented in Tables 4.1 and 4.2, respectively.[10] The corresponding element-enrichments in the samples, as indicated by the values of the Geochemical-Abundance Index (GAI), are also presented in Table 4.1.[11] It should be noted that these element-enrichments are relative enrichments, based on the element contents typically recorded for unmineralised soils, regoliths and bedrocks (Bowen 1979).

The tailings-solid samples were each variously enriched in Ag, Cu, Cd, As, Bi, Sb, Se and Mo (Table 4.1). The Mo contents were 300-420 mg/kg.

The tailings-solids samples mainly comprised quartz and actinolite with an array of accessory components (viz. calcite, chlorite, plagioclase, muscovite, K-feldspar, and clinozoisite) [Table 4.2]. Traces of pyrite, pyrrhotite, molybdenite, arsenopyrite, and chalcopyrite also occurred.

The analysis results indicate that the tailings-solids samples were variously enriched in an array of chalcophyles. However, the degree of minor-element enrichment was not marked.

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[10] The suite of elements listed in Table 4.1 is grouped into (a) the major-elements (viz. Na, K, Mg, Ca, Al and Fe) making-up the lattices of primary-silicates, sulphides, clays, sesquioxides and carbonates, and (b) minor-elements. A distinction is made between minor-elements which, under neutral-to-alkaline conditions, occur (i) as cationic-hydrolysis forms (e.g. Cu), and (ii) as anions/oxyanions (e.g. As). Anionic forms may exhibit moderate solubility under neutral-to-alkaline conditions.

[11] The GAI is defined in Appendix B.

5.0 QUALITY OF TAILINGS-SLURRY-WATER SAMPLES

The analysis results for the tailings-slurry-water samples are presented in Table 5.1.

The tailings-water samples had pH values of 5.8-8.3, and salinities (as Total-Dissolved Solids, TDS) of 460-600 mg/L (Table 5.1). The soluble-salts comprised mainly "NaCl" (viz. halite).

With the exception of Mo, the concentrations of minor-elements were below, or close to, the respective detection-limits (Table 5.1). The low concentrations of soluble metals attest to the efficiency of metal-sorption reactions under neutral-to-alkaline conditions (Sposito 1984).[12]

The Mo concentrations were 0.77-0.87 mg/L, and reflects the moderate solubility of Mo at circum-neutral-pH (Reddy *et al.* 1997; CANMET 1994), especially where clays and sesquioxides are not abundant.[13]

The analysis results indicate that the tailings-water samples were mildly-alkaline (viz. pH 8-9), and brackish-to-saline. The solubility of minor-elements was low, although the Mo concentrations were within the near-mg/L range.

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[12] Sorption reactions include both adsorption and precipitation reactions (Sposito 1984).

[13] A similar Mo solubility was recorded in the GCA (2006) study.

6.0 CONCLUSIONS

Based on the testwork results obtained in this study, it is concluded that there should be minimal variation in tailings-geochemistry associated with the milling of "early-stage-ores" and "later-stage-ores". The tailings-solids should be consistently classified as NAF, due to "trace-sulphides" dispersed throughout a gangue containing "accessory-calcites". Enrichment in minor-elements should also be modest.

The slow release of soluble-Mo forms during weathering is likely the main potential geochemical issue to be catered for in the design, and closure, of the TSF. The Mo concentrations in tailings-pore-fluids may be expected to be within the near-mg/L range, although kinetic-testing (viz. Weathering-Columns) would be required to more fully assess Mo-solubility behaviour (e.g. concentration ranges, and temporal trends, as a function of weathering-history). Such Mo-solubility behaviour may potentially have implications for the form of any (vegetated) store/release-cover system at TSF-closure.

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TABLES

Table 3.1: Acid-Base-Analysis and Net-Acid-Generation Results for Tailings-Solids Samples

GCA-SAMPLE NO.	SAMPLE DETAILS	MC (%, w/w)	TOTAL-S (%)	SO_4-S (%)	Sulphide-S (%)	CO_3-C (%)	ANC	NAPP	NAG	NAG-pH	AFP CATEGORY
							kg H_2SO_4/tonne				
GCA6750	Composite-A-Tailings	14.2	0.49 (0.49)	0.06 (0.06)	0.43	0.29 (0.28)	48 (48)	-34	<0.5	8.1	NAF
GCA6751	Composite-B-Tailings	14.8	0.35	0.06	0.29	0.30	40	-31	<0.5 (<0.5)	8.1 (8.1)	NAF

Notes:

MC = Moisture-Content; ANC = Acid-Neutralisation Capacity; NAPP = Net-Acid-Producing Potential; AFP = Acid-Formation Potential; NAF = Non-Acid Forming; NAG = Net-Acid Generation.
All results expressed on a dry-weight basis, except for NAG-pH.
Values in parentheses represent duplicates.

Table 4.1: Multi-Element-Analysis Results for Tailings-Solids Samples

Note: Refer Appendix B for the definition of the Geochemical-Abundance-Index (GAI) indicated in this table.

ELEMENT	TOTAL-ELEMENT CONTENT (mg/kg or %)		AVERAGE-CRUSTAL ABUNDANCE (mg/kg or %)	GEOCHEMICAL-ABUNDANCE INDEX (GAI)	
	Composite-A-Tailings (GCA6750)	Composite-B-Tailings (GCA6751)		Composite-A-Tailings (GCA6750)	Composite-B-Tailings (GCA6751)
Al	6.3%	5.7%	8.2%	0	0
Fe	5.0%	3.6%	4.1%	0	0
Na	1.5%	1.6%	2.3%	0	0
K	1.4%	1.4%	2.1%	0	0
Mg	2.3%	1.7%	2.3%	0	0
Ca	4.1%	3.1%	4.1%	0	0
Ag	1.7	1.5	0.07	**4**	**4**
Cu	830	650	50	**3**	**3**
Zn	79	68	75	0	0
Cd	1.2	1.1	0.11	**3**	**3**
Pb	10	8	14	0	0
Cr	250	220	100	1	1
Ni	110	70	80	0	0
Co	41	25	20	0	0
Mn	820	560	950	0	0
Hg	0.02	0.02	0.05	0	0
Sn	3.2	2.6	2.2	0	0
Sr	93	110	370	0	0
Ba	120	180	500	0	0
Th	2.2	3.5	12	0	0
U	0.85	1.3	2.4	0	0
Tl	1.1	0.78	0.6	0	0
V	160	99	160	0	0
As	81	63	1.5	**5**	**5**
Bi	4.9	4.3	0.048	**6**	**6**
Sb	11	8.9	0.2	**5**	**5**
Se	1.2	0.83	0.05	**4**	**3**
Mo	420	300	1.5	**6**	**6**
B	<50	<50	10	0	0
P	240	250	1,000	0	0
F	790	770	950	0	0

Note: Average-crustal abundance of elements based on Bowen (1979).

Table 4.2: Mineralogical Results for Tailings-Solids Samples

Composite-A-Tailings (GCA6750)		**Composite-B-Tailings (GCA6751)**	
Component	**Abundance**	**Component**	**Abundance**
quartz	dominant		
actinolite	major	quartz	major
		actinolite	
calcite	accessory	**calcite**	accessory
chlorite		chlorite	
plagioclase		plagioclase	
muscovite		muscovite	
K-feldspar		K-feldspar	
clinozoisite		clinozoisite	
pyrite	trace	**pyrite**	trace
pyrrhotite		**pyrrhotite**	
molybdenite		**molybdenite**	
arsenopyrite		**arsenopyrite**	
chalcopyrite		**chalcopyrite**	
biotite		biotite	
scheelite		ilmenite	
ilmenite			

Notes:

dominant = greater than 50%; major = 20-50 %; accessory = 2-10 %; and, trace = less than 2 %

Table 5.1: Analysis Results for Tailings-Slurry-Water Samples

<u>Note</u>: All results in mg/L, except for pH and EC (µS/cm).

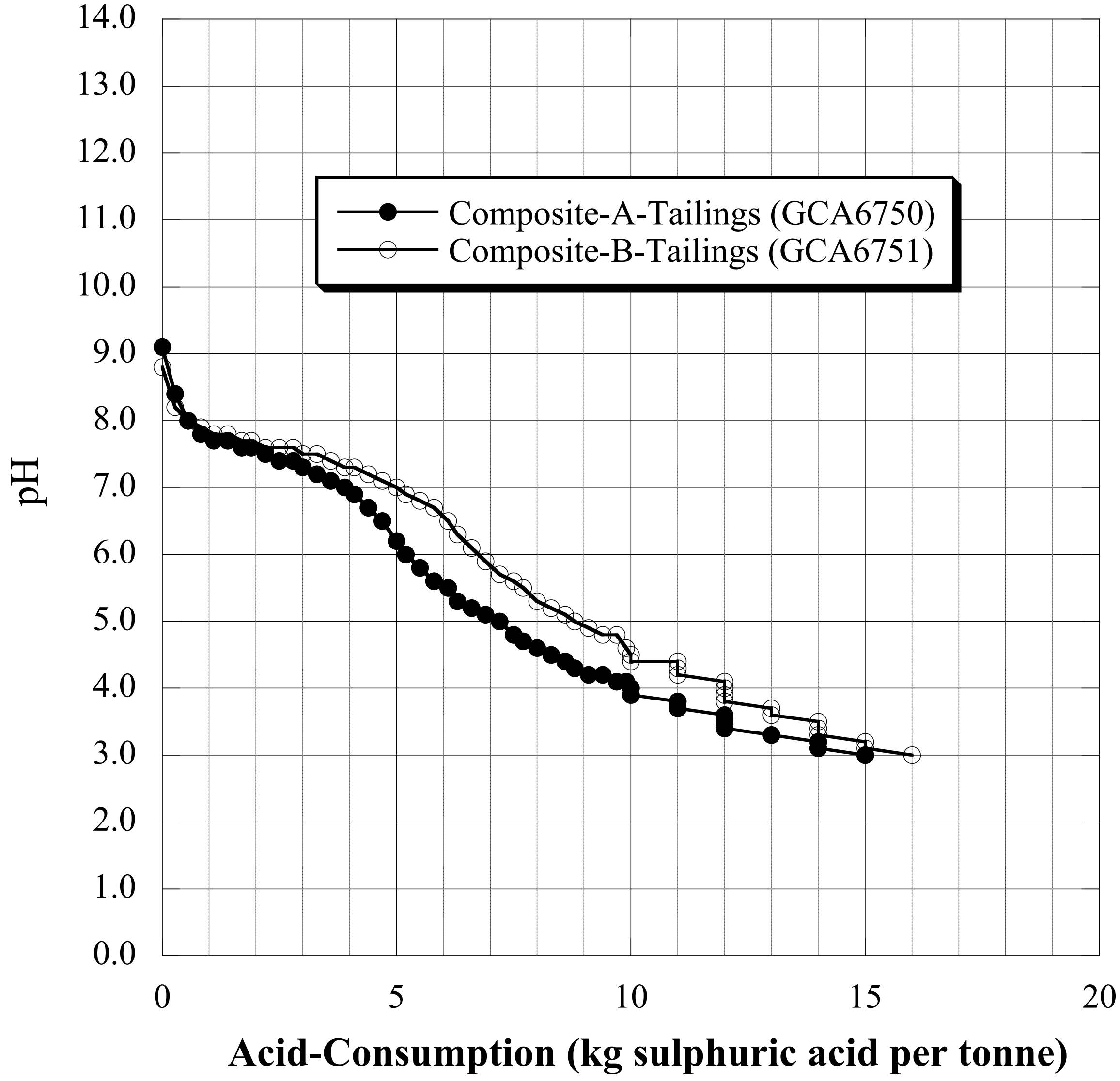
ELEMENT/ PARAMETER	**Composite-A-Tailings (GCA6750)**	**Composite-B-Tailings (GCA6751)**	**ELEMENT/ PARAMETER**	**Composite-A-Tailings (GCA6750)**	**Composite-B-Tailings (GCA6751)**
Major-Parameters			***Minor-Ions***		
pH	8.3	5.8	Fe	<0.01	<0.01
EC [µS/cm]	990	990	Cu	<0.01	<0.01
TDS(gravimetric)	600	460	Ni	<0.01	<0.01
			Zn	0.02	0.01
Major-Ions			Co	0.0003	<0.0001
			Al	0.02	0.04
Na	150	140	Cd	0.00070	0.00073
K	34	31	Pb	<0.0005	<0.0005
Mg	15	14	Cr	<0.01	<0.01
Ca	42	39	Hg	<0.0001	<0.0001
Cl	180	200	As	0.021	0.020
SO_4	41	120	Sb	0.0076	0.0071
HCO_3	190	10	Bi	<0.000005	0.000006
CO_3	<1	<1	Se	0.0011	0.0016
OH	<5	<5	B	0.08	0.09
			Mo	0.77	0.87
Nitrogen-Forms			P	<0.1	<0.1
			F	2.2	2.1
NH_3-N	<0.005	0.017	Ag	0.00001	0.00001
NO_3-N	<0.05	<0.05	Ba	0.017	0.021
			Sr	0.19	0.23
			Tl	0.00002	0.00001
			V	<0.01	<0.01
			Sn	0.0003	0.0007
			U	0.00035	0.00081
			Th	<0.000005	<0.000005
			Mn	0.08	0.07

<u>Note</u>: EC = Electrical Conductivity; TDS = Total-Dissolved Solids

FIGURE

Figure 1

pH-Buffering Curves for Tailings-Solids Samples



Note: The H_2SO_4-addition rates employed in the auto-titrations correspond to sulphide-oxidation rates (SORs) of *c.* 6-7 x 10^5 mg SO_4/kg/flush (= *c.* 3-4 x 10^4 kg H_2SO_4/tonne/year for weekly flushing-drying-cycles) under weathering conditions near-optimal for sulphide-oxidation (viz. typical moisture/aeration-regimes, on a weekly basis, in which sulphide-oxidation is limited by neither the O_2-supply [via diffusion], nor H_2O-supply/flushing).

Given the Sulphide-S values of the tailings-solids samples, these SORs are up to 10^4-10^5 **faster** than those typical for the circum-neutral weathering, under near-optimal conditions, of mine-waste materials that contain "trace-sulphides" that are not atypically reactive (e.g. framboidal-pyrites, and marcasites).

APPENDIX A

DETAILS OF PROCESS-TAILINGS-SLURRY SAMPLES

BATTERYLIMITS

BATTERYLIMITS ABN 41 009 631 654 16 Ventnor Ave West Perth 6005 PO Box 1893 West Perth 6872 T: 61 8 9481 4358 or 61 438 838 600 F: 61 8 9481 4359 www.batterylimits.com.au

MEMORANDUM

TO	Doug Cooper	**COPIES**	File		
FROM	Tony Showell	**JOB NO.**		**DATE**	6 March 2007
SUBJECT	Spinifex Ridge Tailings – Samples for Geo-Chem Testing				

Doug

As requested, two samples of tailings were taken during the pilot plant run at Ammtec in December 2006 for geo-chemical testing by Graeme Campbell & Associates Ltd. The Ammtec pilot plant operated on a continuous basis to represent the processing treatment route proposed for the Spinifex Ridge Project.

For each sample, the total bulk Cu-Mo scavenger flotation tails was diverted to a 200L drum and settled to obtain approximately 20 L of 55% solids slurry for testing. The bulk Cu-Mo scavenger flotation tails makes up approximately 99% of the total tailings from the plant. In order to make the samples representative of the final tailings to the dam, a measured proportional amount of tailings from the copper flotation section (which was piloted separately) was added and blended to the collected sample.

Composite A bulk sample was taken on 6th December 2006. Composite A sample is considered to represent tailings during early years of the plant before significant amounts of Granodiorite ore are mined.

Composite B sample was taken on the 5th December. Composite B feed ore is considered to represent higher grade ore with (increased amount of Granodiorite) representing feed ore in later years of the project.

The two samples were labelled Composite A Tailings and Composite B Tailings and despatched to:

Graeme Campbell & Associates Pty Ltd
Testing Laboratory
Unit B, 15 Rose St.
Bridgetown, WA 6255

Tony Showell

APPENDIX B

TESTWORK METHODS

APPENDIX B

TESTWORK METHODS

B1.0 ACID-BASE-CHEMISTRY TESTWORK ON TAILINGS-SOLIDS SAMPLES

The acid-base chemistry of the tailings-solids samples was assessed by determining:

- Total Sulphur (Total-S) and Sulphate Sulphur (SO_4-S).
- Acid-Neutralisation Capacity (ANC), and Carbonate Carbon (CO_3-C).
- Net-Acid-Producing Potential (NAPP).
- Net-Acid Generation (NAG).

Relevant details of the testwork methods employed are discussed briefly below. Further details are presented in the laboratory reports (see Appendix C).

B1.1 Total-S and SO_4-S Tests

The Total-S values were measured by Leco combustion (@ 1300 °C) with detection of evolved $SO_{2(g)}$ by infra-red spectroscopy. The SO_4-S values were determined by the Na_2CO_3-Extraction Method (Berigari and Al-Any 1994; Lenahan and Murray-Smith 1986).[1]

The difference between the Total-S and SO_4-S values indicates the Sulphide-S (strictly Non-Sulphate-S) content.

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[1] The Na_2CO_3-reagent extracts SO_4-S which occurs as soluble sulphates, and calcium sulphates (e.g. gypsum and anhydrite). It also extracts SO_4 sorbed to the surfaces of sesquioxides, clays and silicates. However, SO_4 present as barytes ($BaSO_4$) is not extracted, and SO_4 associated with jarositic-type and alunitic-type compounds is incompletely extracted.

B1.2 ANC, CO_3-C and pH-Buffering Tests

B1.2.1 ANC Tests

The ANC values were determined by a procedure based on that of Sobek *et al.* (1978). This procedure is essentially the "standard" method employed for estimating the ANC values of mine-waste materials (Morin and Hutt 1997; BC AMD Task Force 1989).

The samples were reacted with dilute HCl for *c.* 2 hours at 80-90 ^{o}C, followed by back-titration with NaOH to a pH=7 end-point to determine the amount of acid consumed.[2] The simmering step for *c.* 2 hours differs slightly from the heating treatment of the Sobek *et al.* procedure wherein the test mixtures are heated to near boiling until reaction is deemed to be complete (viz. gas evolution not visually apparent), followed by boiling for one minute. In terms of dissolution of carbonate, primary-silicate and oxyhydroxide minerals, this variation to the Sobek *et al.* method is inconsequential.

The Sobek *et al.* (1978) procedure exposes mine-waste samples to both strongly-acidic conditions (e.g. pH of 1-2), and a near-boiling temperature. Provided excess acid is added, this method ensures that carbonate-minerals (including ferroan- and manganoan-varieties) are dissolved quantitatively, and that at least "traces" of ferro-magnesian-silicates (e.g. amphiboles, pyroxenes, chlorites, micas, etc.), and feldspars, are dissolved. However, under circum-neutral (viz. pH 6-8) conditions required for mine-waste and environmental management, the hydrolysis/dissolution of ferro-magnesian-silicates is kinetically extremely slow (e.g. see review-monograph by White and Brantley [1995]). Near pH=7, the hydrolysis/dissolution rates (under 'steady-state' conditions, and in the absence of inhibiting alteration-rims) of mafic-silicates and feldspars generally correspond to H_2SO_4-consumption rates 'of-the-order' $10^{-11}/10^{-12}$ moles/m^2/s (White and Brantley 1995). As a guide, for minerals of sub-mm grading, such silicate-dissolution rates correspond to Sulphide-Oxidation Rates (SORs) ranging

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[2] Two drops of 30 % (w/w) H_2O_2 were added to the test mixtures as the pH=7 end-point was approached, so that any Fe(II) forms released by the acid-attack of ferroan-carbonates and -silicates are oxidised to Fe(III) forms (which then hydrolyse to "Fe(OH)$_3$"). This step ensures that the resulting ANC values are not biased "on-the-high-side", due to the release of Fe(II) during the acidification/digestion step. Such potential bias in ANC values may be marked for mine-waste samples in which "Fe-rich" ferroan-carbonates (e.g. siderite) dominate acid consumption. The addition of the H_2O_2 reagent is not part of the methodology described by Sobek *et al.* (1978).

up to 'of-the-order' 1-10 mg SO_4/kg/week (= *c.* 0.1-1.0 kg H_2SO_4/tonne/year).[3] Maintenance of circum-neutral-pH through hydrolysis/dissolution of primary-silicates is therefore restricted to both "mineral-fines", and slow rates of sulphide-weathering.

Despite the aggressive-digestion conditions employed, the ANC values determined by the Sobek *et al.* (1978) method allow an informed, initial "screening" of mine-waste materials in terms of acid-consuming and pH-buffering properties, especially when due account is taken of gangue mineralogy (Morin and Hutt 1997). Jambor *et al.* (2000, 2002) have presented a compendium of 'Sobek-ANC' values for specific classes of primary-silicates, and assists interpretation of the ANC values recorded for mine-waste materials of varying mineralogy.

B1.2.2 CO_3-C Values

The CO_3-C value is the difference between the Total-C and Total-Organic-C (TOC) values.

The Total-C was measured by Leco combustion (@ 1300 °C) with detection of evolved $CO_{2(g)}$ by infra-red spectroscopy. The TOC is determined by Leco combustion on a sub-sample which has been treated with strong HCl to decompose carbonate-minerals.

B1.2.3 pH-Buffering Properties

The pH-Buffering properties of the tailings-solids samples were determined via a Metrohm® 736 Titrino auto-titrator, and 0.05 M-H_2SO_4.

The auto-titrations comprised regular addition of the H_2SO_4 reagent to monotonically decrease the pH values of the test-suspensions to 3.0.[4] The Start-pH values of the test-

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[3] SORs of this magnitude (at circum-neutral-pH) would typically only be recorded for the oxidation of "trace-sulphides" (e.g. Sulphide-S contents less than 0.5 %).

[4] It should be noted that, in titrating to a pH=3.0 end-point, any Fe(II) released through acid attack of ferroan-silicates and -carbonates is not quantitatively oxidised to Fe(III). Furthermore, under the conditions employed in the auto-titration, the equivalent of *c.* 0.5 kg H_2SO_4/tonne was required to decrease the pH of the "solution-only" (i.e. without tailings-solids sample) to pH=3.0. No correction was made for such "electrolyte-consumption" of the 0.05 M-H_2SO_4 titrant.

suspension was *c.* 9. Under the testwork conditions employed, the H_2SO_4-addition rates correspond to very-rapid rates of acid addition.

Further details of the auto-titrations are presented in the laboratory reports (Appendix C).

B1.3 NAPP Calculations

The NAPP values of the tailings-solids samples were calculated from the Total-S, SO_4-S and ANC values, assuming that **all** of the Non-Sulphate-S occurs in the form of pyrite/pyrrhotite. The sulphide-mineral suite in the tailings-solids samples was co-dominated by pyrite and pyrrhotite (Table 4.2). NAPP calculations serve as a starting point in the assessment of the acid-formation potential of sulphide-bearing materials.

The complete-oxidation of pyrite may be described by:

$$FeS_2 + 15/4\ O_2 + 7/2\ H_2O = 2H_2SO_4 + \text{"}Fe(OH)_3\text{"}$$

The complete-oxidation of pyrrhotite may be described by:

$$\text{"}FeS_{(s)}\text{"} + 9/2O_{2(g)} + 5/2H_2O_{(l)} = \text{"}Fe(OH)_{3(s)}\text{"} + 2SO_4^{2-}{}_{(aq)} + 2H^+{}_{(aq)}$$

Pyrrhotite is non-stoichiometric, so that expressing pyrrhotite as "FeS" in the above equation represents an approximation of the oxidation reaction (Belzile *et al.* 2004; Janzen *et al.* 2000). Elemental sulphur (as an intermediate-oxidation product) may also accumulate during pyrrhotite weathering (Nicholson and Scharer 1994), especially at low-pH. However, Elemental-S is ultimately oxidised to H_2SO_4 (albeit via a complex, microbially-mediated pathway involving thiosulphate and an array of polythionates).

It may be shown that, if the Sulphide-S (in %S) occurs as pyrite, and/or pyrrhotite, then the amount of acid (in kg H_2SO_4/tonne) produced through complete-oxidation is given by **30.6 x %S**. The NAPP value of the tailings-solids sample was therefore calculated from the Sulphide-S content (in %S), and 30.6 as the 'conversion-factor' to estimate the amount of acid that may potentially be produced through the aerobic-oxidation of pyrrhotite/pyrite.

It may be shown that, if the Sulphide-S (in %S) occurs as pyrite/pyrrhotite, then the amount of acid (in kg H_2SO_4/tonne) produced through complete-oxidation is given by **30.6 x %S**.

> Note: The above treatment of oxidation-reaction stoichiometry is restricted to oxidation by 'atmospheric-O_2' which is the dominant oxidant at circum-neutral-pH. A different oxidation-stoichiometry applies under acidic conditions (e.g. pH less than 3-4) where soluble-Fe(III) forms prevail, and then function as the chief oxidant (e.g. Rimstidt and Newcomb 1993).

Mechanistic aspects of pyrite-oxidation and pyrrhotite-oxidation at the molecular-scale were recently reviewed by Rimstidt and Vaughan (2003), and Belzile *et al.* (2004), respectively.

B1.4 NAG Tests

The NAG Test is a direct measure of a sample's potential to produce acid through sulphide oxidation, and also provides an indication of the reactivity of the sulphides, and the availability of the alkalinity-forms contributing to the ANC (Miller *et al.* 1997, 1994).

In this test, the sample is reacted with H_2O_2 to rapidly oxidise contained sulphides, and allow the produced acid to react with the acid-neutralising materials (e.g. carbonates). The NAG Test supplements the NAPP-based assessment of the acid-formation potential of mine-waste materials (Morin and Hutt 1997).

The procedure employed in this study is based on that for the 'Static-NAG Test' in its 'single-addition' mode, as described in AMIRA (2002), and by Miller *et al.* (1994, 1997). The Start-pH of the 15 % (w/w) H_2O_2 solution (prepared from A.R.-grade H_2O_2) was adjusted to pH=4.5 using dilute NaOH. In addition, the boiling treatment to decompose residual, unreacted-H_2O_2 following overnight reaction was carried out in two stages (viz. boiling for *c.* 2 hours initially, cooling and addition of 1 mL of 0.02 M-

$CuSO_4$ to the test mixtures, followed by boiling again for *c.* 2 hours). The addition of Cu(II) salts catalyses the decomposition of any unreacted-H_2O_2, and thereby prevents "positive-blank" values being obtained (O'Shay *et al.* 1990). Pulped K-feldspar was employed for the blanks run for the NAG-testwork.

Prior to the boiling-steps, the pH values of the test-mixture suspensions are measured, and invariably correspond to an "overnight-period" of reaction. Such pH values reflect buffering under ambient conditions without accelerated dissolution of gangue-phases through boiling to decompose any unreacted-H_2O_2. In the interpretation of NAG-testwork data, it is important to take note of the pH values recorded prior to the boiling-steps, especially for mine-waste samples that have both Sulphide-S contents less than *c.* 1 %, and ANC values less than *c.* 10 kg H_2SO_4/tonne (as typically recorded for a 'carbonate-deficient' gangue). Furthermore, oxidation by H_2O_2 is generally at least 10^4-10^5 faster than the SORs recorded during 'kinetic' testing (e.g. Weathering-Columns) of mine-waste samples. If circum-neutral conditions are to prevail during NAG testwork, then the rate of acid consumption by gangue-phases must be proportionately faster (c.f. rates for 'ambient-weathering'). This aspect must also be borne in mind when interpreting NAG-testwork data, especially for mine-waste materials that are devoid of carbonates, since the dissolution/hydrolysis kinetics of primary-silicates are strongly pH-dependent.

B2.0 MULTI-ELEMENT ANALYSES ON TAILINGS-SOLIDS SAMPLE

The total contents of a wide range of major- and minor-elements in the tailings-solids samples were determined through the use of various digestion and analytical techniques. The detection-limits employed are appropriate for environmental investigations.

Element enrichments were identified using the *Geochemical Abundance Index (GAI)*.[5]

The GAI quantifies an assay result for a particular element in terms of the average-crustal-abundance of that element.[6] The GAI (based on a log-2 scale) is expressed in 7 integer increments (viz. 0 to 6). A GAI of 0 indicates that the content of the element is less than, or similar to, the average-crustal-abundance; a GAI of 3 corresponds to a 12-fold enrichment above the average-crustal-abundance; and so forth, up to a GAI of 6 which corresponds to a 96-fold, or greater, enrichment above average-crustal-abundances.

B3.0 ANALYSIS OF TAILINGS-SLURRY-WATER SAMPLES

The tailings-slurry-water samples were analysed for pH, Electrical Conductivity (EC), salinity (as Total-Dissolved Solids, TDS), alkalinity forms, Cl, SO_4, NO_3, NH_3-N, and a wide range of major- and minor-elements employing detection-limits appropriate for environmental investigations.

All analyses were performed on appropriately-preserved 'splits' for the determination of specific analytes (see Appendix C).

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[5] The GAI was developed by Förstner *et al* (1993), and is defined as:

$$\text{GAI} = \log_2 [C_n/(1.5 \times B_n)]$$

where:

C_n = measured content of n-th element in the sample.
B_n = "background" content of the n-th element in the sample.

[6] The average-crustal-abundances of the elements for the GAI calculations are based on the values listed in Bowen (1979).

APPENDIX C (not included in web download file)

LABORATORY REPORTS