Acid and Metalliferous Drainage Potential of an Alluvial Gold Mine Operation

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Abstract

A proposed alluvial gold mining project north of Westport has been assessed for the potential to generate acid and metalliferous drainage (AMD) due to a potentially acid forming overburden. Alluvial gold occurs in two heavy mineral sand leads separated by uneconomic interburden sands and gravels, as marine and alluvial terraces preserved during Quaternary-Recent regional uplift. A 2-5 m thick landslide debris deposit overlies the terraces, comprised of sandstone, mudstone, conglomerate and coal derived from Eocene-Oligocene Brunner Coal Measures and Kaiata mudsone. Acid base accounting analysis of the overburden indicates that there is potentially acid forming material associated with the landslide debris, likely pyrite and acidic oxidation products generated from prior pyrite oxidation. Based on a proposed 27 ha mining area, approximately 816,000 m^3 of acid forming waste rock will need to be managed which equates 8.3 vol.% of the total rock to be moved during mining. As the overburden is removed during mining, pyrite could be exposed to water and air, oxidising and potentially resulting in AMD, and oxidation products could be mobilised, both of which could impact the aquatic receiving environment. Management of AMD at the mine site will involve a hierarchical approach to the prediction, prevention, minimisation, control, and treatment. A key component of the AMD management strategy will be planning for mine closure to minimise legacy issues associated with in-perpetuity uncontrolled AMD.

Keywords: Acid base accounting, Brunner Coal Measures, Kaiata Mudstone, landslide, placer gold

Introduction

Alluvial gold mine operations have to manage high suspended solids and turbidity in mine discharge waters (Druzbicka and Craw, 2013; Malloch *et al*., 2017). Issues with acid and metalliferous drainage (AMD) are rare at alluvial operations but can occur where the alluvial deposit or the overburden contain sulfide minerals (*e.g.,* Falconer and Craw, 2005). AMD is more commonly associated with the mining of hard rock sulfide-rich deposits (Lottermoser, 2010) and coal deposits (Pope *et al.*, 2006; Elder *et al.,* 2011; Olds *et al.,* 2013a) and occurs due to sulfide oxidation lowering the pH and releasing metals into solution (Jambor *et al.,* 2000; Bigham and Nordstrom, 2000; Hughes *et al.,* 2004).

This paper investigates the acid potential of an alluvial gold deposit located on the West Coast, to manage potentially acidic drainage when mining. Initial investigations have identified a landslide debris deposit partially comprised of coal measures that are potentially acid forming (PAF) overlying the alluvial gold deposit. Acid base accounting (ABA) on different rock types at the property and an AMD treatability study on the landslide debris are used to assess likely drainage conditions during mining operations and treatment options.

General Setting and Geology

The property is located 7.5 km east of Westport on the Giles Terrace near Sergeants Hill (Fig. 1). The proposed alluvial mining operations will cover an area of approximately 27.2 ha over the life of the mine, progressively mining a placer gold deposit from south to north (Welsh and Calder, 2015). The two terraces on the property are stepped, orientated NE to SW with a scarp approximately 30 m high between them.
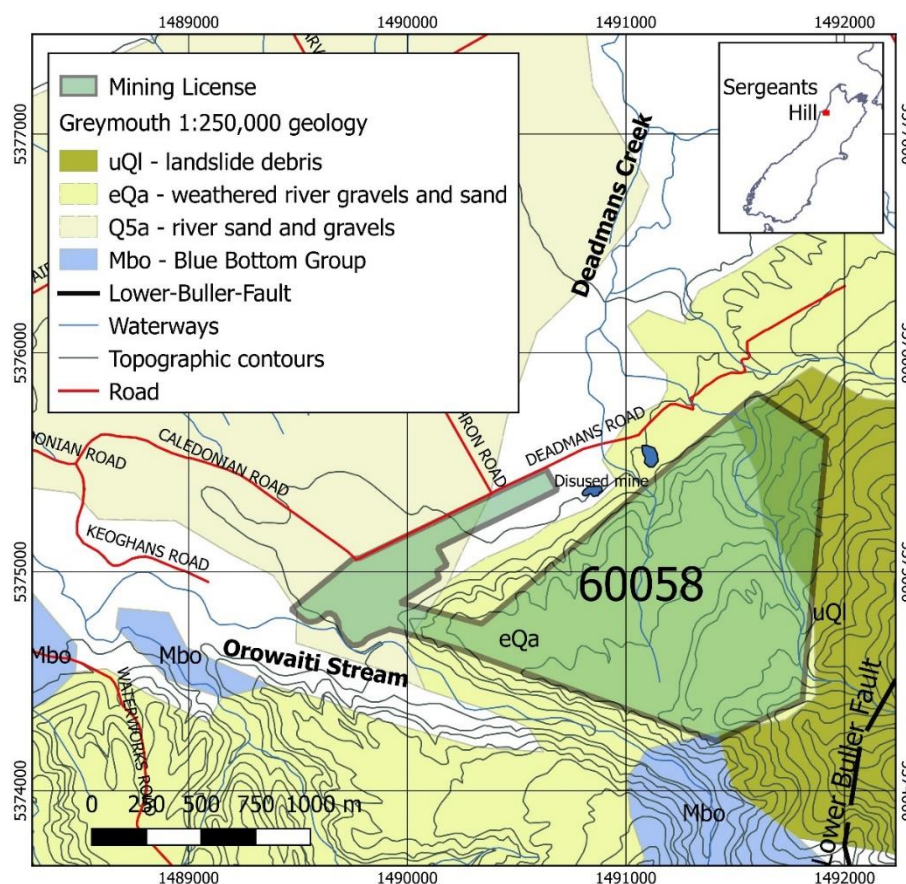

Figure 1. Location map of Sergeants Hill Alluvial Gold property, covered by Mining License 60058. Geology taken from Nathan *et al*. (2002).

Placer gold deposits on the West Coast have been worked for gold since the 19th century gold rushes (Nathan *et al*., 2002). The Giles Terrace has been previously mined by tunnelling into the underlying Miocene to Pliocene Blue Bottom Group sediments to reach the unconformably overlying gold-rich leads in the marine gravels immediately above (Inwood, 1997). One of these tunnels, the Wilsons drive, was worked up to the 1930s (Pfahlert, 1996). Recent activity by Pfahlert (late 1990s) included bulk sampling of gold leads immediately above the Blue Bottom Group by trenching of the lower terrace, near Deadmans Creek (Davidson, 2000).

The gold occurs as fine flakes in marine heavy mineral concentrates separated by uneconomic interburden sands and gravels in marine and alluvial terraces, preserved during Quarternary to Recent regional uplift (Pfahlert, 1996; Black Lion Limited, 2015). Two leads have been identified on the property, the lower 12 grain wash (9 m thick) and the upper 8 grain wash (7 m thick) (Black Lion Limited, 2015).

At the property, 2-5 m of landslide debris deposit overlies the uplifted terraces. Gravitational collapse along the Lower Buller Fault (Kongahu Fault Zone) has formed complex landslide materials over several hundred thousands of years (Inwood, 1997). The landslide debris deposit consists of sandstone, mudstone, conglomerate and coal derived from Eocene Brunner Coal Measures (BCM) and Eocene-Oligocene Kaiata mudstone (KM), as well as granite basement, from the Escarpment above (Inwood, 1997; Nathan *et al.,* 2002). Acid base accounting (ABA) indicates that the BCM and KM are potentially acid forming (PAF) due to pyrite within the deposits oxidising and generating acidity (Hughes *et al.,* 2004; Pope *et al.*, 2006).

Two streams bound the property, the Deadmans Creek to the north and Orowaiti River to the south (Fig. 1.). A small tributary, Deadmans Creek South, drains the property and has the potential to be affected by the proposed mining activities. Baseline water quality sampling for the waterways are pH circum-neutral with low conductivity, low acidity and low dissolved metals suggesting that these waterways are not impacted by AMD (OKC, 2016).

The Orowaiti trial mining pit was recently excavated by Grifis Mining Limited (GML) into the upper 8 grain wash (Fig. 2A-D). Overlying this lead is landslide debris comprised of a dark brown mudstone (either BCM or KM) (Fig. 2B), with a variety of coarser grained boulders and cobbles (10-20 % by volume). The presence of a sulfurous smell, iron staining and yellow-green precipitates, assume to be jarosite, suggest pyrite oxidation. An iron hardpan has formed at the contact between the alluvial gravels with the overlying landslide debris (Fig. 2C).
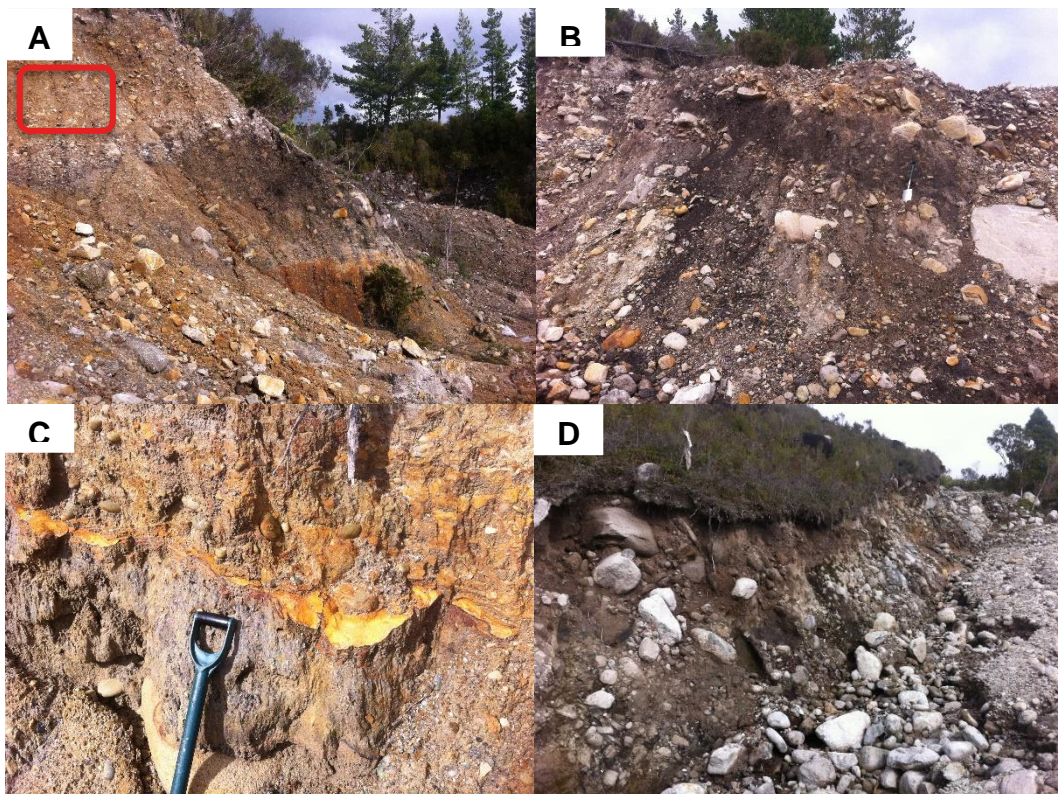

Figure 2. Field photos of lithological units at Giles Terrace A) Orowaiti trial pit, red square indicates where colluvium sample was taken, note iron staining in the landslide debris below. B) Dark brown mudstone in landslide debris, Orowaiti trial pit. C) Iron hardpan between overlying landslide debris and underlying auriferous gravels, Orowaiti trial pit. D) Cutting in the Deadmans Creek test pit exposing oxidised landslide debris.

The historic test pit near Deadmans Creek excavated in the late 1990s for bulk sampling (Pfahlert, 1996; Davidson, 2000) exposes weathered landslide debris (Fig. 2D). The outcrops consists of oxidised brown mudstone, BCM coal and basal conglomerate boulders, with boulders comprising 50% of the material. Iron-staining was minor, and no sulfurous or jarosite was observed in this test pit.

Methodology

Field samples were taken from the Orowaiti trial pit of the overlying colluvium (Fig. 2A), dark brown landslide debris, Fe hardpan, and Fe stained gravels (8 grain wash) beneath the hardpan (Fig. 2B, 2C). Two samples of weathered landslide debris from the historic test pit near Deadmans Creek were combined in the laboratory as a composite sample (Fig. 2D). A road cut along the site access road provided two samples of the interburden between the two auriferous leads. Samples were sent to the International Accreditation New Zealand (IANZ) SGS laboratory in Westport for ABA testwork (Table 1) to provide an indication of the potential to generate AMD.

Table 1. ABA testwork methodologies

Total S	Total sulfur (wt%). determined by LECO furnace methodologies
MPA	Maximum Potential Acidity (kg H_2SO_4 equivalent), where MPA = wt% S multiplied by 30.6 (stoichiometric conversion factor for wt% S to kg H_2SO_4/tonne). All S assumed to be pyrite
ANC	Acid Neutralisation Capacity (kg H_2SO_4 equivalent), determined by acid digest of the sample followed by back titration to pH 7.0 to determine the amount of acidity consumed
NAPP	Net Acid Production Potential (kg H_2SO_4/tonne equivalent), where NAPP = MPA – ANC
Paste pH	pH measurement of a 1:2 solid to liquid solution
NAG	Net acid generation (kg H_2SO_4 equivalent), 2.5 g of waste rock and 250 mL of 15% H_2O_2, which rapidly oxidises any sulfides present thereby releasing acidity and metals. Any acid released reacts with any reactive neutralising gangue minerals that can provide acidity neutralisation to produce a final NAG pH value at the completion of the test. Back titration of this solution to pH 7.0 provides an indication of the NAG acidity on kg H_2SO_4/t

An AMD water analogue was prepared in the laboratory from landslide debris for a AMD treatability study (Sample 3, Table 2.). Preparation involved the mixing of deionised water with the sample at a liquid to solid ratio of 20:1, and stirring gently for four hours to produce an AMD impacted liquor. The digested liquor was filtered and then analysed for Al, Cd, Cu, Fe, Ni, and Zn based on the dataset provided by Pope et al (2010) used to determine contaminants of concern associated with acid-forming coal measures. Acidity in the digestion liquor was then neutralised using 1M NaOH. The neutralisation process was replicated on five different AMD samples with pH endpoints of pH 5, 6, 7, 8, and 8.5. The neutralisation solutions were held at the target pH to allow for pH buffering. Supernatant samples were collected (including a control with no NaOH neutralisation) and submitted for analysis. Acidity neutralised was back calculated based on the amount of NaOH titrated into the sample. Acidity is reported in H_2SO_4 equivalent units. It is assumed that if a calcium based reagent were used for acidity neutralisation (calcium hydroxide - $Ca(OH)_2$, limestone - $CaCO_3$, etc.) the hardness (also reported in H_2SO_4 equivalent units) would be equal to the acidity neutralised.

Results

ABA Analyses

The low paste pH and NAG pH values, negative ANC and positive NAPP from ABA analysis indicates there are PAF rocks present, associated with the landslide debris in the Orowaiti pit (samples 2, 3 and 4 in Table 2). The oxidised landslide debris in the Deadmans Creek pit had higher paste pH and NAG pH values, but the positive NAPP and negative ANC indicate a PAF designation. Sulfide sulfur are typically less than half the total sulfur, which indicates the presence of either organic sulfur, non-acid forming sulfate minerals, or acid forming sulfate minerals. It is likely to be a combination of these. The data clearly indicates a zone of acid forming materials overlying the auriferous gravels, associated with BCM and KM material in the landslide debris. Circum-neutral NAG and paste pH of the auriferous gravels (8 grain wash) and interburden material and negative NAPP values indicate low/ negligible acid potential.

Table 2. Results from ABA testwork on lithologies at Giles Terrace

Sample Type	Field Description	Sulfur (Total)	Sulfur (Sulfide)	MPA (Total S)	MPA (Sulfide S)	Paste pH	NAG pH	ANC	NAPP (based on Total S)
		$wt\%$	$wt\%$	kg H_2SO_4/t	kg H_2SO_4/t	$-Log_{10}[H^+]$	$-Log_{10}[H^+]$	kg H_2SO_4/t	kg H_2SO_4/t
1) Orowaiti - colluvium	Mixed, weathered	0.005	0.005	0.153	0.15	6.3	6.1	5.0	-4.85
2) Orowaiti - landslide debris	Black KM, jarosite, sulfurous	0.233	0.05	7.13	1.53	3.9	3.7	-7	7.13
3) Orowaiti - landslide debris	Black KM, jarosite, sulfurous	0.614	0.23	18.79	7.04	3.7	2.8	-10	18.79
4) Orowaiti - landslide debris	Coarser grained KM	0.475	0.1	14.54	3.06	4.6	3.2	-8	14.54
5) Orowaiti – gravels (Au)	Fe colour/ cement	0.039	0.01	1.1934	0.31	6.4	6.2	8	-6.81
6) Orowaiti - Fe hardpan		0.031	0.005	0.9486	0.15	6.1	7.4	19	-18.05
7) Dead-mans Creek	Oxidised, landslide debris	0.272	0.005	8.3232	0.15	5.1	4.5	-15	8.32
8) Road cutting - interburden material	Fe stained poorly indurated	0.002	0.005	0.0612	0.15	6.3	6	7	-6.94

Red cells indicates potential PAF materials based on NAPP; red text = half the Limit of Reporting (LOR)

Field observations in the Orowaiti pit of a sulfurous smell, iron staining and the presence of jarosite, all suggest pyrite oxidation and confirm the possibility of acid and metalliferous mine drainage (AMD) (Fig. 2; Bigham and Nordstrom, 2000; Jambor *et al.,* 2000). Iron hardpan

formation indicates the mobilisation of Fe from the landslide debris, again likely due to pyrite oxidation.

AMD Analogue Treatability Study

The AMD water analogue had an acidity to pH 8.5 of 280 mg H_2SO_4/L (Fig. 3A). The acidity titration data shows hydrolysis of the 39.3 mg/L Al causes buffering in the pH 4 to 5 range. In addition to Al, Fe is a major contributor to sample acidity, with both Al and Fe concentrations removed by titration to pH 5 (Fig. 3B). Removal of Al and Fe corresponds to neutralisation of the majority (210 mg H_2SO_4/L) of sample acidity. Increasing pH triggered removal of minor elements by a combination of hydrolysis and adsorption reactions; at pH 5 for Cu, pH 6 for Zn, and pH 7 for Cd and Ni (Fig. 3C).
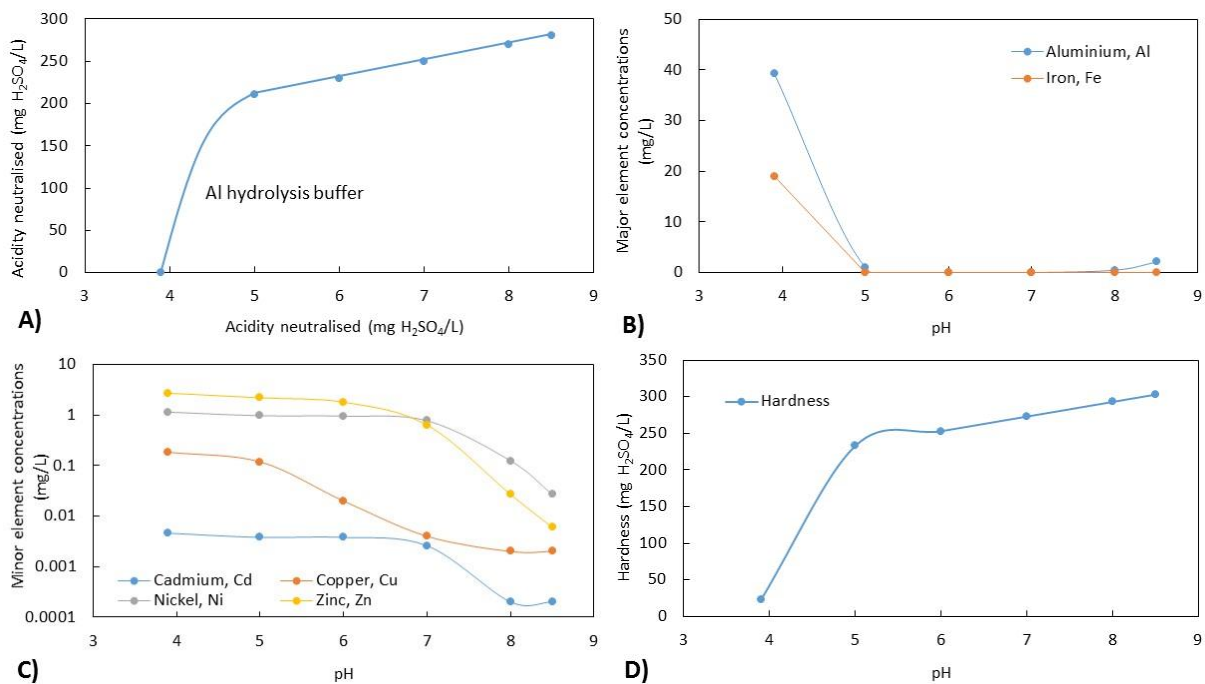

Figure 3. AMD analogue sample for landslide debris at Grifis. A) Acidity neutralisation as a function of pH. B) and C) Metal concentration as a function of pH. D) If a calcium-based neutralent was used to correct AMD, there would be a significant increase in hardness.

Metal eco-toxicity quotient (MEQ) analysis is used to identify contaminants of concern with respect to water quality compliance limits or trigger values (Weber and Olds, 2016). Trigger values may be set by resource consents, agreed community targets, or published guidelines (*e.g.,* ANZECC, 2000). Compliance limits for Cd, Cu, Ni and Zn have been corrected for site specific hardness according to ANZECC (2000) guidelines, assuming that a calcium-based neutralent will be used to correct discharge pH. The MEQ value for a given parameter is determined by dividing the measured concentration by the compliance limit / trigger value (Fig. 4A-F). MEQ values greater than 1 indicate parameters which exceed water quality guidelines. Conversely, MEQ values less than 1 are below compliance and are unlikely to require routine monitoring.

Neutralisation of the AMD to pH 7 is likely sufficient for the removal of Cu and Zn below the site specific resource consent limits (RC conditions, Fig. 4C, 4F). While not regulated by the site resource consent, neutralisation of AMD to pH 8-8.5 will be required to meet ANZECC

(2000) guidelines for Cd and Ni (Fig. 4C, 4E). Due to the amphoteric nature of Al, neutralisation of AMD above pH 7 results in an Al concentration rebound and at pH 8 MEQ exceeds 1 indicating non-compliance (Fig. 4A). Iron compliance is unlikely to be an issue if discharge water is kept circum-neutral (Fig. 4D).
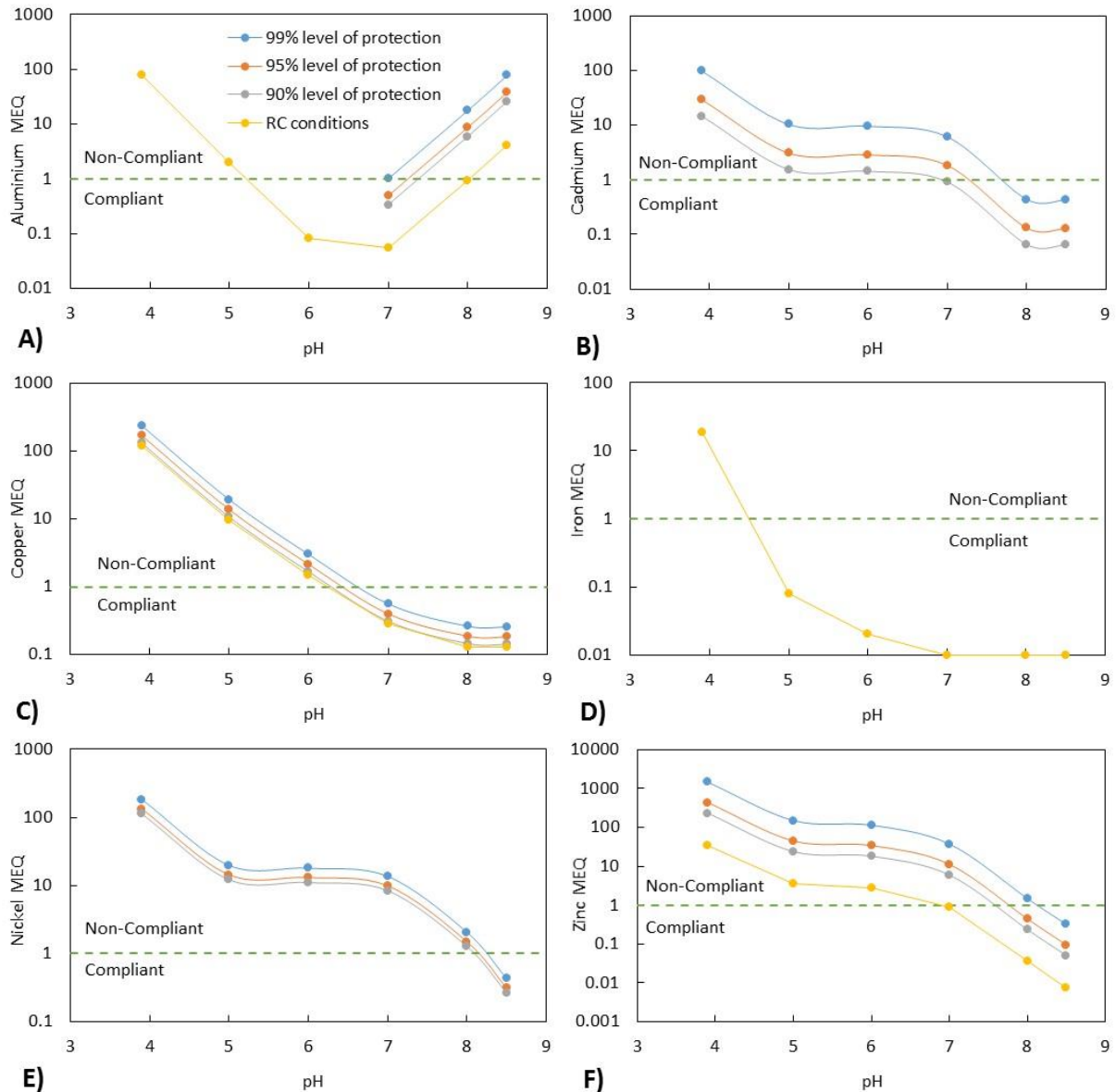

Figure 4A-F. MEQ values as a function of pH (The first three compliance guidelines are from ANZECC (2000), RC conditions are resource consent guidelines specific to the Grifis site).

Discussion

Acidic Drainage Potential

Initial baseline water quality data indicate that local creeks are not affected by AMD (OKC, 2016). ABA analysis has determined that the landslide debris overburden has the potential to produce acidic drainage during mining. However, the entire unit is not comprised of PAF rock, with 10-20% of the landslide debris comprised of large sandstone boulders (non-acid

forming, NAF) at Orowaiti and 50% of the landslide debris at the historic pit at Deadmans Creeks comprise of NAF boulders. Based on a proposed 27 ha mining area, approximately 816,000 m^3 of acid forming landslide debris waste rock will need to be managed which equates 8.3 vol.% of the total rock to be moved during mining. As the overburden is removed during mining, pyrite will be exposed to water and air, oxidising and potentially resulting in AMD that could impact the aquatic receiving environment. Stored acidity associated with oxidation products could also contribute to poor water quality if water mobilises this contaminant load.

Based on negative ANC values and paste pH data the total sulfur data would be more appropriate for NAPP calculations. It is likely total sulfur data could be used to confirm AMD potential during operational activities, although more data will be required (Olds *et al*., 2015). The treatability study confirmed that AMD can be generated from the landslide debris with Al, Cd, Cu, Fe, Ni and Zn leached from the material. In laboratory trials, without treatment, the concentration of these metals in the AMD were above the site specific resource consent compliance and ANZECC compliance limits (Fig. 4).

Implications for Discharge Compliance

Processes including hydrolysis and adsorption/co-precipitation to Fe and Al hydroxide precipitates remove Cd, Cu, Ni and Zn at increasing pH levels from the AMD analogue sample. Where the AMD analogue was neutralised to pH 8.5, the reduction in metallic element concentration was between one and three orders of magnitude. If a calcium based neutralent is used to raise the pH and remove the metals, a significant increase in water hardness will occur (Fig. 3D). This has important implications from a compliance prospective, where the toxicity of Cd, Cu, Ni and Zn may be ameliorated by increased water hardness (Fig. 4B-C, 4E-F; ANZECC 2000).

MEQ analysis indicates that a neutralisation of AMD to at least pH 7 prior to discharge from the site will be required for compliance with site resource consent conditions. This is governed by Zn where an increase to pH 7 is required to achieve a hardness modified MEQ value of less than 1. Compliance with the more stringent ANZECC for Cd, Ni, and Zn would require an increase to pH 8 prior to discharge, though this is not formally required by the resource consent. The benefit of additional removal of Cd, Ni, and Zn would have to be evaluated against the potential rebound in Al concentration at higher pH.

The 280 mg H$_2$SO$_4$/L acidity of the AMD used in this treatability analysis is relatively low compared to Ni (1.15 mg/L) and Zn (2.73 mg/L) concentrations. At the nearby Stockton Coal Mine these Ni and Zn conventions are more commonly associated with an acidity of approximately 800 mg/L (Elder et al, 2011; Olds et al, 2013a). Incorporating the additional hardness generated by neutralising an acidity of 800 mg H$_2$SO$_4$/L would decrease the MEQ values shown in Fig. 4 by a factor of approximately 2.5. At pH 7 the additional hardness would be sufficient for ANZECC 90th and 95th percentile level of protection compliance for Cd, and at pH 8 Cd and Ni would be compliant with all ANZECC levels of protection criteria.

Engineering Controls to Mitigate AMD

The prevention of AMD is achieved by preventing the interaction of the principal constituents of the AMD production process, namely sulfide minerals such as pyrite and stored oxidation products, with oxygen and water (Jambor *et al.,* 2000; Hughes *et al.,* 2004). Where prevention

is not possible, the objective is to minimise oxidation of sulfide minerals, minimise transportation (by water) of stored oxidation products and hence minimise the impact of AMD on the receiving environment. It is proposed that some PAF landslide overburden will be placed within an engineered landform (ELF), to minimise oxygen ingress by diffusion and thereby limiting sulfide oxidation. Any AMD from the ELF will be treated by passive treatment technologies to prevent the release of untreated AMD influenced water to the receiving environment. It is expected that PAF materials will also be placed within the pit during operations, eventually buried beneath the final rehabilitated ground level. Such an opportunity for in-pit disposal, which is different to the original conceptual mine plan, will be developed as further data becomes available (*e.g.,* permeability of the underlying strata) under an adaptive management approach of AMD.

Water quality monitoring during mine operation will be an important component of understanding whether control strategies will be effective. AMD management will include planning for mine closure to minimise legacy issues associated with in-perpetuity uncontrolled AMD.

Conclusion

Acid base accounting has identified PAF rock overlying an alluvial gold deposit that will require management during mining and closure to minimise AMD impacts to the receiving catchment. PAF rock is comprised of BCM and KM landslide debris containing pyrite, that when exposed to the environment, oxidises producing acidity and releasing metals. A treatability study of the AMD resulted in Cd, Cu, Fe, Ni and Zn leaching from the landslide debris. Without treatment, the concentration of these metals were above site specific resource consent compliance. Mining will create 816,000 m^3 of acid forming waste rock, equating to 8.3 vol.% of the total mined mass. Construction of an ELF will initially facilitate the management of PAF exposed during the box-cut. Any AMD impacted water from the ELF will be managed by low-cost passive treatment technologies. After this initial box-cut, subsequent PAF materials will be buried in-pit to minimise the generation of AMD. Monitoring of water quality during mining operations and after closure will be an important component of AMD management.

Acknowledgements

References

ANZECC. 2000. Australian and New Zealand guidelines for fresh and marine water quality. Paper no. 4. Volume 1: the guidelines. Australian and New Zealand Environment and Conservation Council, Agriculture and Resource Management Council of Australia and New Zealand.

Bigham JM, Nordstrom DK. 2000. Iron and aluminium hydroxysulfates from acid sulfate waters. Reviews in Mineralogy and Geochemistry 40: 351-403.

Black Lion Limited. 2015. Sergeants Hill project geotechnical report. Prepared for Grifis Mining Limited, dated 22 December 2015.

Davidson NC. 2000. Final report PL 312695 Giles Terrace. Ministry of Economic Development, Mineral Report Series, MR3777.

Druzbicka J, Craw D. 2013. Turbidity development and dissipation in paleoplacer gold deposits, southern New Zealand. Environmental Earth Sciences 68: 1575-1589.

Elder DM, Pizey MH, Weber PA, Lindsay P, Rossiter PJ, Rutter GA, Thomas DG, Crombie FM, Cooper T, Wildy JJ. 2011. Addressing the environmental effects of mining on the Ngakawau River. Water New Zealand Annual Conference, Rotorua 9-10th November, 2011.

Falconer DM, Craw D. 2005. Fluvial quartz pebble conglomerates as a source of acid rock drainage and trace elements: a case study from Belle-Brooke, Southland. In: Moore TA, Black A, Centeno JA, Harding JS, Trumm DA. (eds) Metal contaminants in New Zealand. Resolutionz Press, Christchurch, 139-152.

Hughes J, Lindsay P, Peake B, Craw D. 2004. An environmental evaluation of the geochemical properties of Kaiata Mudstone and Brunner Coal Measures, Cypress and Stockton Mines, West Coast, NZ. Proceedings of the Australasian Institute of Mining and Metallurgy, New Zealand branch annual conference proceedings, 29 August to 1 September 2004, Nelson: 41-50.

Inwood KS. 1997. Geologic setting, gravity collapse and hazard assessment of the Kongahu Fault Zone, Westport. Unpublished MSc thesis, University of Canterbury, Christchurch, New Zealand.

Jambor JL, Nordstrom DK, Alpers CN. 2000. Metal-sulfate salts from sulfide mineral oxidation. Reviews in Mineralogy and Geochemistry 40: 303-350.

Lottermoser, B.G. 2010. Mine Wastes: Characterization, Treatment and Environmental Impacts, 3rd ed. Springer-Verlag, Berlin Heidelberg, 400p.

Malloch K, Kerr G, Craw D. 2017. Placer gold in the Cretaceous Blue Spur Conglomerate at Waitahuna, southern New Zealand. New Zealand Journal of Geology and Geophysics in press.

Nathan S, Rattenbury MS, Suggate RP. 2002. Geology of the Greymouth area: scale 1:250,000. Lower Hutt: Institute of Geological & Nuclear Sciences, 58p.

OKC, 2016. Assessment for acid and metalliferous drainage potential – Sergeants Hill alluvial gold project. O'Kane Consultants (NZ) Ltd (OKC) report for Grifis Mining Limited.

Olds WE, Bird B, Pearce JL, Sinclair E, Orr M, Weber PA. 2015. Geochemical classification of waste rock using processing flow diagrams. AusIMM NZ Conference.

Olds WE, Tsang DCW, Weber PA, Weisener CG. 2013a. Nickel and Zinc Removal from Acid Mine Drainage: Roles of Sludge Surface Area and Neutralising Agents. Journal of Mining, vol. 2013, Article ID 698031, 5p.

Olds WE, Weber P, Pizey M. 2014. Alkalinity producing covers for minimisation of acid mine drainage generation in waste rock dumps. In: Miller H, Preuss L. (eds) Proceedings of the eighth Australian Workshop on Acid and Metalliferous Drainage, 253-262.

Pfahlert RT. 1996. Prospecting report PL 31 2695 Giles Terrace. Ministry of Economic Development, Mineral Report Series, MR3776.

Pope J, Newman N, Craw D. 2006. Coal mine drainage geochemistry, West Coast, South Island – a preliminary water quality hazard model. Proceedings of the Australasian Institute of Mining and Metallurgy, New Zealand branch annual conference proceedings, Waihi.

Pope J, Newman N, Craw D, Trumm D, Rait R. 2010. Factors that influence coal mine drainage chemistry West Coast, South Island, New Zealand. New Zealand Journal of Geology and Geophysics 53: 115-128.

Weber, P. and Olds, W. (2016). Optimised water assessment for the environmental management of mining projects. In: Fergusson, D (ed). Proceedings, AusIMM NZ Branch 2016 Conference, Wellington, p. 455 – 466.

Welsh C, Calder S. 2015. Sergeants Hill Project. Resource consent application and assessment of effects on the environment. Prepared by Resource and Environmental Management Ltd for Grifis Mining Limited.