Coal Mine Drainage Geochemistry, West Coast, South Island – a Preliminary Water Quality Hazard Model

J. Pope[1], N. Newman[1], and D. Craw[2]

[1] CRL Energy Ltd, PO Box 29415, Christchurch. j.pope@crl.co.nz

[2] Geology Department, University of Otago, Dunedin

Abstract

Previously published stream quality data and AMD (acid mine drainage) analyses have been collated into a database (DAME – Database for Assessment of Mine Environments) and additional samples including NMD (neutral mine drainage) have been collected from coal mine drainages on the West Coast. Variations in the chemistry of mine drainage samples can be related to four factors:

1. Regional Geology (Brunner Coal Measures or Paparoa Coal Measures)
2. Mine Type (open cast or underground)
3. Hydrogeology
4. Local geology

In general mines hosted in Paparoa Coal Measures produce NMD whereas mines hosted in Brunner Coal Measures produce AMD with highly variable chemistry. Differences in coal mine drainage chemistry between mines hosted in Brunner and Paparoa Coal Measure sequences can be measured with acid-base accounting geochemistry. Correlation of ANC (acid neutralising capacity) and MPA (maximum potential acidity) analysis of rocks with mine drainage samples is substantially better than correlation of NAG (net acid generation) analysis with mine drainage chemistry. It is likely that NAG analysis over estimates acid generation potential of some samples due to release of organic acids that are not released under environmental conditions. In general, differences in mine drainage chemistry between Brunner and Paparoa hosted mines are attributed to the effect depositional environment and diagenesis on coal measure composition. Exceptions to generalisations relating mine drainage to Paparoa or Brunner host rocks are likely where local geological conditions cause increased deposition of pyrite in Paparoa rocks and additional analyses are required to confirm interpretations.

Based on the interpretation of these results a mine drainage chemistry hazard model has been constructed. The hazard model predicts likely variations in mine drainage chemistry based on the four factors listed above. The hazard model has implications for mine related water quality risks. For example, ecotoxicity, human health affects and selection of remediation techniques are all sensitive to mine drainage chemistry.

Keywords: Acid Mine Drainage, Neutral Mine Drainage, Acid Base Accounting, Greenland Group, Brunner Coal Measures, Paparoa Coal Measures.

Introduction

Coal mine drainage chemistry on the West Coast of the South Island is highly variable. Mine drainage chemistry ranges from highly acidic and/or trace element enriched water that requires remediation or treatment to water with composition near background. In general, West Coast coal mine drainage related publications focus on water quality problems such as; low pH, high acidity (dissolved Fe and Al) and/or elevated environmentally sensitive trace elements (de Joux, 2003; de Joux and Moore, 2005; James, 2003; Lindsay et al., 2003). Research focused on water quality problems ensures that appropriate mitigation or remediation options (Trumm et al., 2003; Trumm et al., 2005) can be selected and implemented to minimise negative environmental or human health affects. However, a dataset focused only on water quality problems is not appropriate to assess the hazard to water quality posed by mining because some mines produce NMD (neutral mine drainage) that have little environmental impact.

To assess the hazard to water quality posed by mining on the West Coast requires a wide dataset must be examined that includes mine drainage with poor water quality as well as mine drainages that have chemistry similar to background. In addition, rock geochemistry in a selection of areas with variable mine drainage chemistries should be examined. Hazards to water quality from mining are also influenced by mining method, mine hydrogeology. This paper presents a coal mining related, water quality hazard model based on a broad water quality dataset, rock geochemistry and related field information.

Coal Mine Drainage Chemistry

Coal mining on the West Coast occurs in either Cretaceous to Paleocene Paparoa Coal Measures, Eocene Brunner Coal Measures or Miocene Rotokohu Coal Measures. Mine drainage geochemistry from coal mines is highly variable, from low to near neutral pH, variably enriched in trace elements and acidic metals such as Fe and Al.

Previously published West Coast stream water and AMD analyses (de Joux, 2003; de Joux and Moore, 2005; James, 2003; Lindsay et al., 2003) been collated and added to datasets from mining companies and regional councils. All analyses have been centralised in a GIS Database (Pope et al., 2005), DAME (Database for Assessment of Mine Environments). Additional samples of mine drainages in Paparoa and Brunner Coal Measures have been collected (Table 1). In general, mines in the Paparoa Coal Measures produce NMD pH 6.5-7.5 with low Fe and Al concentrations whereas mines in the Brunner Coal Measures produce AMD variably enriched in Fe and Al. Currently, data are not available from mines in the Rotokohu Coal Measures.

Table 1. Mine drainage chemistry a selection of Brunner Coal Measures and Paparoa Coal Measures mines.

Mine Site	pH	ec	Dissolved Fe mg/L	Dissolved Al mg/L	Al/Fe(mol)
Brunner Coal Measures Open Cast Mines					
Herbert 05/10/05	2.85	308	3.49	10.2	2.92
Whirlwind 05/10/05	3.46	107	0.72	5.73	7.96
C Drive Seep 05/10/05	3.23	133	0.72	8.53	11.85
A Drive 05/10/05	3.01	380	1.81	46.9	25.91
S4 Herbert B 05/10/05	3.06	238	1.77	15.9	8.98
Hoods Seep 05/10/05	2.66	943	43.4	115	2.65
Fly Creek Silt Pond 05/10/05	3.46	141	1.08	14.6	13.52
Mangatini Headwater 05/10/05	2.61	896	39.7	83.7	2.11
0941 Herbert Stream 27/09/05	2.85	291	3.11	7.77	2.50
Granity 21/11/05	2.6		24.5	50.7	2.07
Island Block 2 22/11/05	3.1		1.01	16	15.84
Highwall 22/11/05	2.8		5.88	11.4	1.94
Echo 1	3.78		0.56	0.153	0.27
Echo 2	5.85		5.3	0.021	0.00
Echo 3	3.41		1.51	6.21	4.11
Echo 13	2.97		36.1	36.7	1.02

Mine Site	pH	ec	Dissolved Fe mg/L	Dissolved Al mg/L	Al/Fe(mol)
Echo 14	2.93		2.89	12.3	4.26
Brunner Coal Measures Underground Mines					
Alborns 1	2.58	376	11.5	5.66	0.49
Alborns 2	2.99	424	4.6	9.66	2.10
Alborns 3	3.45	26	0.91	0.618	0.68
Alborns 4	3.64	149	2.61	1.66	0.64
Alborns 5	2.82	504	18.3	11.6	0.63
Alborns 6	3.76	62	2.01	1.33	0.66
0942 Bellview Mine 28/09/05	2.55	1366	98.4	43.2	0.44
0947 Escarpment Mine 28/09/05	2.75	597	55.3	11.9	0.22
0949 DIP Portal 27/09/05	2.85	814	14.2	28.9	2.04
0651 Photo 1 27/09/05			16.2	0.21	0.01
Jubilee Mine	2.91	330	6.71	3.23	0.48
Echo 15	3.79		94.7	22.1	0.23
Upper Mine	2.71		84.5	159	1.88
Mine portal	2.97		25.1	87.4	3.48
Plateau mine	3.20		6.12	15.1	2.47
Mine Ck2 bdge	2.90		15.1	41.8	2.77
Sullivans West lower adit	2.97		41.7	12.8	0.31
Escarpment adit 10m d/s	3.01		32.7	12.5	0.38
Castle Pt mine	2.53		14.5	58.9	4.06
Near Bellvue	2.41		134	216	1.61
Paparoa Coal Measures Underground Mines					
Mt Davy 12/1/06	6.8		11.9	0.003	0.00
Strongman 1 12/1/06	7.3		0.66	0.004	0.01
Strongman 2 12/1/06	7.2		0.04	0.005	0.13
Paparoa Coal Measures Open Cast Mine					
Strongman o/c 12/1/06	7.0		0.27	0.204	0.76

Selected analyses in Table 1 have been contributed by; Jon Harding (University of Canterbury), Brent Francis (Francis Group), Phil Lindsay (Solid Energy), Dave Trumm (CRL Energy).

In detail, AMD samples from mines in the Brunner Coal Measures are highly variable. The pH is typically between 2.5-4, Fe and Al concentrations can be extremely enriched and the Al:Fe ratio is highly variable.

To establish a water quality hazard model the variations in mine drainage chemistry are related to geochemistry of mined rocks (acid base accounting data), geology, hydrogeology and variations in mine method.

Acid Base Accounting Data

Acid base accounting analyses conducted on rocks disturbed by mining are often referred to as static tests and include several commonly applied procedures (Smart, 2002).

1. Maximum Potential Acidity (MPA). This test typically uses total sulphur analysis to determine the maximum possible acid generation assuming all S is bound in pyrite.

Although this assumption usually valid (for rocks – not coal), it is possible that sulphate minerals or organically bound S could provide an exaggerated result. Pyrite-specific S analyses can be used for calculation of MPA if necessary.

2. Acid Neutralising Capacity (ANC). This analysis determines the acid consumption of a crushed rock sample by reaction with a known quantity of acid. Most ANC measured in this analysis relates to carbonate minerals. Fe rich carbonate minerals have reduced ANC because Fe hydrolysis release acid.

3. Net Acid Production Potential (NAPP). This analysis is the difference between MPA and ANC

$$NAPP = MPA – ANC$$

4. Net Acid Generation (NAG). This analysis oxidises all reactive pyrite to form acid that reacts with any ANC in the rock. Acidity titrations and pH measurements of the reaction liquor are used to quantify the acid producing potential. False positive analyses can occur in NAG data if samples contain abundant organic material because organic acids can be released (Smart, 2002).

Acid base accounting data for coal measure rock types on the West Coast show a wide range of values (Table 2). In general, Brunner Coal Measures are NAPP positive whereas Paparoa Coal Measures are NAPP negative. Comparison of MPA data to NAG data suggests that NAG analyses often indicate a false positive acidity and are unreliable for coal measure samples.

Table 2. Acid Base Accounting from a selection of Brunner Coal Measures and Paparoa Coal Measures rocks.

Sample_Description	**TotalS wt%)**	**MPA kg(H_2SO_4)/t**	**ANC kg(H_2SO_4)/t**	**NAPP kg(H_2SO_4)/t**	**NAG kg(H_2SO_4)/t**
Brunner Coal Measures					
coarse sandstone	<0.01		1.80	-1.8	11.5
med-coarse sandstone	0.01	0.3	0.60	-0.3	11
medium sandstone	0.68	20.8	0	20.8	21.1
coarse sandstone	0.05	1.5	0	1.5	12.2
med-coarse sandstone	0.04	1.2	0.20	1	13.4
fine sandstone	0.89	27.2	2.50	24.7	29
laminated fine sandstone	1.08	33	1.50	31.5	31.9
med-fine sandstone	0.07	2.1	0.60	1.5	14.5
laminated fine sandstone	1.00	30.6	0	30.6	22.9
fine sandstone	0.71	21.7	0	21.7	24.9
sandy siltstone	0.79	24.2	0	24.2	21.2
carb. siltstone	2.38	72.8	4.80	68	84.1
carb. mudstone	1.91	58.4	1.50	56.9	79.8
carb. mudstone	3.08	94.2	0.90	93.3	68
carb. mudstone	0.03	0.9	0	0.9	15.7
muddy coarse sandstone	0.82	25.1	6.10	19	24.8
muddy coarse sandstone	0.28	8.6	13.50	-4.9	14.1
coarse sandstone	0.32	9.8	2.10	7.7	15.6
med sandstone	0.10	3.1	3.20	-0.1	11
muddy coarse sandstone	0.50	15.3	3.50	11.8	14.7
baked sandstone	0.29	8.9	5.40	3.5	9.8
muddy coarse sandstone	1.14	34.9	0	34.9	23.8
muddy coarse sandstone	0.66	20.2	0	20.2	22

Sample_Description	TotalS wt%)	MPA kg(H_2SO_4)/t	ANC kg(H_2SO_4)/t	NAPP kg(H_2SO_4)/t	NAG kg(H_2SO_4)/t
Paporoa Coal Measures					
muddy sandstone	0.01	0.31	2.35	-2.04	10.3
coaly mudstone	0.10	3.06	2.88	0.18	114.1
sandstone	<0.01	0	4.59	-4.59	0.0
	<0.01	0	9.01	-9.01	0.0
muddy sandstone	0.01	0.31	8.27	-7.96	33.2
carbonaceous mudstone and coal laminae	0.01	0.31	4.09	-3.78	91.3
sandy mudstone	0.01	0.31	2.86	-2.55	22.1
mudstone - siltstone	0.02	0.61	4.33	-3.71	49.1
coarse sandstone	0.05	1.53	4.19	-2.66	13.4
carbonaceous mudstone	<0.01	0	5.56	-5.56	7.8
mudstone	0.06	1.84	6.78	-4.94	99.4
carbonaceous mudstone	0.03	0.76	4.44	-3.67	41.8

Data from unpublished sources; Brent Francis (Francis Group) and Phil Lindsay (Solid Energy).

Discussion

AMD chemistry and acid base accounting data presented indicate a substantial difference in the hazard to water quality between mines within the Brunner Coal Measures compared to the Paparoa Coal Measures. Samples from the small selection of Paparoa Coal mine drainages are environmentally benign in contrast to highly variable AMD from the Brunner Coal Measures (Figure 1).

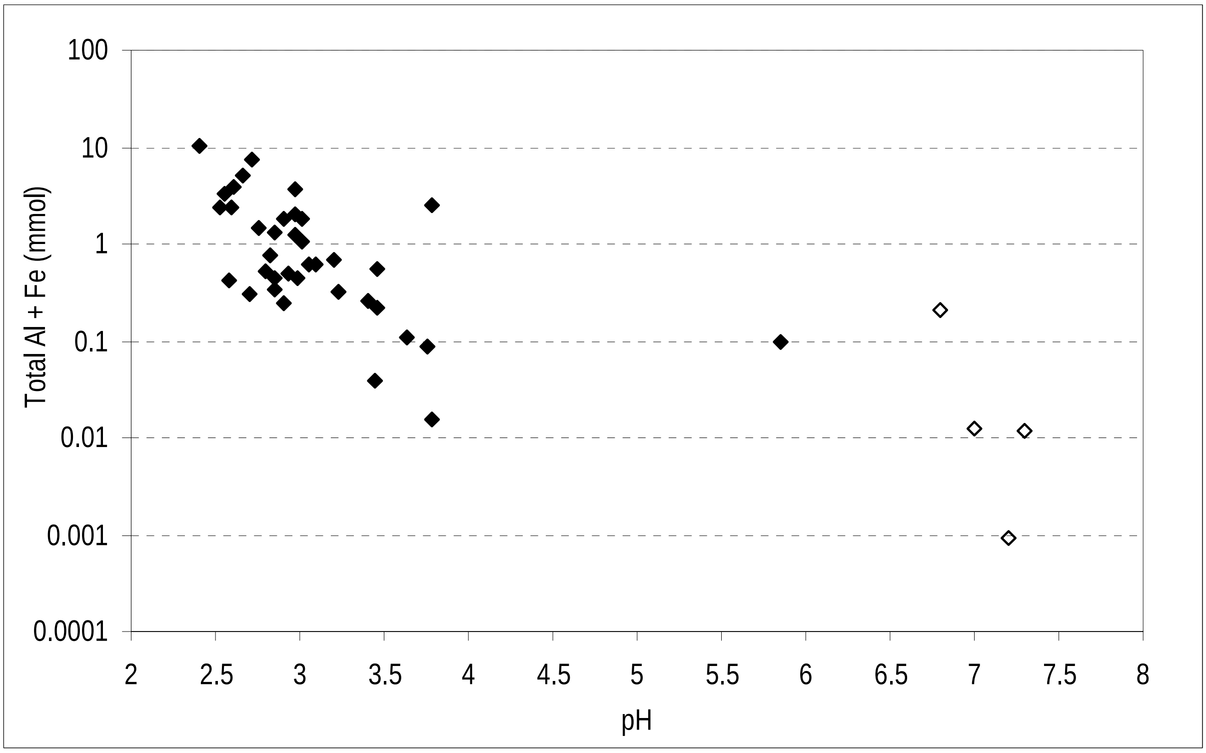

Figure 1. Mine drainage chemistry from Brunner Coal Measures (solid symbols) and Paparoa Coal Measures (open symbols).

The differences in mine drainage chemistry are best indicated bythe NAPP data from Paparoa and Brunner Coal Measures. Paparoa Coal Measure samples typically have substantial ANC and are NAPP negative (or have excess ANC over MPA). Brunner Coal Measures samples typically have very low or no ANC, substantial MPA and therefore are typically NAPP positive (or have excess MPA over ANC). Note that sample sites are geographically restricted, representing several active mining areas. Additional samples from a broad area are required to confirm these trends.

There is poor correlation between NAG and MPA analyses for the Brunner and Paparoa Coal Measures and where NAG exceeds MPA, the NAG analysis is inaccurate for pyrite generated acidity. When the mine drainage chemistry (Figure 1) is examined it is clear that Paparoa mine drainage sampled to date is not acidic and so better reflected by MPA values than NAG values for the host rocks. It is likely that the false positive acidity is related to release of organic acids by reaction of carbonaceous material during the NAG test (Smart, 2002).

Geology of the Paparoa and Brunner Coal Measures

Geological reasons for the differences in mine drainage chemistry and acid base accounting data presented above can be related to variations in depositional processes and diagenesis of the Paparoa and Brunner Coal Measures.

Provenance

Both Paparoa and Brunner Coal Measure sediments are mostly derived from Cambrian to Ordovician Greenland Group meta-sediments and Devonian to Cretaceous Granites. Locally and regionally within the Paporoa and Brunner Coal measures there are variations in the relative abundance of Greenland Group rock fragments and quartz and feldspar (Boyd and Lewis, 1995). Greenland Group rocks contain disseminated carbonate minerals and elevated carbonate mineral content associated with mesothermal alteration (Christie and Brathwaite, 2002; Woodward-Clyde, 1994). If carbonate minerals in the Greenland Group rock fragments survive depositional processes and diagenesis they could contribute to ANC in the Paparoa or Brunner Coal Measures.

Depositional Processes

Paparoa Coal Measures are interpreted to have deposited in a fluvial to lacustrine environment within complex fault bounded sedimentary basins. Peat mires and streams within the basin are thought to have been variable in character and size (Newman and Newman, 1992). In this setting little reworking of sediment occurred, sediment accumulation was rapid and survival of carbonate bearing Greenland Group rock fragments is favoured.

The depositional environment for the Brunner Coal is interpreted to be paralic or estuarine. Deposition of Brunner Coal Measures sediments was typically slow, involved repeated reworking of sediments and was unfavourable for the preservation of carbonate bearing Greenland Group rock fragments.

Diagenesis

Diagenetic processes can substantially alter sediment composition after deposition, especially in the case of relatively unstable or soluble minerals such as sulphides and carbonates. Diagenetic emplacement of carbonate minerals or cements is common in sedimentary basins depending on the composition of formation fluids. Carbonate minerals including siderite, calcite and dolomite occur in the Paparoa Coal and calcite, dolomite and rare ankerite occur in Brunner Coal (Newman, 1988). Carbonate emplacement is often an early diagenetic process as indicated by carbonate replaced plant fragments occasionally preserved in coal that predate coal compaction (Newman, 1988). Paparoa Coal Measures contain common contain spherulitic masses and rhombohedral grains of carbonate (siderite > magnesite > calcite) locally up to 30% by volume (Boyd and Lewis, 1995).

Pyrite emplacement by diagenetic processes is probably the most important process controlling the acid base accounting characteristics of coal measure sediments. Typically the pyrite content and MPA of Brunner coal Measures is substantially higher than that of the Paparoa Coal Measures (Table 2). The source of most sulphur in Brunner Coal Measures is water from overlying marine sediments including the Kaiata Mudstone and Island Sandstone (Suggate, 1959). The degree of sulphur enrichment of the Brunner Coal Measures is controlled by the permeability of the interval between the Brunner sediments and overlying marine units; a sandstone rich interval commonly causes substantial diagenetic sulphur enrichment. In extreme cases where marine rocks rest directly on Brunner Coal both organic and pyritic sulphur is abundant. In general the Paparoa Coal Measures are protected from marine derived sulphate by thick impermeable sedimentary sequences. The cases where Paparoa Coal Measures contain significant pyrite can be related to the absence of Brunner Coal Measures (Nathan, 1986) or hydrologic connection between Paparoa Coal Measures and sediments by faults or permeable sequences. In both sets of coal measures diagenetic pyrite replaces carbonate (therefore reducing ANC) as well as organic matter, quartz and other silicates (Newman, 1988).

Summary

Depositional environment favours preservation of carbonate bearing Greenland Group rock fragments in the Paparoa Coal Measures compared to the Brunner Coal Measures. If these carbonate minerals survive diagenesis they could be a source of ANC for Paparoa Coal Measures.

Both sets of coal measures contain diagenetic carbonate minerals, however, diagenetic pyrite is much more widespread and abundant in the Brunner coal and coal measures compared to the Paparoa coal and coal measures. This compares well with the high MPA in the Brunner Coal Measures compared to the Paparoa Coal Measures. Sulphides can be present in the Paparoa Coal Measures where Brunner Coal Measures are absent or where hydrologic connectivity to the overlying marine sediments occurs. Acid base accounting and mine drainage analyses are required from areas where Brunner Coal Measures do not cap Paparoa Coal Measures.

Brunner Coal Measures AMD

AMD samples collected from mines hosted in Brunner Coal Measures are highly variable and several factors that influence the chemistry of mine drainage can be identified.

Mine Type

AMD from open cast mines hosted in the Brunner Coal Measures typically has a higher Al:Fe ratio than AMD from underground mines (Figure 2). The most likely source of Al in Brunner Coal Measures AMD is reaction between H_2SO_4 produced by pyrite oxidation and aluminium bearing silicate minerals in the coal measures such as clays and feldspars. In general these reactions can proceed more rapidly and to a greater extend in open cast mines because coal measure sediments are more disturbed in mine pits compared to underground mines and a wide range of sediments can be exposed to weathering processes. In underground mines there is less reaction between the H_2SO_4 from pyrite oxidation and coal measure sediment and therefore relatively higher Fe compared to Al. In addition the coal measures sediment immediately surrounding coal seams are often feldspar depleted and therefore relatively low in available Al compared to sediments further from the coal seams (Newman, 1988).

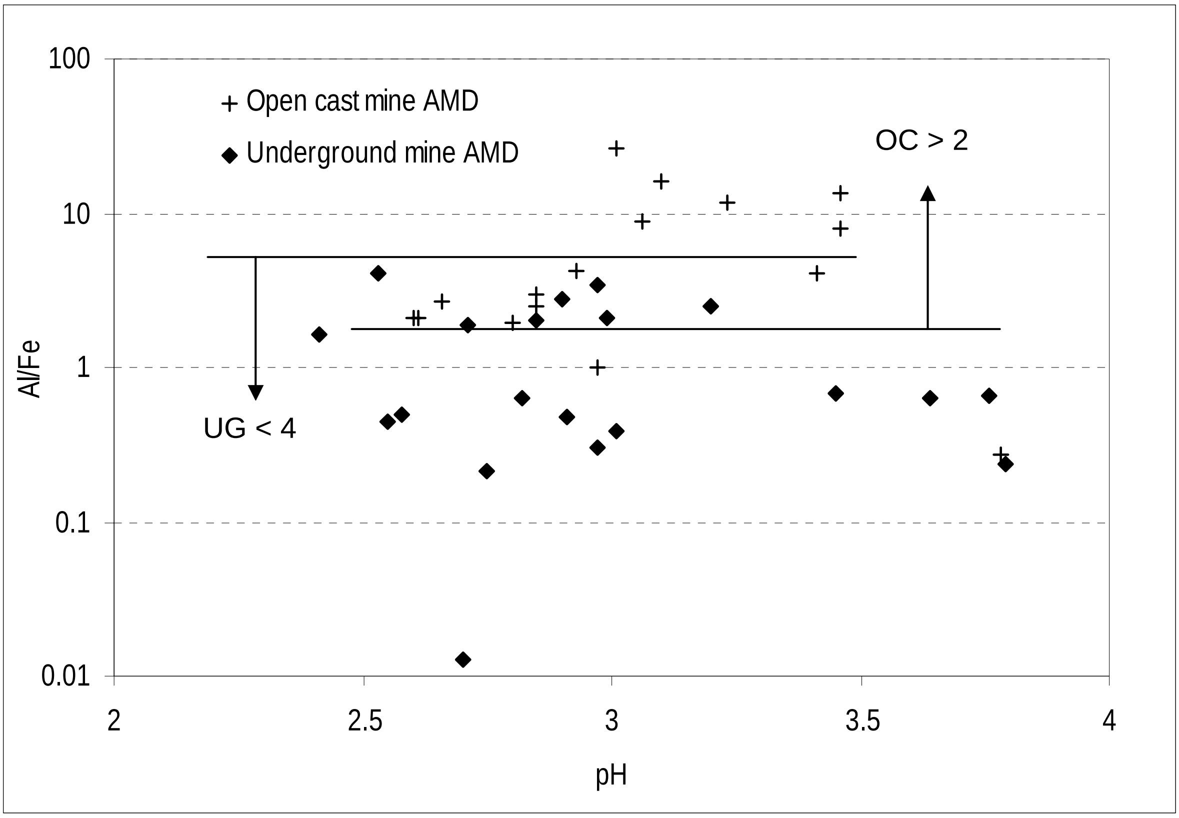

Figure 2. In general the Al:Fe ratio is higher in open cast mine AMD compared to underground mine AMD. Al:Fe is typically greater than 2 in open cast mines and less than 4 in underground mines.

Hydrogeology

Several samples have been collected from flooded or partially flooded underground mines in the Brunner Coal Measures (Figure 3). In general these samples have lower total acidity compared to underground mines where groundwater can escape freely (Perry and Rauch, 2006; Scousen et al., 2006). Deliberate flooding of underground mines is a method of AMD mitigation because the inflow of oxygenated water is reduced and pyrite oxidation reaction slowed (Stortz et al., 2001).

Local Geology

At Stockton Brunner Coal Measures AMD from mudstone rich areas has higher total acidity than AMD from sandstone rich areas (Figure 3). It is likely that pyrite in mudstone is finer (more reactive) and more abundant than pyrite in sandstones, therefore mudstone derived AMD is likely to have a higher total acidity. In addition the surface area of Al bearing minerals is greater in fine sediments so reactions between H_2SO_4 from pyrite oxidation and silicates will proceed more rapidly than in coarse sediments. Other elements also occur at higher concentrations in mudstone derived AMD compared to sandstone derived AMD (Alicorn Leon and Anstiss, 2002).

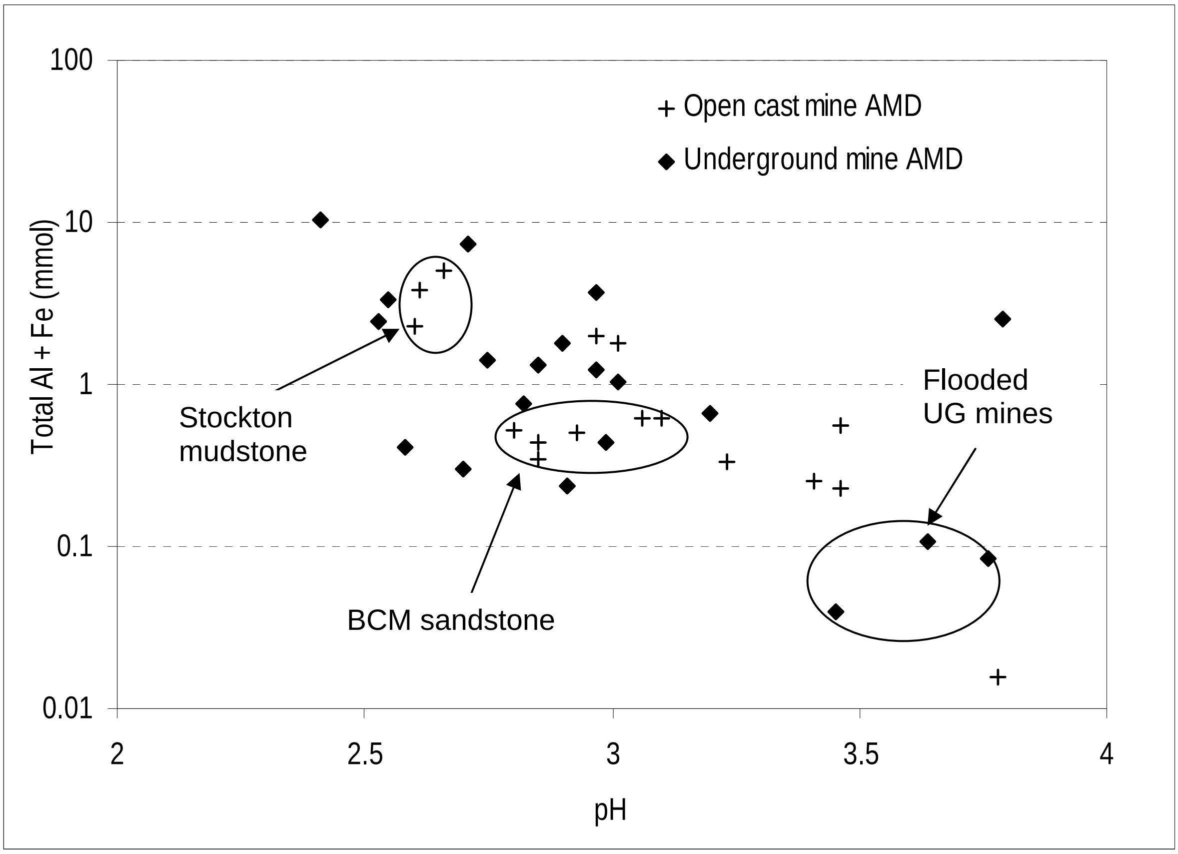

Figure 3. Several samples from flooded underground mines have lower total acidity and higher pH samples from free draining underground mines. Stockton total acidity in mudstone rich areas is higher than sandstone rich areas. Underground and Open cast mines have similar range of acidity values

Summary

The type and intensity of acidity in Brunner Coal Measures derived AMD can be related to; mine type, mine hydrogeology, and local geology. Underground and open cast mines in the Brunner Coal Measures have a similar range of acidities (Figure 3). In general open cast mines in Brunner Coal Measures are likely to have a more Al rich AMD than underground mines. Flooded underground mines have less acid chemistry than free draining mines. It is likely that flooded waste rock dumps at open cast mines would also have less acid AMD than waste rock left exposed to the atmospheric conditions, however, this field setting was not encountered during sampling.

Open cast mines in Brunner Coal Measures mudstone are likely to have more acidic AMD than open cast mines hosted in Brunner Coal Measures Sandstone. Similar relationships are difficult to establish for underground mines because geological details are not readily available.

Hazard Model

A hazard model (Figure 4) that predicts the type and intensity of mine drainage chemistry has been developed. The model suggests that Paparoa Coal Measures are less likely to produce AMD than Brunner Coal Measures. Geological interpretation of trends in mine drainage and ABA data indicates that exceptions are likely in specific geological settings, for example where Brunner Coal Measures do not cap Paparoa Coal Measures. Additional acid base accounting data are required to check these interpretations. The chemistry of Brunner Coal Measures AMD is influenced by mine type, hydrogeology and local geology.

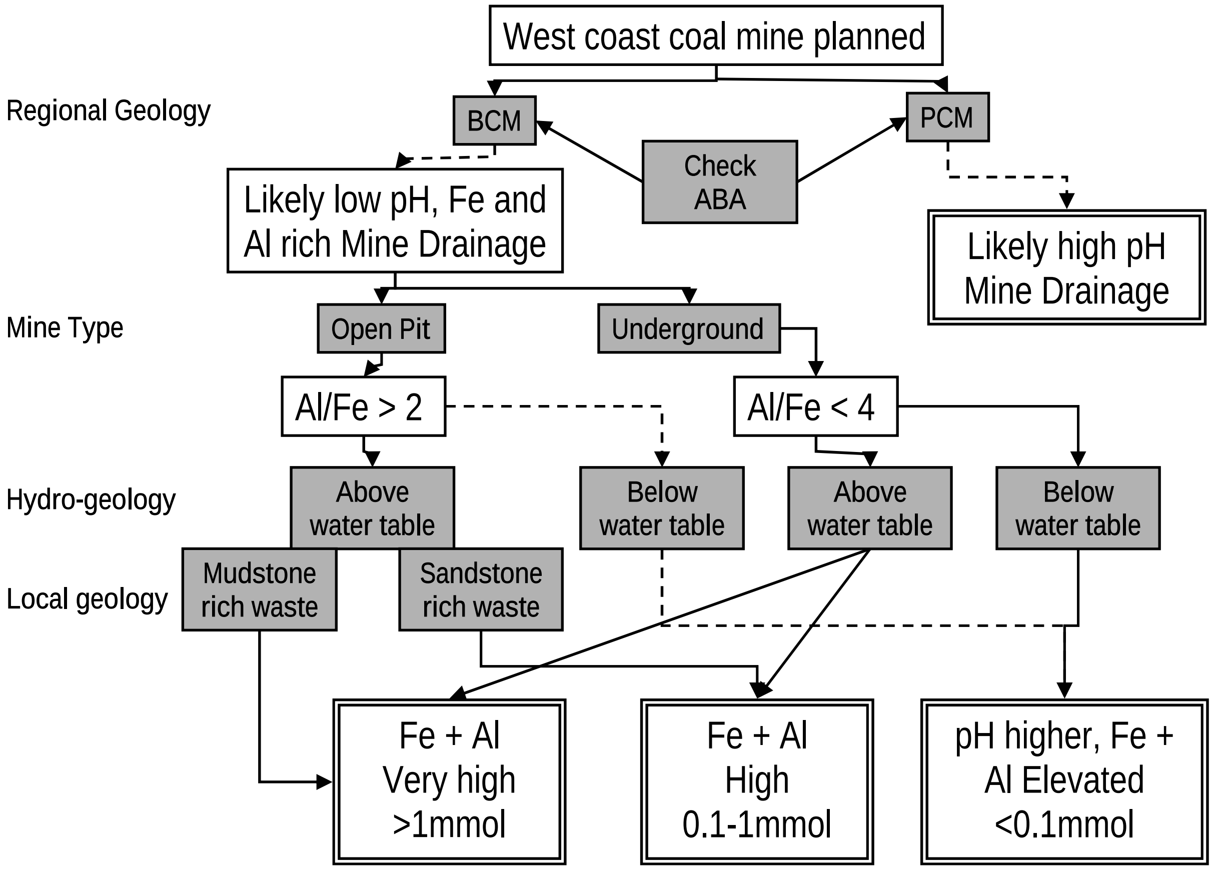

Figure 4. Hazard model that predicts mine drainage chemistry based on regional geology, mine type, hydrogeology and local geology. Dashed lines indicate more data is required to confirm interpretations (PCM & BCM – Paparoa & Brunner Coal Measures respectively).

Summary and Conclusion

Collection and collation of an AMD chemistry dataset into DAME (Database for Assessment of Mine Environments) has been interpreted and a hazard model for mine drainage chemistry for West Cost coal mines has been developed. This dataset includes NMD from areas where there are no water quality issues down stream of mining as well as data from mines that produce AMD.

The hazard model predicts the type and intensity of acidity associated with coal mining based on four factors.

1. Regional Geology
2. Mine Type
3. Hydrogeology
4. Local Geology

These factors can be fitted into a hazard model to predict the mine drainage acidity characteristics. The intensity and type of acidity (Fe rich or Al rich) has implications for water quality hazard because these elements are associated with different ecotoxicity, human health issues. In addition, selection of appropriate remediation techniques is sensitive to mine drainage chemistry

Acknowledgements

This work is part of a FRST programme, developing pathways to mineral wealth and environmental sustainability conducted by CRL Energy, the University of Canterbury, Otago University and Landcare Research. Proprietary data from several mining companies has been made available for this programme, data included in this paper includes analyses from Solid Energy and Francis Group.

References

Alicorn Leon, E., and Anstiss, R.G., 2002, Selected trace elements in Stockton, New Zealand waters.: New Zealand Journal fo Marine and Freshwater Science, v. 36, p. 81-87.

Boyd, R.J., and Lewis, D.W., 1995, Sandstone diagenesis relating to varying burial depth and temperature in the Greymouth Coalfield, South Island, New Zealand: New Zealand Journal of Geology and Geophysics, v. 38, p. 333-348.

Christie, A.B., and Brathwaite, R.L., 2002, Hydrothermal alteration of metasedimentary rock hosted orogenic gold deposits, Reefton Goldfield, South Island, New Zealand: Mineralium Deposita, v. 38, p. 87-107.

de Joux, A., 2003, Geochemical Investigations and Computer Modelling of Acid Mine Draiange, Sullivan Mine, Denniston Plateau, West Coast [MSc thesis]: Christchurch, University of Canterbury.

de Joux, A., and Moore, T.A., 2005, Geological Controls on the Source of Nickel in Rapid Stream, South Island, *in* Moore, T.A., Black, A., Centeno, J.A., Harding, J.S., and Trumm, D.A., eds., Metal Contaminants in New Zealand: Christchurch, Resolutionz Press, p. 261-276.

James, T., 2003, Water Quality of Streams draining various Coal Measures in the North Central West Coast., Opportunities for the New Zealand Mining and Minerals Industry: Greymouth, p. Not Paginated.

Lindsay, P., Kingsbury, M., and Pizey, M., 2003, Impact of mining on the Lower Ngakawau River, Opportunities for the New Zealand Mining and Minerals Industry: Greymouth, Crown Minerals, MED, p. Not Paginated.

Nathan, S., 1986. Cretaceous and Cenozoic sedimentary basisn of the West Coast region, South Island New Zealand: Wellington, New Zealand Geological Survey.

Newman, J., and Newman, N.A., 1992, Tectonic and paleo-environmental controls on the distribution of Upper Cretaceous coals on the West coast of, *in* McCabe, P.J., and Parish, J.T., eds., Controls on the Distribution and Quality of Cretaceous Coals, Volume 267: Boulder, Geological Society of America.

Newman, N.A., 1988, Mineral matter in Coal of the West Coast, South Island, new Zealand. [PhD thesis]: Christchurch, University of Canterbury.

Perry, E.F., and Rauch, H.W., 2006, Water quality evolution in flooded and unflooded coal mine pools, *in* Barnhisel, R.I., ed., ICARD: Lexington, American Society of Mining and Reclamation, p. 1565-1581.

Pope, J., Singh, B., and Thomas, D., 2005, Mining Related Environmental Database for West Coast and Southland: Data Structure and Preliminary Geochemical Results, AUSIMM 2006: Auckland, AUSIMM, p. 7.

Scousen, J., McDonald, L., Mack, B., and Demchak, J., 2006, Water Quality from above-drainage underground mines over the 35 year period, *in* Barhhisel, R.I., ed., ICARD: Lexington, American Society for Mining and Reclamation, p. 2044-2054.

Smart, R., 2002. Project P387A Prediction and Kinetic Control of Acid Mine Draiange: Melbourne, AMIRA, International Ltd, Ian Wark Research Institute.

Stortz, M., Hughes, M., Warner, N., and Farley, M., 2001, Long Term Water Quality Trends at a Sealed Partially Flooded Underground Mine: Environmental and Engineering Geoscience, v. 7, p. 51-65.
Suggate, R.P., 1959. New Zealand Coals, Their Geological Setting and its Influence on their Properties: Wellington, New Zealand geological Survey, Bulletin 134. 113 p
Trumm, D., Black, A., Cavanagh, J., Harding, J.S., de Joux, A., Moore, T.A., and O'Halloran, K., 2003, Developing assessment methods and remediation protocols for New Zealand sites impacted by Acid Mine Drainage (AMD), Sixth International Conference on Acid Rock Drainage: Cairns, p. 223-232.
Trumm, D., Black, A., Gordon, K., Cavanagh, J., O'Halloran, K., and de Joux, A., 2005, Acid Mine Draiange Assessment and Remediation at an Abandoned West Coast Coal Mine, *in* Moore, T.A., Black, A., Centeno, J.A., Harding, J.S., and Trumm, D.A., eds., Meal Contaminants in New Zealand: Christchurch, Resolutionz Press, p. 317-340.
Woodward-Clyde, 1994. Globe Progress Mine Geochemistry: Auckland. Confidential client report.