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Prediction of reactive ground using geoscientific datasets

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ABSTRACT

The presence of reactive ground – rocks which undergo a spontaneous exothermic reaction on contact with nitrates, represents a significant risk in many mines, and requires the use of costly alternatives to traditional ammonium nitrate explosives. Prediction of the likelihood of occurrence of reactive ground using typical mine datasets has the potential to reduce costs for explosives and increase mine safety. The standard test for reactive ground according to Australian codes of practice is the Isothermal Reactive Ground Test, in which a mixture of rock, ammonium nitrate and an acidic "weathering by-products" solution are heated in a sealed vessel.

In this contribution we present a case study in which a large dataset of reactive ground tests was assessed against geological and geochemical drill datasets in order to develop criteria for prediction of reactive ground. Testing of geological criteria such as pyrite content, presence of carbonaceous material and evidence of leaching showed little correlation with test results, and the control of variation in rock type also appeared to be unclear. A number of geochemical proxies were tested which were successfully able to predict strongly reactive ground with relatively low rates of false positives and false negatives. In this case study, the presence of carbonate appears to suppress reactivity, and it is important to consider the degree to which code of practice test is valid in carbonate-bearing potentially-reactive materials.

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INTRODUCTION

Reactive ground relates to the situation where certain rocks spontaneously undergo exothermic reactions on contact with nitrites. Reactive ground of this nature requires the development of particular risk approaches as spontaneous combustion in underground mines is difficult to control once the reaction starts and often results in ores that are difficult to mine and may introduce metallurgical challenges.

This study was undertaken in response to the need for an improved ability to predict the location of reactive ground in the Mount Isa Copper orebodies. The focusing questions were “Could a more accurate predictive tool be developed using existing mine datasets?” and “If existing mine datasets are not applicable, can a new effective test be developed that is both cost effective and able to produce results in time for production requirements?”

The study area was limited to the Glencore Plc owned Mount Isa 500 copper orebody in northwest Queensland Australia. The copper orebodies of the Mount Isa deposit are hosted in a brecciated variably calcified and silicified package of altered mid-Proterozoic siltstones and shales of the Urquhart Shales within the Mount Isa Group (Perkins, 1990).

A thorough compilation of the history of reactive pyrite incidents and assessments (Campbell and Bunker, 2017) captures the current understanding and knowledge gaps regarding causes and prediction of reactivity (eg Smith, 1963; Hewitt, 1968; Leahy, 1988; Campbell and Bunker, 2017). As well as detection and risk assessment approaches on the basis of knowledge relating to reactive ground (eg Bellairs, 2006; Faulkner and Davis, 2008; O’Sullivan, 2017). However; none of these studies have attempted to integrate reactive ground datasets with mine geological drill datasets, geotechnical information and underground mapping to look for correlations that could assist in the development of methods for prediction of reactive ground risk.

Challenges

The prediction of where reactive ground will be encountered is governed to a degree by oxidation processes which are due to the localised structural weakness on the ground surrounding the 500 orebody (Smith 1963). Smith refers to the spontaneous combustion of parts of the orebody as “hot” ground and observes that due to the high variability of the oxidised rock it is very difficult to predict where the reactive ground will be concentrated enough to cause a risk to mining.

Subsequent work has focused more on risk recognition and mitigation (eg Bellairs, 2006) as well as mapping of the boundaries of the areas of reactive ground risk (eg David and Dare, 2008, Wong, 2010). More recently, Connell (2016) carried out a program of sampling, isothermal reactive ground testing, and geochemical analysis with samples mainly derived from the deeper Enterprise Copper Mine at Mount Isa.

METHODOLOGY

Data integration and database validation

A variety of information was provided for the study from different areas including; a reactive ground register containing 462 drill samples and 155 development samples; dxf surface files relating to important controlling faults and contacts; geological and geotechnical logs; assays; a partial set of sample photographs and additional reports relating to reactive ground in the 500 orebody and elsewhere in the copper mine.

The data points were initially classified on the basis of reactivity derived from the isothermal tests carried out at the Ernest Henry laboratory. Samples which were not reactive were assigned a reactivity number of 1; those reactive at 105°C were assigned a reactivity number of 2; those reactive at 65°C were assigned a reactivity number of 3; and those reactive at 55°C were assigned a reactivity number of 4. In the database, 229 samples (48%) were non-reactive; 120 samples were weakly reactive (reactivity number 2); 59 were strongly reactive (reactivity number 3); and 67 were very strongly reactive (reactivity number 4) (Figure 1).

Assessment of established criteria

Assessment criteria for the recognition of reactive ground risk (Bellairs, 2006; as summarised in Campbell and Bunker 2017) are presented in Table 1. Assessment of these variables was carried out as part of the sampling program and included in the reactive ground register independently of the test data and the other external datasets. None of the samples in the database were noted as having displayed the heating criteria, so that characteristic was not included in further analysis.

Table 1 Reactive ground risk criteria from the sample register, along with an explanation and total number of samples displaying each criteria.

Criteria	Explanation	Number of samples in register
Sulph >1%	The presence of sulphides estimated to be greater than 1%	265
Mixed Sulp	The presence of multiple types of sulphides (eg coarse and fine pyrite, or pyrrhotite)	184
FG Sulp	The presence of fine-grained pyrite	161
Graphic SH	The presence of graphite or carbonaceous material	27
LCH GRO	The noted presence of leaching	254
Corrosion	Evidence of oxidation of iron sulphide minerals	138
Salts	The presence of salt precipitates on the sample	78
SO2 Smell	A sulphurous smell noted to be associated with the sample	4
Heating	Heating of the sample noted, indicating an exothermic reaction	0

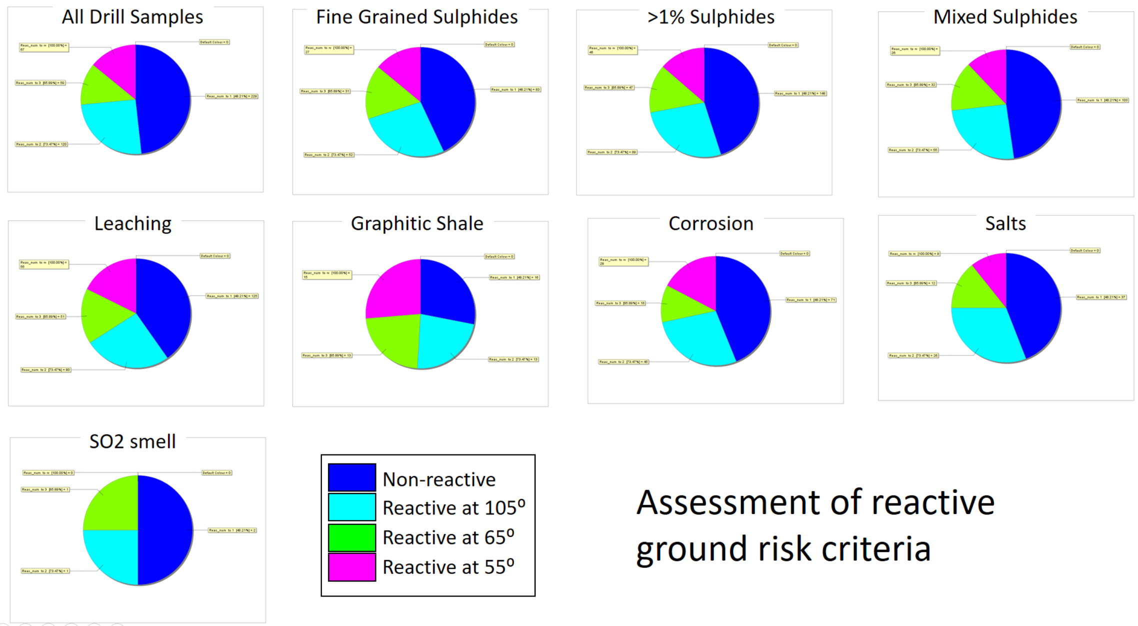

Figure 1 Summary figure of the proportion of samples of varying reactivity classified on the basis of the presence of identified reactivity risk factors.

Pie charts of the mix of sample reactivities for each of the risk criteria (Figure 1) show some minor variations in the ratio of reactivities, though for most criteria the relative proportion of non-reactive and moderately reactive samples remained relatively constant. The presence of carbonaceous material and/or graphite showed the greatest association with more reactive samples, though this characteristic was noted in relatively few samples. Each of the selected reactive ground indicators was assessed to determine its relationship to reactive ground and use as a predictive indicator.

Fine grained sulphides: There does not appear to be a strong relationship between the quantitative estimates of fine-grained pyrite and reactivity.

Leaching. Leaching at moderate or greater level is noted in a relatively large number of samples. The ratio of reactive to non-reactive samples is slightly greater in the samples in which leaching is noted.

Corrosion. The noted presence of corrosion does not appear to modify the proportions of sample reactivities to any great extent.

Number of Indicators. Analysis of sample reactivity divided on the basis of the number of risk indicators predicts that the likelihood of samples being strongly reactive increases as the number of risk indicators increases. However, even samples with a large number of risk indicators showed a relatively strong likelihood of being non-reactive or only moderately reactive (Figure 2).

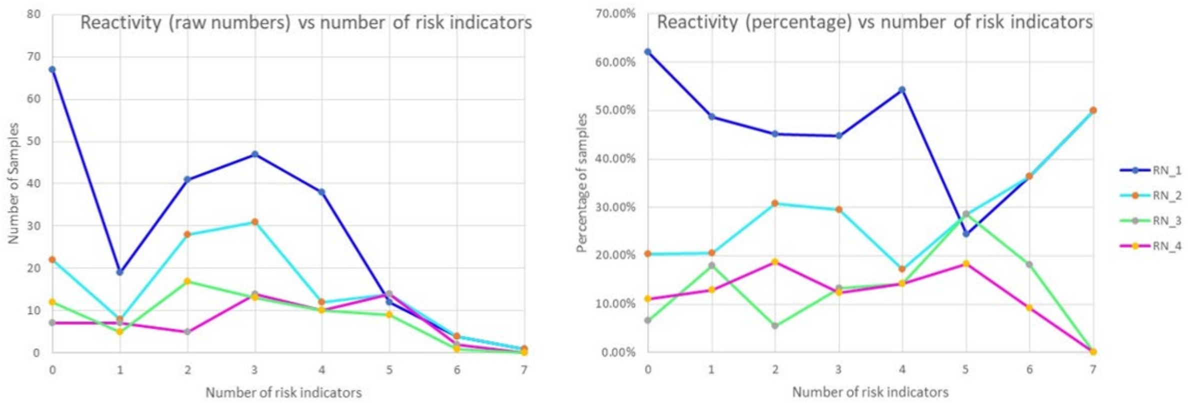

Figure 2 Raw and normalised totals of samples of varying reactivity as a function of the number of indicators noted in the sample

Geochemical correlations: A set of log-log plots for the assay values associated with the reactive ground sample datasets is shown in Figure 3, with samples colour-coded by reactivity. CaO shows the clearest relationship with reactivity, so was used as the Y-axis in each plot.

In terms of the relationship between assay values and reactivity there is a relatively strong correlation between higher reactivities and low CaO values. Al2O3 and SiO2 show similar patterns to each other, in that samples with low Al2O3 and SiO2 tend to have lower reactivities, though samples with higher Al2O3 and SiO2 show no preferential pattern of reactivity. There appears to be no correlation between Cu content and reactivity. Similarly, there does not appear to be any notable correlation between Fe and S values and reactivity. MgO and CaO show a distinctive pattern, with high values linearly correlated and probably reflecting the presence of dolomite. Importantly, samples with higher Mg/Ca ratios tend to be more reactive, suggesting that this ratio may be a proxy for leaching.

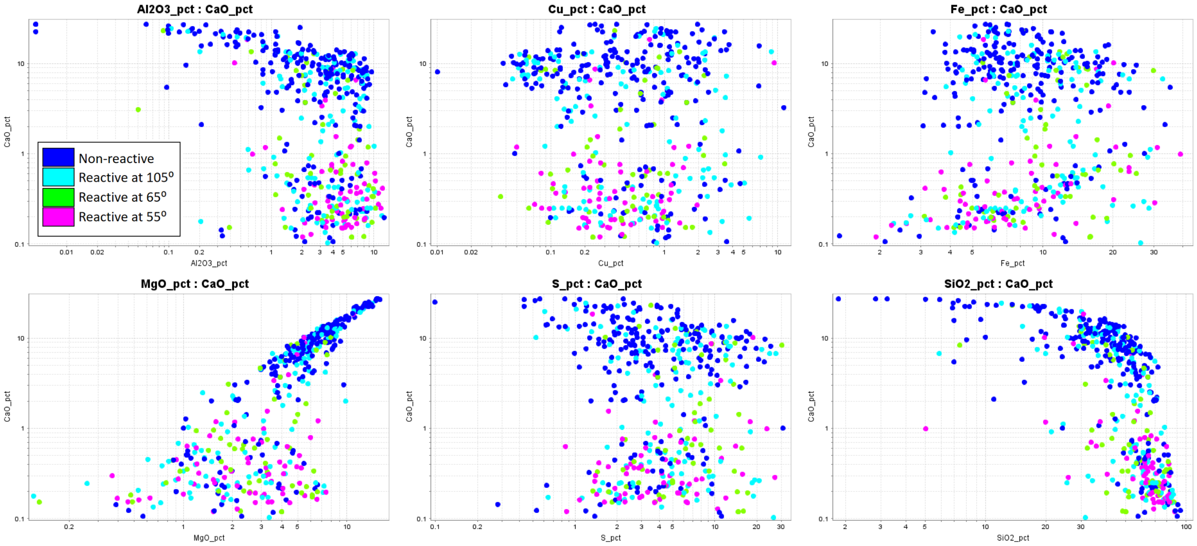

Figure 3 Log-log plots of element abundances from assays, with samples colour coded on the basis of reactivity.

Development of Proxies

The assessment of logging and geochemical data has shown a number of trends which could potentially be applied as proxies for assessment of reactive ground risk in untested drill holes. Some of the criteria and potential proxies are assessed in Table 2.

Table 2 Assessment of criteria and potential proxies for estimation of reactive sample risk.

Criteria	Effectiveness as a potential proxy	Potential proxy
Sulp >1%	Very little correlation between reactivity and sulphide content	Fe or S
Mixed Sulp	Very little correlation between this characteristic and reactivity	
FG Sulp	Weak correlation with logged sulphidic rocktypes	Logged percentage
Graphic SH	Graphitic rocks preferentially reactive, but graphitic/carbonaceous material noted in very few samples	
LCH GRO	Presence and intensity of leaching do correlate with increased reactivity.	Inverse CaO; CaO/(CaO+MgO)
Corrosion	Increased proportion of reactive samples show evidence, but not a strong correlation in geochemical datasets	(Fe+Cu+Pb+Zn)/S
Salts	Only very minor evidence of a link with reactivity in the dataset	
SO2 Smell	Not assessed	
Heating	Not assessed	

Figure 4 plots sample reactivity vs logCaO and shows a distinctive pattern in which low values of CaO have a much higher proportion of strongly reactive samples. This pattern is by far the strongest of any of the correlations between raw assay values and reactivity (eg Figure 3). The logCaO values, however, do not appear to differentiate mildly reactive samples to any great extent, with a broadly equal proportion of mildly reactive samples occurring at both lower and higher values.

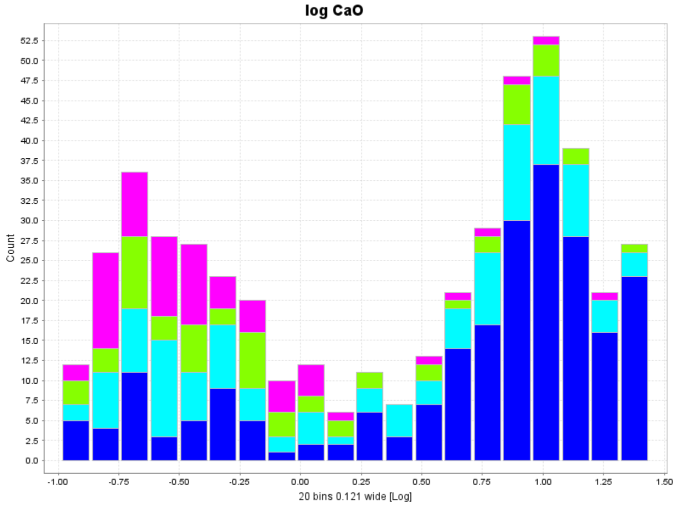

Figure 4 Abundance of samples of varying reactivity as a function of log CaO. See figure 3 for legend.

RESULTS AND DISCUSSION

The aim of development of a proxy for prediction of reactivity risk is to be able to develop a more effective means of identifying areas within the orebody which are subject to higher risk of the occurrence of reactive ground. Consideration of any proxy of this type requires assessment of thresholds for identification of non-reactive, moderately reactive and strongly reactive ground, as well as assessment of the prevalence of "false positives" and "false negatives" in the data.

Three separate approaches to reactive ground risk prediction were tested: (a) a simple CaO threshold; (b) a MgO/(MgO + CaO) ratio threshold; and (c) a robust linear regression based on 11 explanatory variables. A number of observations can be made regarding the various proxies tested:

- All of the approaches are moderately effective at separating strongly reactive samples from non-reactive samples.
- When considering the thresholds that yield a strongly reactive false negative rate of approximately 15-16%, all three measures result in a correct negative rate of approximately 70%, and a strongly reactive positive rate of approximately 85%.
- The use of a more complex multi-variable regression did not produce an improvement in the ability to predict the degree of reactivity, as a simple threshold based on CaO assay produces comparable results.
- None of the measures are effective at predicting the occurrence of samples which are reactive at 105°

There are at least two possibilities which may explain the relatively strong correlation between CaO values and sample reactivity; firstly this pattern may reflect the distribution of zones of leaching with low CaO values reflecting areas with permeability to allow the ingress of fluid and oxygen to promote the heat-producing sulphide breakdown reaction; and/or secondly the areas of low CaO represent areas where the ability of carbonate in the rock to suppress the reaction <Iron sulphides + Oxygen + water → Ferrous ions + Sulphuric Acid> no longer exists.

A plot of the <2% and <4% CaO shells generated in Leapfrog (Figure 5) shows that these shells encompass the main area of highly reactive samples within the 500 orebody, though they also enclose a number of non-reactive samples which would be modelled as false. The zone of low CaO is similar to, but not exactly coincident with the Base of Moderate Leaching (BOML).

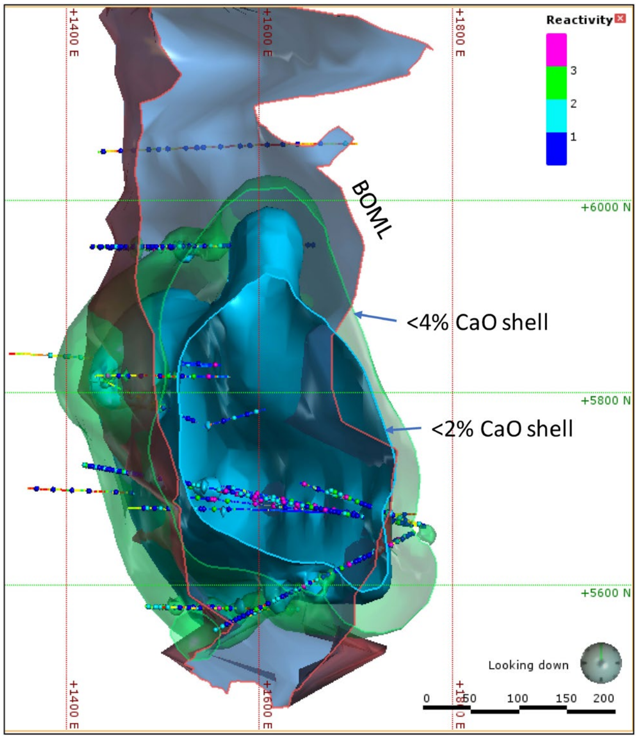

Figure 5 Plan slice through the sample and drill dataset at 2993 RL showing the <4% and <2%CaO shells calculated isotropically within Leapfrog, along with the geometry of the BOML.

CONCLUSIONS

Consideration of all relevant geoscientific data in the combined database for the 500 orebody at Mount Isa enabled the development of a reactive ground prediction methodology that improved on traditional methodologies. It was determined that the previously established criteria for prediction of reactive ground such as sulphide content and composition, noted presence of leaching/corrosion, presence of carbonaceous material, salts and other indicators do not provide an effective means to differentiate between reactive and non-reactive ground in drill datasets with any degree of confidence. Reactive samples show a notable association with low CaO values and high MgO/(MgO

+ CaO) ratios, as well as a weak positive correlation with Al2O3 and SiO2. There is very little correlation with other elements such as Fe, S, and Cu. The three separate approaches to reactive ground risk prediction produced comparable outcomes, successfully predicting 85% of highly reactive samples and 70% of non-reactive samples. On this basis, the simple threshold of 4% CaO was deemed to be the most easily applied to the 500 orebody, though the extent to which it can be applied elsewhere in the mine is yet to be established. A simple shell model of CaO differentiates higher-risk and lower-risk areas on both sides of the BOML boundary, providing an additional constraint for prediction of areas of high reactive ground risk which could easily be applied to a larger drill dataset.

The results of the study suggest that the key factors in predicting reactive ground areas/zones are the presence of fracture-related permeability and the lack of acid-buffering carbonates, which can be due to either due to original rock composition or leaching-related depletion. The lack of correlation with iron sulphide content is explained by the observation that pyrite is essentially ubiquitous in the mine environment, and exists in sufficient quantities to produce reactive ground in the presence of the other necessary facilitating factors. In this case study, the presence of carbonate appears to suppress reactivity, and it is important to consider the degree to which the code of practice test is valid in carbonate-bearing potentially-reactive materials.

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