Acid Mine Drainage in a Tropical Environment: A Case Study from the Tanjung Enim Coal Mine Site in South Sumatra, Indonesia

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Abstract

Indonesia is one of the world's most important coal producers and exporters. The state owned mining company (PT Bukit Asam or PTBA) operates an open pit coal mine at Tanjung Enim in South Sumatra; extracting Miocene/Pliocene coal from a back arc basin which has been influenced by igneous activity. Mining takes place in 3 separate pits called Air Laya, Muara Tiga Besar Utara (MTBU) and Banko Barat. These pits each contain pit lakes which are filled, predominantly, by rainwater. This region has a tropical climate. Field and laboratory measurements reveal that the pit lakes vary from acidic (pH 2.6) to circum-neutral (pH 6.6) and this is reflected in the chemistry of the waters. The waters are calcium, magnesium sulfate dominated but show elevated Al, Fe and Mn (26.7, 60.2 and 21.3 mg/L respectively) in the most acidic examples. The mine waters also show variation in trace elements linked to the acidity. Treatment of the mine waters is performed using a range of passive to semi-passive methods which include lime addition (up to 1800 t a^{-1}), settling lagoons and reed/floating plant beds. During the wet season the peak flow from the largest pit to one of the treatment systems is 875 L h^{-1}. Chemical stratigraphy of the overburden/interburden rocks reveals differences in the leachable trace elements which can be linked to the potential acid formation.

Keywords: Indonesia | South Sumatra | AMD|Coal mine water | Water treatment

Introduction

Indonesia is the world's 5th largest producer and its second highest exporter of coal (BP 2017). The estimated value of coal exports from Indonesia in 2016 was more than 18 billion US dollars. Coal mining is concentrated on the islands of Kalimantan and Sumatra. Here we describe the hydrochemistry of mine drainage at the Tanjung Enim mine site in south Sumatra; the largest open pit coal mine in Sumatra. This site lies approximately 165 km from the city of Palembang. PT Bukit Asam (PTBA), a state-owned mining company, operates the mine, at Tanjung Enim. The mine is located within the South Sumatra Basin; an extensional basin which lies to the east of the active volcanic arc in South Sumatra. This basin was formed in a back-arc setting during the pre-early Tertiary Period (Daly et al. 1987). At the mine site, the rocks belong to the Muara Enim Formation (MEF), which consists of mudstones, siltstones, sandstones, and coal beds that were deposited during the Late Miocene to Early Pliocene Periods. Amijaya and Littke (2006) interpret this as a shallow marine to non-marine sequence linked to a tropical deltaic system. Later deformation has given rise to set of NW-SE to E-W trending folds which develop local dips of between 5° and 30°. During the Late Tertiary and Early Quaternary Periods the area was subjected to igneous intrusions, of an andesitic composition, that caused local thermal metamorphism, resulting in an increase in the grade of some of the coals.

There are three coal seams at the Tanjung Enim site, which are, from oldest to youngest, the Petai, Suban and Mangus seams. Locally these are known as the C (Petai), the B2 and B1 (Suban) and the A2 and A1 (Mangus). These seams range in thickness: the C seam is between 7 and 10 m; the B2 seam is between 4 and 5 m; the B1 seam is between 8 and 12.3 m; the A2 is between 9 and 12.8 m and the A1 is between 6.5 and 10 m. Previous work by Gautama (1994) and Gautama and Hartaji (2004) has shown that acid mine drainage is an important issue at the Tanjung Enim mine. Gautama and Hartaji (2004) demonstrated that the source of the AMD is predominantly from the overburden and inter-seam rocks (interburden) and they were able to differentiate between potentially acid forming (PAF) and non-acid forming (NAF) rocks by the application of both static and kinetic testing procedures.

The mine site is bisected by the Enim River with two open pits (Air Laya and Muara Tiga Besar [MTBU]) to the west and Banko Barat to the east (Fig. 1). PT Bukit Asam has a total mining licence for 66,414 ha at Tanjung Enim and in 2017 the three open pits had a combined area of 15,421 ha; the individual areas being: MTBU 3300 ha; Air Laya 7621 ha and Banko Barat 4500 ha (PTBA 2017). It is informative to note that the three mine pits remove coal from all of the seams from C to A1 and thus there is no difference between the coals extracted from the individual open pits.

South Sumatra has a tropical climate, which shows only a limited change in temperature throughout the year. At Tanjung Enim the annual mean temperature is 26.6 +/- 0.4 °C with a maximum of 31.8 °C. The rainfall at the mine site is seasonal with the wettest months being December and January (with typical rainfall totals of 378 and 395 mm, respectively) and the driest months being June, July and August (with typical rainfall totals of 137, 110 and 130 mm, respectively) – these data are sourced from Climate-Data.org. The rainfall is the greatest source of water at the mine site since there is limited groundwater infiltration to the open pits. The tropical climate combined with the seasonal and stormy nature of the rainfall, makes the treatment of mine water challenging. Mine water is pumped from the open pits up to a maximum rate of 875 m^3 h-1 and treated in a variety of passive/semi-passive treatment systems (which are described below) before being discharged into the local river. The mine is governed by the Decree of the Minister of the Environment Nr. 113 year 2003 on Effluent Environmental Standard for Coal Mining Activities. This states that discharges must not exceed: pH 6-9; TSS 400 mg/L; Fe (total) 7 mg/L; Mn (total) 4 mg/L. Prior to this study there was only limited data on the chemical composition of the water from the mine site, driven by the requirements of the Decree, and limited information regarding the temporal variability in water chemistry. In addition, this study considers the implications of the nature and variability of mine water chemistry on treatment approaches.

Methods

A series of water samples were collected at the mine site between October 2015 and February 2018 so that both 'dry season' and 'wet season' data were available. In addition to the sets of discrete sampling operations, in July of 2016 a time series of field measurements was made at the outlet from one of the passive treatment systems at the site (see logging site Fig. 1), in order to better understand the short-term variability in the chemistry of waters subjected to treatment. This set of data was collected every 10 minutes from 15:45 on 22nd July to 12:05 on 24th July (total time of 43 hours and 20 minutes). This time series was able to collect data through a rainstorm event at 21:24 on 22nd July. Water chemistry was recorded by an Aquaread AP-800multi-probe/datalogger and flow stage by In-Situ Inc. Rugged Troll 100 water level logger with an additional barometric pressure logger. The sampling sites are shown on Figure 1 together with a set of unified sample location names/numbers. Samples were collected from the pit lakes, as close as possible to the floating pumping pontoons and also from the inlet and outlet of the different treatment systems. As far as possible the 'outlet' sampling points in this study correspond with points used by PTBA for their routine discharge monitoring.

In the field the pH, oxidation-reduction potential, temperature and some conductivity measurements of the waters was monitored using portable (Hanna) meters and probes. Discharge data was also measured/estimated at each site and calibrated using staging points where possible. Water samples were filtered in the field using a hand-held syringe system and 47 mm diameter 0.45µm cellulose nitrate membrane filter. Samples for cation analysis were acidified in the field whilst those for anion analysis were not. Chemical analyses were conducted in the laboratories at Aberystwyth University and the Laboratory of Hydrogeology & Hydrochemistry, Bandung Institute of Technology. Major cations were determined using atomic absorption spectrophotometry using multi-element synthetic calibration standards, minor and trace elements were determined by ICP-MS and anions were determined by ion chromatography

Results

Field measurements of the water in the open cast pits of the three mine areas reveal a distinct and consistent variation in the pH of the waters, with those samples from Air Laya and MTBU having a higher pH than the two pit lakes of Banko Barat (pit 1 and pit 3). The pH values were typically 6.3 (Air Laya), 4.1 (MTBU), 2.8 (Banko Barat pit 1) and 3.1 (Banko Barat pit 3). The field observations show that the pit lake at Banko Barat (especially pit 1) has a red colouration which is distinct from the other pit lakes. Throughout this study the pH values have remained fairly constant even when comparing 'wet' and 'dry' season results. The typical range of the pit lake surface pH is included in Table 1. This is somewhat surprising since the pit lakes represent rainfall collected in the pit bottom rather than the influx of groundwater; which is known to be a limited influence at this site. It might be expected that during the wet season dilution by rainwater would affect the pH of the pit lakes but this is not the case. Field measurements of ORP were also collected during the 2016 dry season sampling and these data show a range from 85 mV for the Air Laya pit to 483 mV for the Banko Barat pit 3. These data can be used to plot the position of each water sample on an Eh-pH diagram for iron species; adjusted to the measured water temperature of ≈ 32°C. These data show that the pit lake waters are close to the boundary between Fe^{2+} in solution and iron oxy-hydroxide precipitates and this could be buffering the pH/ORP within the mine waters.

The time series for water monitored at a treatment pond outlet shows a diurnal variation in temperature of ≈5° C with the lowest temperature recorded at ≈07:00 (27.3°C) and the highest temperature recorded at 16:30 (32.6° C). This change is not reflected in the ORP or DO data which only show minor fluctuations through the 43 hour period. The storm event produced a marked change in the discharge and an accompanying increase in the turbidity of the water (from a baseline of ≈10 NTU to a peak of ≈130 NTU before the readings stabilised at ≈50 NTU for the remainder of the time period). The changes in the water quality are the result of increased run-off from the coal stockpile because the pumps that deliver water from the Air Laya pit were turned off at the time of the data collection. The changes in water chemistry following the storm event also highlight the challenge posed by these events in the management and treatment of mine waters.

Laboratory measurements on the water samples have been used to characterise these mine waters for the first time. The major elements in the waters shows that they are dominated by calcium and magnesium sulfate as shown by the data in Table 1. Analysis of the waters collected during the dry season in 2016 confirms that these waters are saturated or close to saturated with anhydrite and gypsum. In addition to the major elements the mine waters have elevated levels of aluminium, iron and manganese (highest values of 26.7, 60.2 and 21.3 mg/L respectively in the waters of the Banko Barat pit 1).

The waters show differences that reflect the pH and Eh conditions illustrating the increased solubility of elements in more acidic waters. There is a number of elements which are a cause for concern because they exceed the environmental legislation in Indonesia (Fe and Mn). Furthermore there are elements which are potentially toxicity to the local aquatic environment (Al being one of the more important). Most of these elements are found at their highest concentration in the waters from Banko Barat pit 1 with intermediate concentrations in MTBU and Banko Barat pit 3 waters and the lowest concentrations in Air Laya

Table 1. Major element composition of mine waters from the 4 pit lakes (Air Laya, MTBU, Banko Barat (BB))– data for July 2016 (all results in mg/L).

Site name	Na	K	Ca	Mg	pH range	SO_4
Air Laya	200	15.4	134	45.8	5.8-5.9	936
MTBU	83.6	12.5	129	54.5	3.5-4.2	1000
BB pit 1	135	15.4	200	126	2.6-2.9	2010
BB pit 3	37.6	9.0	110	58.3	3.1-3.9	868

Table 2. Trace element composition of mine waters from the 4 pit lakes (Air Laya, MTBU, Banko Barat (BB))– data for July 2016 (dry season) and December 2107** (wet season). All results in ug/L except Mn and Fe in mg/L).*

Site	Al	Mn	Fe	Co	Ni	Sr	Ba	ΣREE	Th	U
Air Laya*	14	5.0	0.03	38	46	954	47	1	n.d	n.d
MTBU*	1360	7.73	2.5	89	106	1040	47	52	0.2	0.8
BB pit 1*	7730	21.3	60.2	273	338	1680	38	1250	5.5	3.6
BB pit 3*	2143	7.65	9.5	96	117	577	49	107	1.9	2
Air Laya**	111	6.1	0.1	45	52	900	40	6.1	0.7	0.5
MTBU**	1120	6.81	0.28	77	84	913	50	43	0.1	0.3
BB pit 1**	8950	11.1	21.2	199	261	943	51	261	8.5	5.5
BB pit 3**	3450	7.45	3.76	138	179	585	59	130	1.2	2.4

waters. This can be illustrated by considering a selection of trace elements with data presented in Table 2 for both the dry and wet seasons.

The data for Air Laya shows relatively low concentrations of all of the trace elements when compared to the other sites; which is consistent with the circum-neutral pH of this pit lake. The high Fe and Mn content of Banko Barat pit 1 is also reflected in the high Al, other first row transition metals, Sr, total REE and Th and U. It seems reasonable to suggest that many of the elements are elevated because of the acidic nature of these waters but that there is also a lithological/mineralogical control on the chemistry that reflects the spatial distribution of the extraction pits. This is best illustrated by comparing the waters from MTBU and Banko Barat pit 3. These two waters have similar pH values and also similar major element concentrations but the two vary in their total REE and Th and U concentrations; suggesting a source for these trace elements that is spatially controlled and generally higher in the Banko Barat area than the MTBU area. Equally the source of Sr and Ba favours the sites to the west (Air Laya and MTBU). Gautama et al. (this volume) have investigated the link between the potential acid formation of the overburden/interburden at the Tanjung Enim site and their data shows that trace elements are not homogeneously distributed through the different horizons. Vanadium and Mo, as an example of trace elements commonly associated with coal-bearing rocks, show their highest concentrations in the interburden between the A1 and A2 seams whereas Sr shows a peak in concentration in the same horizon followed by a general decrease in the deeper interburden rocks. Nickel and Cr show a general increase in concentration with depth whereas Ce and U are highest in the middle of the sequence.

All of the pit lakes exceed the permissible concentration for Mn but only the Banko Barat pits exceed the limits for Fe. These waters require treatment before they can be discharged into the local river.

Each of the mining areas has at least one passive/semi-active water treatment system. These range from settlement lagoons, which generally have some lime addition at the inlet, to a complex treatment system involving reed beds and floating plant-based adsorbers. PTBA uses around 1800 tonnes of lime per year which is added to the more acidic waters prior to the treatment cells. During this study samples were collected at the inlet and outlet

Table 3. *Major element composition of mine waters treated in the Air Laya/Stockpile treatment system data for July 2016 (all chemical results in mg/L).*

Site name	pH	Eh(mv)	K	Mn	Fe	SO_4
Inlet water	6.13	220	30.3	0.69	0.52	106
Intermediate 1	6.02	62	5.59	0.66	0.58	191
Intermediate 2	6.45	64	4.92	0.65	n.d.	204

of some of the treatment systems to gauge the efficiency of Fe and Mn removal. The treatment system employing reed beds to treat the water from the Air Laya pit as well as water draining from one of the main coal stockpiles at the site was considered in more detail, with samples collected from intermediate stages as well as the inlet and outlet. This scheme covers an area of approximately 62,000 m^2 and consists of a series of 12 ponds which are, in order: 3 settlement ponds; 4 typha reed beds with floating ferns (T*ypha sp.* and *Salvania natans*); 3 ponds with floating vetiver plants for metal removal (*Viveria zizanoides*) and 2 ponds with common water hyacinth (*Eichhornia crassipes*). In the study four sites were selected which covered both the inlet and outlet of passive treatment beds as well as two intermediate sample points; one at the inlet to the middle typha bed and one at the inlet to the first floating vetiver lagoon. The results from 2015 show that the treatment system removes Al and Fe to below the limit of detection and the Mn from 24.5 mg/L to 0.1 mg/L. When the system was studied in detail in 2016 the concentration of elements in the input water was lower because the only water being treated was draining from the coal stockpile. In 2016 the intermediate samples showed that Fe was removed but Mn remained constant (at ≈650 μg/L) until the final outlet sample. The same sample set showed that K was depleted by a factor of 6 because it is an important nutrient whereas Ca, Mg and Sr all increased from the dissolution of added lime. Results for the 2016 study of this treatment system are shown in Table 3.

Dry season data for the MTBU treatment cells show that these work to remove Fe (2.5 to 0.2 mg/L) but have little effect on the Mn (6.6 to 5.8 mg/L) which reflects the difficulty in removing Mn by settlement lagoons or pH adjustment alone. This mine water would not comply with the Indonesian Government Decree of 2003.

Conclusions

We have reported new data for the Tanjung Enim open pit coal mine waters for the first time. We have shown that much of the mine water at the Tanjung Enim site has elevated concentrations of Fe and Mn which exceed the permissible discharge limits for Indonesian coal mines. There are, in addition, other potentially harmful elements present in the mine waters that are not routinely analysed such as Al. There are only limited seasonal effects at this site with some dilution demonstrated in the wet season data. There is a spatial difference in the pit lake chemistry that cannot be easily linked to the coal being extracted from the different mine pits and must, therefore, be related to the distribution of potential acid formation in the interburden across the area.

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References

Amijaya H, Littke R (2005) Microfacies and depositional environment of Tertiary Tanjung Enim low rank coal, South Sumatra basin, Indonesia. Int J Coal Geology 61:197-221, doi: 10.1016/j.coal.2004.07.004

BP Statistical Review of World Energy June 2017 (2017) – 66th edition

Daly MC, Hooper BGD, Smith, DG (1987) Tertiary plate tectonics and basin evolution in Indonesia. Proceedings of the 6th Regional Congress on Geology, Mineral and Hydrocarbon Resources of Southeast Asia (GEOSEA VI), Jakarta, 1-28

Gautama RS (1994) Acid water problem in Bukit Asam Coal Mine, South Sumatra, Indonesia. Int Mine Water Association Proceedings 1:533-542

Gautama RS, Kusuma GJ, Pujiantoro E, Wisnugroho PH (2018) On The Spatial Variation of Rock Geochemical Characteristics in Coal Mining: Case Bukit Asam Coal Mine in South Sumatra, Indonesia. This volume.

Gautama RS, Hartaji S (2004) Improving the accuracy of geochemical rock modelling for acid rock drainage prevention in coal mine. Mine Water Environ 23(1):100-104

PTBA Annual Company report (2017) PT Bukit Asam Tbk. Jakarta

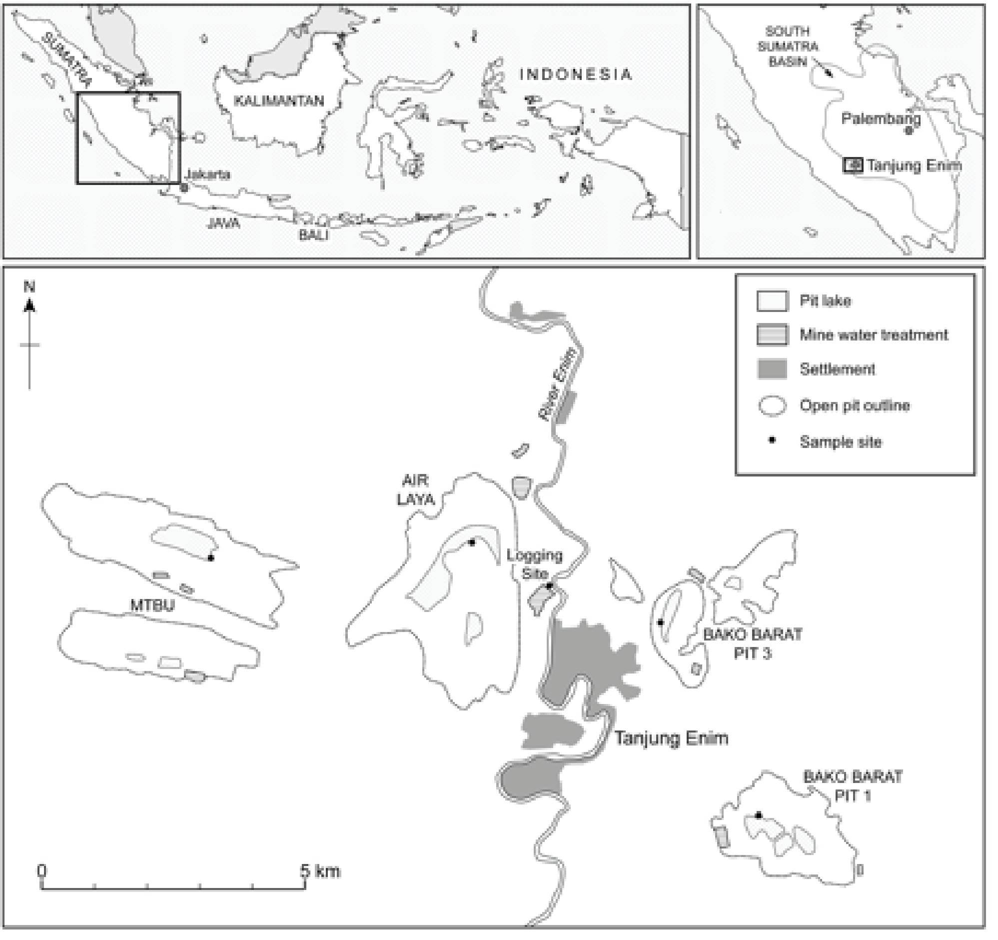

Figure 1 Study location map showing the position of the south Sumatra basin and the area of the mine (top left) and a detailed map of the Tanjung Enim site with the individual mine pits indicated, the pit lakes and the key sampling locations shown.