UNDER PEER REVIEW

Monitoring of blasting operations techniques and assessment of their impacts on groundwater in the context of underground mining: Case of ROXGOLD SANU, Burkina Faso.

Abstract

This study focused to study the blasting operations and to evaluate their impacts on Groundwater at the ROXGOLD SANU underground mine in Burkina Faso. ROXGOLD SANU is a mining and exploration company, under Burkinabe law and the State is a non-contributing shareholder up to 10%. The seismic vibration values measured on the ground are between 0.075 and 8.45 mm/s. These values are therefore all below the limit value of 10 mm/s defined by the Burkinabe law for mining operations carried out in quarries and mines and in compliance with the IFC standard. The values of acoustic overpressure were also all below 122 dB, i.e. below the limit value of 125 dB allowed for blasting in quarries and solid rock mines. The analysis of groundwater levels recorded since 2014 showed that the different water tables on the site do not communicate with each other. The impact of mining activities on groundwater levels is limited mainly to one piezometer. ROXGOLD SANU has therefore implemented good blasting practices, as the average values of the data collected during blasting are well below the recommended thresholds. Nitrate values measured in mine water in 2016 ranged from 7.1 mg/l to 1054 mg/l. However, in 2018 an average concentration of 484 mg/l was measured. Nitrite values ranged from 0.015 mg/l to 51.5 mg/l in 2016. In 2018, a concentration of 1.9 mg/l of nitrite was observed in the study area. As for ammonium, its concentrations measured in the field in 2016 vary from 0.08 to 145 mg/l. Thus, it emerges that the concentration values of Nitrites, Ammoniums and Nitrates measured in the field are higher than the limit of the regulations in force. These high values of Nitrites (NO_3^-), Ammoniums (NH_4^+) and Nitrates (NO_2^-) observed in mine water of the study area could be directly linked to the blasting operations which release nitrogen into the environment. The mine water of the study area is not dumped on the ground. It is carefully managed and controlled, in case of flooding it is sent to the TSF and does not flow into nature. Nevertheless, It is therefore important to set up a mechanism for complaints and requests from the local population to study the effects of blasting in depth.

Keywords: Blasting, Groundwater, Underground Mine, Nitrites, Ammoniums, Nitrates

Introduction

In many areas of the mining industry, the economic activity intervenes in a specific and sometimes decisive way, and they often appear as the best solution to carry out certain works, in many cases ensuring lower costs, and this is the case in open pit and underground mining. Controlling the cost of the project (mining and quarrying) and achieving a high yield requires an optimal exploitation plan, the latter is closely related to the degree of influence of the study of the characterization of rock massifs and their classifications **[1]**. Thus, to achieve this goal, in all mining operations, one of the links of technological processes of exploitation of useful mineral deposits is the preparation of rocks for extraction. This stage of preparation predetermines the performance of machinery, work safety and, in general, the efficiency of open-pit and underground mining operations. In most cases, the preparation of rock for mining is based on the destruction of the rock mass until pieces of the necessary and permissible size are obtained for the normal work of the whole mining and transporting complex. Just as it must ensure a minimum degree of mixing of waste rock and ore in order to have the smallest possible dilution **[2]**; **[3]**. Mines and quarries are subject to regulations on blasting, seismic shaking and acoustic vibrations. Repeated production blasting can influence ground stability: on the one hand because of the destabilizing shock pressure forces they can generate, and on the other hand because they degrade the mechanical properties of the massif in the long term, these can contribute to decrease its shear strength. Blasting with explosives always causes significant damage beyond the theoretical extraction area. In general, the deformations are not directly visible to the naked eye and result in a variation of the cracking and especially in the rejection of pre-existing cracks which eventually favour the alteration, the evolution and then the instability of the rock faces **[4]**. The repetitive blasting of mining production influences the stability of underground structures, land around the mining perimeters, as well as on the inhabitants of the study area, due to the generated impacts, pressures and destabilizing shocks **[5]**. In the long term, rock and ore mining also degrade, the mechanical properties of the massif with the consequence of decreasing its shear strength; disturbing the geological environment and groundwater regime and also altering the quality of the water table.

In our mines, the number of blasts and the quantity of explosives used vary according to the characteristics of the deposit and the techniques used. The effects of blasting operations are all characterized by the fact that they are always linked to the site and the areas involved, particularly with regard to the environmental, social and infrastructural context.

Indeed, blasting appears today as the simplest and most widespread technique in mines and quarries. The principle of the explosion is based on the transformation of a potential chemical energy into mechanical energy communicated to the outside environment. An explosive is a mixture of chemical substances that are not very stable, which, when subjected to energy (thermal or mechanical, for example), is likely to decompose rapidly. Blasting makes it possible to fragment large volumes of rock for the recovery and processing of the blasted product **[6]**. This process has many advantages, but it should be noted that blasting is accompanied by human and environmental risks. Indeed, dynamites contain from 10 to 90% nitroglycerol (NGL), a mixture of nitroglycerin and dinitroglycol, a component that ensures the antifreeze quality of the dynamite. Nitroglycerin is very sensitive to shock and friction and are to be handled with gloves to limit the toxic effect of nitroglycerin **[7]**. These explosives used in mines therefore generate major environmental concerns, due to air pollution caused by the emission of dust and nitrogen oxides (NO_x) from the blasting and also because of their adverse effects on groundwater **[8]**.

The control of risks related to the use of explosives and the standardization of their effects are more than necessary in a context where several are in operation in Burkina Faso. The laws and regulations in force for the protection of man and the respect of his environment for the exercise of mining activity in Burkina Faso specify that: "the activities and installations governed by the mining code must be conducted with respect for the protection and preservation of the environment in accordance with the texts in force, in particular the environmental code, the mining code as well as the laws and related texts. The objective of this study is to identify and minimize the environmental effects of blasting operations in a way that is consistent with the ROXGOLD SANU underground mine in Burkina Faso. It is a mining and exploration company, under Burkinabe law, and the State is a non-contributing shareholder up to 10%. At this mine, two types of blasting are used, one at the development level and another at the production level. The rock blasted is then handled with 15-ton haulage equipment and evacuated to the surface. This process of drilling, blasting and loading the rock is continued continuously in batches. The ramp continues to be developed at depth following the deposit to facilitate production activities.

Materials and Methods

Presentation of the study area

Yaramoko, located at 11°48'0" N and 3°16'60", is a village in the Bagassi department, Bale province in western Burkina Faso. The village is made up of two main districts (Yaro and Moko), located on either side of a river that feeds a dam with a surface area of 16.8 km^2. The village is located in the South Sudanian type climate zone **[9]** (**Figure 1**). The average rainfall between 1978 and 1980 was 950 mm. Data for the year 2004 gives an average of 800 mm **[10]**. Les Balés is one of the 45 provinces of Burkina Faso, located in the Boucle du Mouhoun region. The province borders the Hauts-Bassins region to the southwest, the South-West region to the southeast, the Centre-West region to the east and the Mouhoun province to the northeast. Boromo (or Borom) is the capital of the province, which is administratively headed by a high commissioner, appointed by the government and placed under the authority of the governor of the region. The high commissioner coordinates the local administration of the prefects appointed in each of the departments. The Bale province is administratively composed of ten departments or communes. Nine are rural communes, Boromo is an urban commune whose capital city, subdivided into 4 urban sectors, is also the province's capital (three of the nine rural communes, among the largest in the province are now populated enough to eventually move to urban commune status, although they are still composed only of self-contained villages) **[11].** The climate of this locality is semi-arid with a rainy season from April to October and a hot dry season from November to February and warm from March to June. Temperatures range from a minimum of about 15 degrees Celsius (°C) in December to maximums of about 45 °C in March and April. Total annual precipitation in the region averages 800 millimetres (mm).

ROXGOLD is a Canadian exploration and mining company listed on the Toronto Stock Exchange (TSX Venture: ROG). Its subsidiaries in Burkina Faso are: ROXGOLD Burkina which initiated the exploration work and ROXGOLD SANU SA which is a company under Burkinabe law and the State is a non-contributing shareholder of 10%. The company holds five mining concessions in Burkina Faso: Yaramoko, Boussoura, Solna, Yantara and Teyango; but at the moment activities are focused on the development and further exploration of the Yaramoko project its main asset, (Roxgold Inc. Report, 2018). The high grade Yaramoko gold mine, is located in the Houndé greenstone belt in Burkina Faso. Bagassi South, the company's first growth project, is currently in development. The feasibility study describes an after-tax IRR of 53.2% with a return on investment of 1.8/year based on a gold price of $1,300/ounce. Roxgold is listed on the Toronto Stock Exchange under the stock symbol ROXG and as ROGFF on the OTC market. The nearest major city to the Yaramoko gold mine is Boromo, located 50 km away. It is served by the national power grid and is home to a hospital and additional suppliers. However, the main purchases and supplies come from Ouagadougou. It can be accessed via the highway network by travelling west from Ouagadougou on a tarred highway for about 200 km, or alternatively east from Bobo-Dioulasso for about 150 km to the village of Ouahabou, and then north-northwest on a laterite road for about 20 km to the village of Bagassi **[12]**.

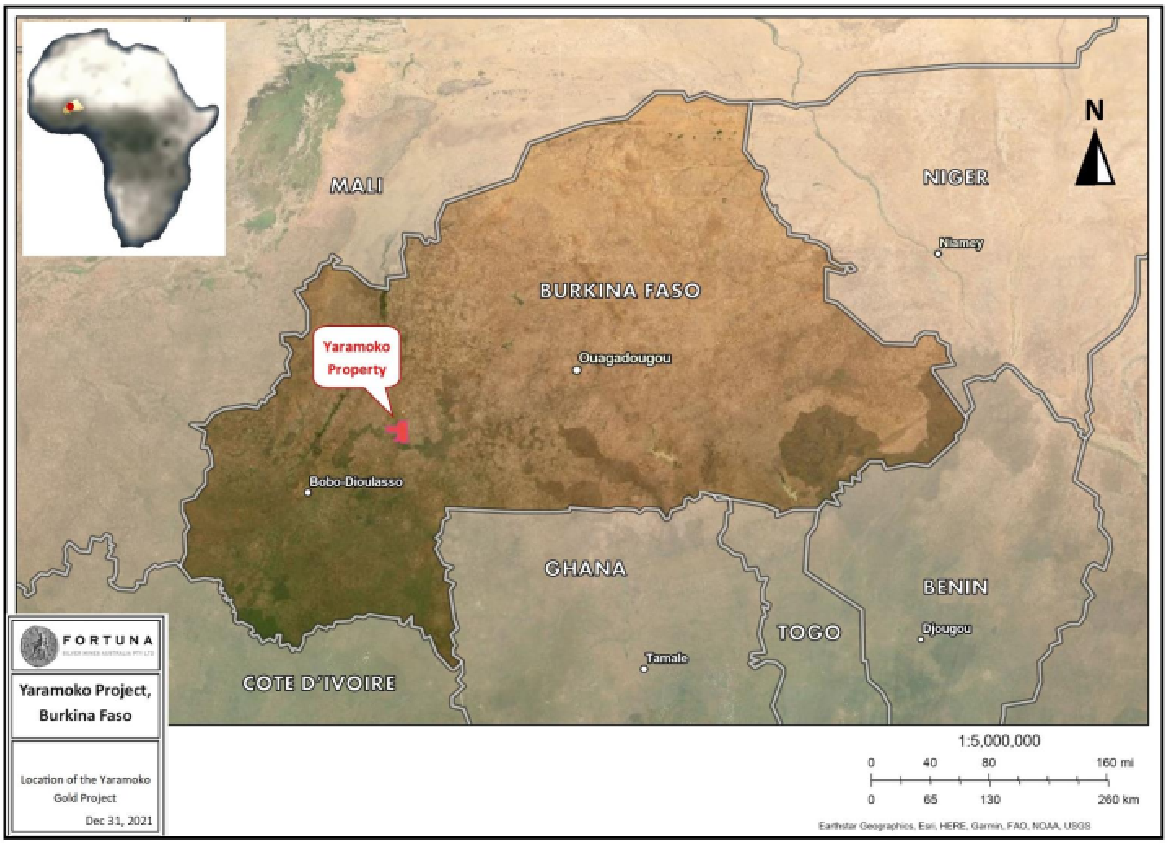


Figure 1: Study area **[12]**

The north-northeast trending Boni shear zone divides the Yaramoko gold mine between the predominantly Houndé volcanic and volcaniclastic rock to the west and the Diébougou granitoid domain composed mainly of granitic rock with minor volcanic rock to the east. The main lithological units are mafic volcanic rocks, felsic intrusions and late dolerite dykes. This area is considered prospective for orogenic gold deposits, which generally have a strong relationship with regional networks of major shear zones. The largest granitic intrusion found on the Yaramoko concession hosts the Zone 55 and Bagassi South gold deposits. Both deposits are located on the eastern margin of the intrusive in the footwall of the Yaramoko shear along conjugate dextral faults located in the extensional position of the regional shear zone. Most of the gold mineralization occurs in the dilatation segments of the shear zones where the quartz veins are thicker and have greater continuity. The Bagassi South deposit is located 1.8 km south of Zone 55 and the surface definition of the veins can be traced over a length of approximately 800 m and dips to the northeast. Gold is generally coarse free grain in quartz and is associated with pyrite **[12]**.

Blasting Operation Methods

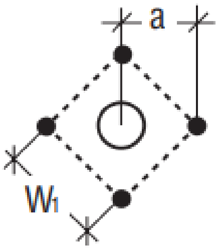
In the study area, in the context of gold mining, two types of blasting are used in the field: blasting for the advancement of the ramp, cross benches and main galleries and production blasting.
In the case of advancing shots, the surface of the shot is constituted by the face of the mine. The horizontal holes are therefore perpendicular to this surface which does not constitute a real free surface. This configuration requires the use of more specific energy in underground workings to extract the materials. For the explosion to be effective, a free surface must first be created. The first mining operation is therefore the creation of this free surface, the so-called plug holes. These holes are the first ones initiated in the firing sequence, they allow to enlarge the cavity of the clearance hole, thus creating the free surface necessary for the other mines. The next mine holes allow to enlarge the cavity of the plug; they are the degreasing mine holes. Then, the blasting holes are used to fragment the rock in the space created by the plug and the degreasing blasting holes. Several types of blasting

holes can be identified, among which we can distinguish the lifting mine holes, placed below the plug, which have a direction of release directed upwards; the cushion mine holes, adjoining the cutting zone, corresponding to a cushioned line of fire; the production mine holes, placed above the plug, which have a direction of release directed downwards; the facing mine holes, placed to the right and left of the plug, which have a horizontal direction of release. In addition, contour holes are sometimes associated with cushioned shotgun mines. We distinguish between contour holes such as crown blasting holes which cut the upper vault; facing blasting holes: they cut the profile of the excavation laterally; invert blasting holes which are at the base of the section. Finally, the corner blast holes, which are the holes at the lower ends of the face. They must be loaded with enough explosive to allow the final invert rib to be obtained. The different holes are connected with the detonating cord and the corner holes are loaded with power gel (megamite), unlike the other holes which are loaded with ANFO (Figure 2; Figure 3; Figure 4; Figure 5). Equation 1 can be used for the geometric design of the cutting area [**13**]. The different cuts are shown in Figure 1, Figure 2, Figure 3 and Figure 4.

ø =d$\sqrt{n}$ $\emptyset = d\sqrt{n}$ equation 1

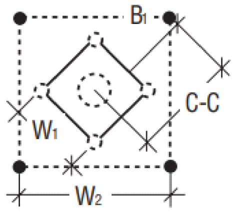
Where: d = diameter of empty reamer holes ;

n = number of bore holes.



where $a = 1,5ø \,;\, W1 = a\sqrt{2}$

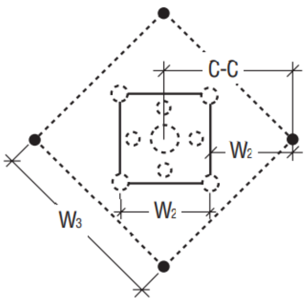
Figure 2: The 1st square cut.



Where $B1 = W1 \,;\, C - C = 1.5W1 \,;$

$W2 = 1.5W1\sqrt{2}$

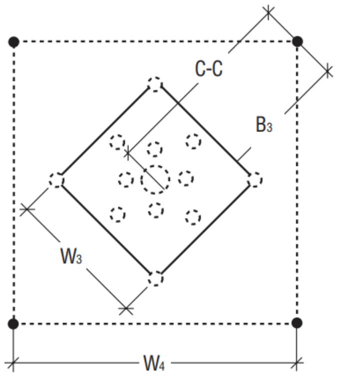
Figure 3: The 2nd square cut.



Where $B2 = W2 \,;\, C - C = 1.5W2 \,;$

$W3 = 1.5W2\sqrt{2}$

Figure 4: The 3rd square cut.



Where $B3 = W3 \,;\, C - C = 1.5W3 \,;$

$W4 = 1.5W3\sqrt{2}$

Figure 5: The 4th square cut.

In the case of production blasting, the boreholes are drilled almost vertically, at about 17m, parallel to the free surface. The ore and waste material are removed by gravity and stored at the bottom of the chamber and then evacuated through galleries located below the mined level. The mined materials are moved by loaders. The mining process therefore consists of cutting down the stope between levels. The progression of this method is downward and the mining is done by first plugging the bottom of the holes with the bags of ANFO already used. We tear and then introduce one or two Megamite cartridges at the bottom of the holes. Then a small amount of ANFO is introduced and an electronic detonator primed with a booster. Then a small amount of ANFO is added and a second electronic detonator primed with another booster is introduced and completed with ANFO. The electronic detonators are then connected to the firing line and the detonation sequence of the holes is programmed. Finally, we proceed to the firing after evacuation.

Method for Determining the Firing Parameters and Energetic Properties of Explosives and the Priming Plan and Initiation Sequence

In the classification of explosives, several subfamilies can be distinguished. They are distinguished from each other by the chemical formation of the explosive compound, by its structure, and are generally classified according to their speed of decomposition, particularly the speed of detonation. The nature and speed of their decomposition depend on the power of the explosion and the total energy released during the reaction.

The different technical parameters of a shot are the surface of the shot in m^2 (average length multiplied by the average width); the volume of rock removed in m^3 (average shot area multiplied by average drilled height) and the tonnage of rock removed in T (Volume of rock removed multiplied by the density of the rock). For the technical parameters, the unit load Q in kg/m, the quantity of explosive loaded per hole, Qch in Kg and the specific consumption, CS in kg/m^3 are determined using Equations 2, 3 and 4. The mass energy, which is the product of the quantity of explosive loaded and the mass energy of the explosive, is also calculated. The total specific energy expressed in Mj/m^3 is also determined by taking the ratio of the total mass energy by the volume to be shot.

$$unit\ charge\ (Q) = \pi \times r^2 \times d \times 1 \qquad \text{Equation 2}$$

Where: Q = unit charge (kg/m); r = hole radius (m) and d= density of the explosive.

$$Quantity\ of\ explosive\ charged\ (Qch) = Q \times lch \qquad \text{Equation 3}$$

With : Qch= Quantity of explosive charged per hole and Lch = length of charge

$$\textbf{Specific consumption (SC)=} \frac{Quantity\ of\ explosive\ charged}{volume\ to\ be\ cut\ down} \qquad \text{Equation 4}$$

In the study area, initiation is done by means of detonators, which are the initiators of detonation. Three priming devices are used, namely electric detonators to initiate NONEL detonators in development; NONEL, NON-Electric detonators, which are used without the use of electric current and are conventionally delayed (in development) and programmable electronic detonators used in production blasting. At the time of the explosion of the charge of a mine hole, the fragmentation is better as well as the piling up, when it has several free surfaces. This is the main reason for the use of delays between blast holes, called the second reason, which corresponds to the reduction of the instantaneous unit load and at the same time attenuates the vibrations of the medium. The delay is chosen in advance, and is programmed at the production level. For the development, the detonation of the holes is done according to the different numbers and the holes with the same number detonate at the same time although the shots are not at the same level.

To manage gas and dust nuisance in the mine, the ramp is used to provide ventilation and air services throughout the drifts. Runways are regularly watered and drilling is done with water, which significantly reduces dust generation. In addition, the ramp is also the main ventilation artery of the mine with fans blowing air from the surface into the ramp and venting underground air to the surface through lifts. The design of the access roads and ventilation systems provides a safe working environment, with good ventilation and safe access and egress systems for personnel. With regard to rock vibration and fractures, a system of friction bolts and anchor cables (growling) are installed to prevent rockfall and falling rock pieces on personnel and equipment. With this system, huge bolts are anchored into the boulders and fix them together. The cable system is combined with the bolt system and reinforces the stability of the tunnel walls. This anchoring increases the pressure in these rocks and makes them more stable. Also, the network of bolts and cables supports a mesh that holds the small pieces of rock.

Results and Discussion

Shooting Operations

Table 1 presents the different measurement points and Figure 6 shows the location of the measurement points. Indeed, from a technical point of view, the shot can be evaluated according to: the shot granulometry, the good functioning of the cap, etc. We can also evaluate its nuisances: gases, dust, vibrations, aerial overpressure. The analysis of the results allows to size the shots in order to optimize them and to reduce the nuisances.

To assess the effects of blasting on the environment, including seismic and acoustic effects, measurements with the Micromate Instantel were performed.

Table 1: Measurement points

Measurement points	UTM coordinates (X)	UTM coordinates (Y)	Altitude (m)
P1	0469117	1298971	5312
P2	0469963	1299482	5338
P3	0469518	1298298	5305
P4	469445.875	1299170.125	5235.7330
P5	0469517	1298296	5294
P6	0469094	1298940	5314
P7	0469203	1299220	5324

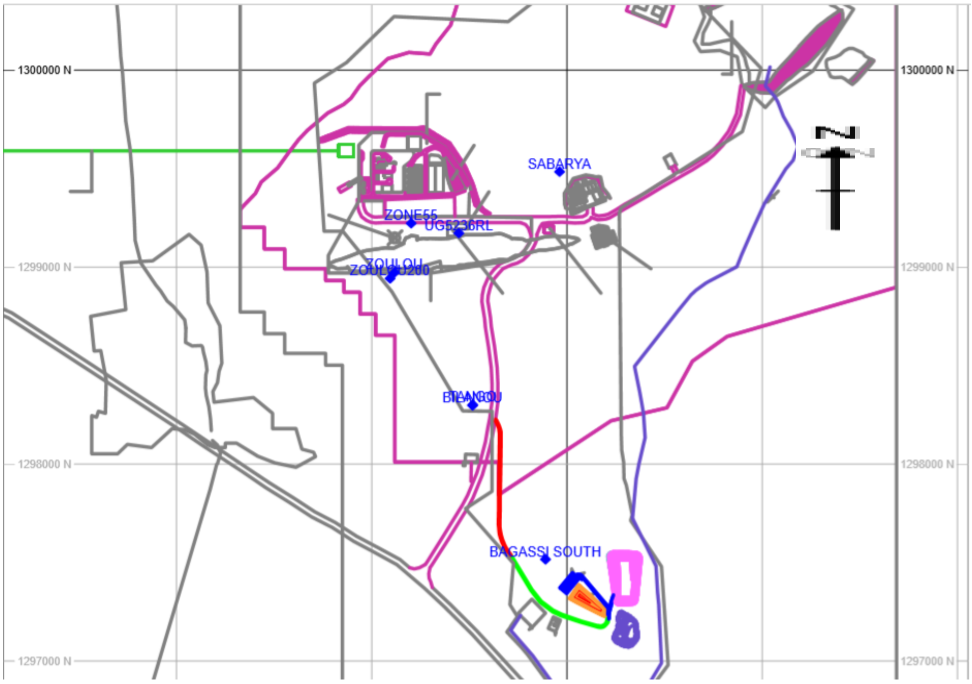


Figure 6: location of the measurement points (Scale: 1/500000)

The shootings are carried out between 5.30 pm and 6 pm for the day stations and between 5.30 am and 6 am for the night stations. Indeed, as the Micromate Instantel records the highest particle velocity at a time T; it was retained the highest particle velocity in these intervals of time (5h30 - 6h and 17h30 - 18h). The different theoretical particle velocities were then compared to determine the shot that corresponds to each measurement with a K=2500. The following table 2 shows the measurements made on 08/01/17 in development and in production. By setting k = 2500 and V = K $(\frac{D}{\sqrt{Q}})^{-1.8}$ one can proceed to the comparisons of the theoretical particle velocities deduced for a k=2500 . Table 3 describes the method used to assign the measurements to each shot.

Table 2: Measurements made for production and development shoots

Date	**Time**	**Production**		**Development t**					
08/01/17	17:42:39	Fire 202_03 R9-12	Fire 236_28 R18-21	168 ODW35	168 ODE 38	Sum load (kg)	Sum distance (m)	Medium distance (m)	Measured particle velocity (mm/s)
+distance		148,08	276,31	305	503,6	-	808,6	404,3	2,58
CUI		34,17	38,34	27,6	27,6	55,2	-	-	

Table 3: Assignment of a measure to a shot

Name of the shot	**Fire 202_03 R9-12**	**Fire 236_28 R18-21**	**Development** **168 ODW35 and 168 ODE 38**
shooting distance (m)	148,082	276,31	404,3

unit load (kg)	34,17	38,34	55,2
theoretical particle velocities	7,4	2,7	1,9

The analysis of this Table 3 shows that the Fire 202_03 R9-12 gave the highest theoretical particle velocity, which proves that it is the shot measured that day. The table below shows the recorded data. The following Table 4 and 5 show the results of the Micromat measurements and their statistical descriptions. The analysis of Table 5 indicates that the seismic vibration values of the study area vary between 0.737 and 8.450 mm/s with an average of 3.62 mm/s. These values are all lower than 10 mm/s, the limit value defined by the decree of 22/09/1994 for blasting in quarries and mines and in compliance with the IFC standard. The analysis of Table 4 shows that the values of acoustic overpressure all gave values below 122 dB, i.e. below the limit value allowed for blasting in quarries and solid rock mines (125dB). The highest measurements for the same blast (8.45mm/s and 121.4 dB) were recorded respectively on 10/12/16 (distance: 274.37 m; unit load: 82.80 kg; particle velocity: 8.45 mm/s; air overpressure: 107 dB) and on 16/12/18 (distance: 182.743 m; unit load: 41.33 kg; particle velocity: 8.187 mm/s; air overpressure: 121.4 dB) Indeed, good blasting practices assume compliance with the recommended thresholds in the working environment at 125 dB for acoustic vibrations and 10 mm/s for seismic vibrations in the mine. The device did not record vibrations at the following measurement points: Tango and at Bilanou. All the measurements made at these points were null. Indeed, the smallest value that the device is able to measure is 0.5 mm/s. We can conclude that there is almost no influence at these points.

Table 4: Micromate measurement results

Location	**Distance (m)**	**CUI (kg)**	**Particle velocity (mm/s)**	**Acoustics (dB)**
Area 55	230,66	82,80	8,15	108
Area 55	274,37	82,80	8,45	107
Area 55	274,69	82,8	1,08	107
Area 55	258,40	110,40	2,45	107
Area 55	223,74	55,20	1,58	107
zulu	148,08	34,17	2.58	107
200 m of zulu	148,32	34,17	4,33	108
Zulu	124,54	45,44	2.288	-
C. sabarya	763,979	27,6	0.737	-
Zulu	136,53	30,36	1.451	-

Zulu	251,636	36,15	1.867	-
Zulu	223,046	25,99	2.176	-
5236 acess	217,6	29,31	8.248	105.0
5236 acess	182,743	41,33	8.187	121.4
C.sabarya	27,6	770,389	0,806	-

Table 5: Descriptive statistics of the results of the measurements made with the Micromate

Parameters	Minimum	Maximum	Mean	Std. Deviation
Distance (m)	27,600	763,979	232,39560	161,901589
CUI (kg)	25,990	770,389	99,26060	187,491893
Particle velocity (mm/s)	0,737	8,450	3,62533	3,018517

Determination of K Coefficient and Particle Velocity Prediction

In this study, the value of the site coefficient was determined using the formula from Chapot's law (Equation 5) as follows:

$$V = K\left(\frac{D}{\sqrt{Q}}\right)^{-1.8}. \qquad \text{Equation 5}$$

$$\text{Hence } K = V\left(\frac{D}{\sqrt{Q}}\right)^{1.8}$$

The following Table 6 shows the results of descriptive statistical analysis of C.U.I (kg) Distance (m) Particle velocity (mm/s) and k coefficient measured at different dates in the study area. The analysis of this Table 6 shows that the values of C.U.I vary between 25.99 and 110.4 K with an average of 54.30 Kg. The values of the distances considered vary between 124.53 and 811.38 m with an average of 252.93 m. The values of particle velocity oscillate between 0.737 mm/s and 8.45 mm/s with an average of 3.48 mm/s. The values of the terrain coefficient deduced from the Chapot formula vary between 435.82 and 4183.34 with an average of 1765.53.

Table 6: Descriptive statistical analysis of C.U.I (kg) Distance (m) Particle velocity (mm/s) and k

Parameters	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**	**Variance**
C.U.I (kg)	25,99	110,4	54,3085	26,52661	703,661
Distance (m)	124,539	811,389	252,9341154	176,0627922	30998,107
Particle velocity(mm/s)	0,737	8,45	3,48738	2,857247	8,164
Coefficient k	435,8241	4183,341	1765,528769	1354,828681	1835560,754

The average value of the site coefficient found (K = 1765.53), a prediction of the theoretical particle velocity at different points was made. Table 7 below presents the matrix related to the prediction of the particle velocity. This matrix allowed to anticipate the effects of a shot before it takes place. It is elaborated as a function of the shot-sensor distance and the instantaneous unit load. Referring to the IFC standard of 10 mm/s (identical to the French circular of the decree of 22/09/1994 relating to quarrying and mining) which is the threshold of the particle velocity not to be reached, a legend has been drawn up.

Table 7: Particle Velocity Prediction Matrix

shooting distance (m)	unit load (kg)											
	10	20	30	40	50	60	70	80	90	100	110	120
50	12,3	22,9	33,0	42,7	52,2	61,5	70,7	79,7	88,6	97,4	106,2	114,8
75	5,9	11,0	15,9	20,6	25,2	29,7	34,1	38,4	42,7	47,0	51,2	55,3
100	3,5	6,6	9,5	12,3	15,0	17,7	20,3	22,9	25,5	28,0	30,5	33,0
125	2,4	4,4	6,3	8,2	10,0	11,8	13,6	15,3	17,0	18,7	20,4	22,1
150	1,7	3,2	4,6	5,9	7,2	8,5	9,8	11,0	12,3	13,5	14,7	15,9
175	1,3	2,4	3,5	4,5	5,5	6,5	7,4	8,4	9,3	10,2	11,1	12,0
200	1,0	1,9	2,7	3,5	4,3	5,1	5,8	6,6	7,3	8,0	8,8	9,5
225	0,8	1,5	2,2	2,8	3,5	4,1	4,7	5,3	5,9	6,5	7,1	7,7
250	0,7	1,3	1,8	2,4	2,9	3,4	3,9	4,4	4,9	5,4	5,9	6,3
275	0,6	1,1	1,5	2,0	2,4	2,9	3,3	3,7	4,1	4,5	4,9	5,3
300	0,5	0,9	1,3	1,7	2,1	2,4	2,8	3,2	3,5	3,9	4,2	4,6
350	0,4	0,7	1,0	1,3	1,6	1,9	2,1	2,4	2,7	2,9	3,2	3,5
400	0,3	0,5	0,8	1,0	1,2	1,5	1,7	1,9	2,1	2,3	2,5	2,7
450	0,2	0,4	0,6	0,8	1,0	1,2	1,4	1,5	1,7	1,9	2,0	2,2
500	0,2	0,4	0,5	0,7	0,8	1,0	1,1	1,3	1,4	1,5	1,7	1,8
600	0,1	0,3	0,4	0,5	0,6	0,7	0,8	0,9	1,0	1,1	1,2	1,3
700	0,1	0,2	0,3	0,4	0,5	0,5	0,6	0,7	0,8	0,8	0,9	1,0
800	0,1	0,2	0,2	0,3	0,4	0,4	0,5	0,5	0,6	0,7	0,7	0,8
900	0,1	0,1	0,2	0,2	0,3	0,3	0,4	0,4	0,5	0,5	0,6	0,6
1000	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,4	0,4	0,4	0,5	0,5
1100	0,0	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,3	0,4	0,4	0,4
1200	0,0	0,1	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,3	0,3	0,4
1300	0,0	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,3	0,3	0,3	0,3
1400	0,0	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2	0,3	0,3
1500	0,0	0,1	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2	0,3
1600	0,0	0,0	0,1	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2	0,2
1700	0,0	0,0	0,1	0,1	0,1	0,1	0,1	0,1	0,2	0,2	0,2	0,2
1800	0,0	0,0	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,2	0,2	0,2
2000	0,0	0,0	0,0	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,2

Legend

🟩	**Sought values (0 - 3.99)**
⬜	**Acceptable values (4 - 7.99)**
🟧	**Tolerable values (8 - 9.9)**
🟥	**Critical values ≥10**

Impacts of Blasting Operations on Groundwater

The results of weekly groundwater level monitoring are used to determine the water recharge mechanism and flow paths and slopes. Seven observation boreholes, five conventional wells, and four boreholes developed for monitoring the tailings facility are used. The following Figure 6 shows the groundwater level fluctuations from January 2015 to present in the study area. The analysis of this figure shows that the water levels at different monitoring points show a decreasing trend throughout the report period (2015-2018) except for the village wells in which an early increase was influenced by the rainy season. The results also indicate that the average water levels for this report period remain very similar to the same period of the previous two years with the exception of piezometer YRM-WH05 in which the water level continues to decline compared to the water level of previous years (2015, 2016 and 2017). Considering the location of this borehole (located above the underground mine), it can be concluded that the dewatering of the mine has a direct impact on this borehole. On the other hand, the change in the other boreholes (especially the wells) is simply due to the seasonal effect. The results of groundwater levels recorded since 2014 show that the impact of mining activities on groundwater levels is limited to the area directly above the underground mine. Therefore, the environmental impact of blasting on this water was assessed using the results of the mine water analysis.

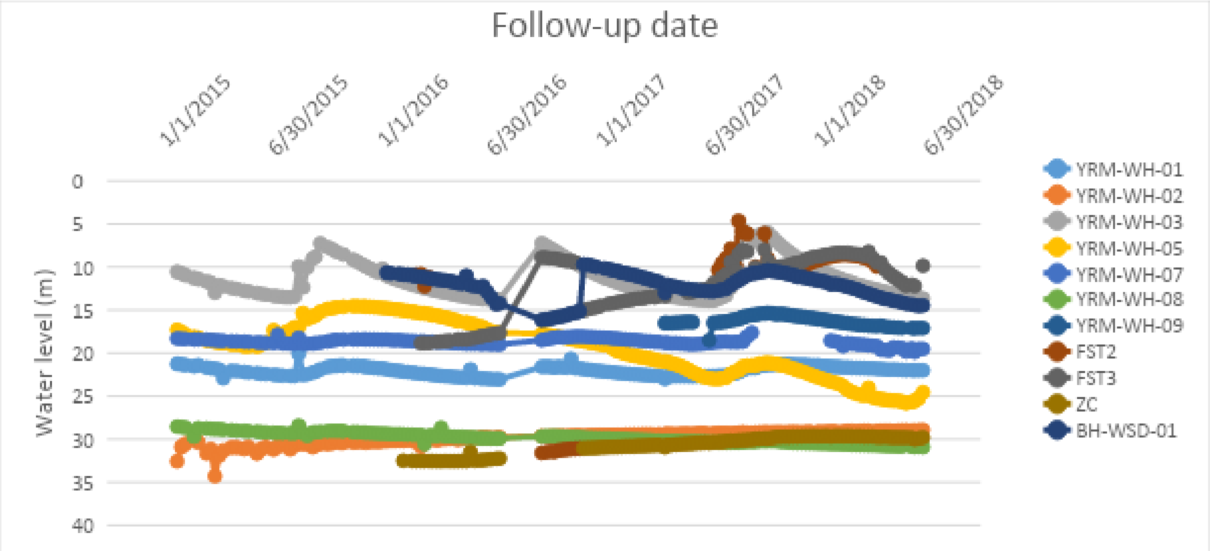


Figure 7: Fluctuation of piezometric levels in the structures of the study area

The following Table 8 shows the different values of nitrate, nitrite and ammonium measured in the mine water. The analysis of this table shows that the nitrate values measured in 2016 vary from 7.1 mg/l to 1054 mg/l. On the other hand, in 2018 an average concentration of 484 mg/l was measured. The nitrite values vary between 0.015 mg/l and 51.5 mg/l in 2016. In 2018, a concentration of 1.9 mg/l of nitrite was observed in the study area. As for ammonium, its concentrations measured in the field in 2016 vary from 0.08 to 145 mg/l. The Burkinabe regulation on the setting of standards for the discharge of pollutants into the air, water and soil stipulates in its article 10, that the acceptable limit of nitrate discharge is 90 mg/l, for nitrite it is 10 mg/l and for ammonium it is 1 mg/l. It appears that the concentration values of Nitrites, Ammoniums and Nitrates measured in the field are higher than the limit of the regulation in force. Indeed, nitrates although considered the most prevalent groundwater contaminant and nitrification of water resources can have potentially serious health effects, the assessment of nitrate-related impacts is often oversimplified and attributed to "inadequate remediation" without further consideration of the nitrogen cycle and identification of other potential sources or pathways, including surface and/or underground mining, that may be contributing to this problem **[14]**; **[15]**. In the presence of oxygen, ammonium undergoes rapid oxidation to nitrate. It has been noted that, in general, nitrate contamination of groundwater occurs when nitrate input to the soil exceeds the requirements for plants and denitrification **[16]**; **[17]**; **[18]**). Mining activities can be considered as one of the causes of elemental nitrogen release (present in soil or geological formations) as a result of bedrock disturbance. Similar to the release of geological sulphur (S) during the mining process, elevated nitrate levels in mines are generally the result of the disturbance of nitrogen (N)-bearing bedrock by blasting operations. In addition to causing the geological disturbance discussed above, blasting often involves the use of ammonia-based explosives, which contribute to higher nitrate levels, particularly in open pit/underground mines, as the tailings from blasting are disposed of with the waste rock or remain behind in the excavation. Unused explosives are sometimes destroyed on burning ground, which is often not lined, and once nitrification occurs, nitrate can enter the groundwater environment from these storage areas **[14]**; **[19]**). Thus, the use of ammonium-based explosives is one of the main causes of increased nitrate level in groundwater in the study area. High nitrate levels in water or in the environment in general are likely to cause long-term health problems such as increased risks of methaemoglobinaemia and cancer **[20]**; **[21]**) and environmental impacts such as eutrophication of surface waters due to excess nutrients **[22]**; **[23]**.

Table 8: Variation in nitrate, nitrite and ammonium concentrations

Years	Pollutants	Concentrations (mg/l)
2016	Nitrates	7,1
2016	Nitrites	0,015
2016	Ammonium	0,08
2016	Nitrates	1054
2016	Nitrites	51,5
2016	Ammonium	145
2018	Nitrites	1,9
2018	Nitrates	484

Conclusion

The aim of this study is to study the blasting operations and to evaluate their impacts on Groundwater at the underground mine of ROXGOLD SANU in Burkina Faso. It is a mining and exploration company, under Burkinabe law and the State is a non-contributing shareholder up to 10%. The success of blasting operations depends on factors such as: the mechanical properties of the rock mass; the specific consumption of the explosive; the inclination of the hole; the construction of the charge inside the hole and the mode of initiation of the charges. The main nuisances linked to blasting are: vibrations, linked to the elastic deformation of materials; projections; noise or acoustic energy; production of toxic residual gas. Results from blasting operations indicate that seismic vibration values in the study area average 3.62 mm/s. Acoustic overpressure values are of the order of 122 dB, i.e. below the limit value allowed for blasting in quarries and solid rock mines (125dB). The nitrate values measured in the mine water sometimes reached 1054 mg/l in 2016. Nitrite values varied between 0.015 mg/l and 51.5 mg/l in 2016. In 2018, a concentration of 1.9 mg/l of nitrite was observed in the study area. As for ammonium, its concentrations measured in the field in 2016 range from 0.08 to 145 mg/l. The tests carried out show that the concentration values of Nitrites, Ammoniums and Nitrates measured in the field are higher than the limit of the regulations in force; this reflects that the use of ammonium explosives is one of the main causes of the increase in the level of nitrate in the groundwater of the study area.

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