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# Eleveted Stress Regime within Birimian Metallurgenic Province of Ghana-Implications to Deep Level Mining

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**Abstract:** This study aims at evaluating the likely effect of high stress regime within the rocks of the *Birimian Supergroup* of Ghana, dated middle Precambrian and offer remediation strategies. The stress levels were therefore assessed between 26-level to 50-levels (i.e., 755 to 1500 m deep) within the deepest mine in the formation. Results indicated that pre-and-post mining stresses levels were 75 and 200 MPa, respectively. These levels are quite high and could induce stress related instabilities. Fundamental studies of failure behaviour of the rockmass show that elevated stress regime of this kind poses great potential for eminent rock bursting within the Birimian. Such situations demand concerted efforts of strategic mine design measures, including modified excavation geometry and destressing or preconditioning. These methods could be exploited to extend the normal zone of stress induced fractured rock to a greater depth ahead of the excavation face. Support could be improved further by adopting higher rockbolting density or tougher mesh together with shortcrete. If the excavation becomes prone to moderate rockbursting, provision of appropriate support structure can also be made either to limit the bulking process or reduce excessive rock deformation.

**Key words:** Birimian supergroup, elevated stress, graphitic shear, monitoring, rockburst, support unit

## INTRODUCTION

Generally as excavation progresses deeper, stress levels are affected. Elevated stress regime results in concomitant increases in rock fracturing and mining induced deformations. The ambient state of the stress in an element of rock in the ground surface is determined entirely by the current loading regime in the rockmass as well as the stress path defined by the geologic history (Brady and Brown, 1985). It is a fact also that rock failure in the periphery of the excavation is partially stress related and therefore important to ascertain the extent of stress levels within a given rock formation of economic interest such as the Birimian of Ghana.

The rocks of the Birimian Supergroup are the dominant formation hosting over 80% of the major economic mineral in Ghana and covers approximately 17% of the total land area of the country (Kesse, 1985). Many large operating companies across the world such as Anglogold-Ashanti, Newmont, Goldfields among others own large tracks of concessions within the Birimian and have proven gold reserves in millions of tonnes at deep levels. Well over 20 mining companies operate in this formation.

Earlier works done by some researchers (Affam and Archibold, 2010; Batcha, 2006) in deep mines in the Birimian which involves mapping the orientation and distribution of discontinuities on the skin of excavations and surrounding rocks as well as stress determination indicates that the formation has high stress levels at deeper levels exceeding 1000 m. These high stress signatures have greater potential for fracturing, severe rockmass deformation and excavation instabilities. The development of multiple level excavations within the formation could also generate stress concentrations on the boundaries of between 2 to 3 times the *in-situ* stress field, depending on the shape and the *k*-ratio (Jager and Ryder, 1999).

In the context of rockburst, as mining progresses to greater depth, high ground stresses and mining geometry as well as critical pillar configurations become significant (Arjang, 1996). Rockbursting could become imminent depending on the competence of the rockmass, the stress regime, support performance and structurally-controlled instabilities (or geological discontinuities) among other factors. The design of underground openings and the selection of ground support systems taking into consideration the inelastic deformations generated by

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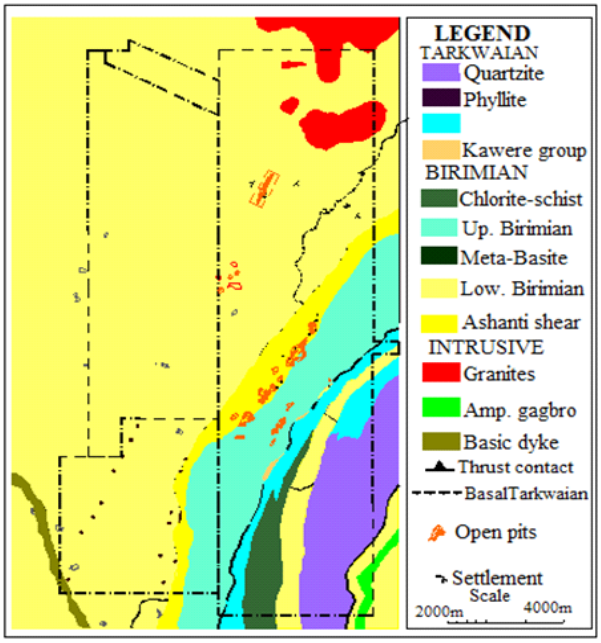



Fig. 1: A typical section of the Birimian geology

stress-induced fracturing could also be an intrinsic problem. Underground openings and pillars at depth undergo generic stages of failure under extreme static stress conditions. Consequently, this sometimes leads to a violent rupture or collapse of excavation walls if the stress propagation is not arrested.

It is observed thatalthough stiffness of the loading system does not play a part in the failure initiation process, at the microcracking level, the failure is dictated by the intrinsic material properties and heterogeneities within the rockmass. These among others, generates research interest in deep mines within the Birimian Supergroup (e.g., Ashanti Mines) to evaluate unfavourable deformational events within the formation as depth and loading increases.

## MATERIALS AND METHODS

**Geological settings:** The Birimian rocks are classified within the Precambrian Guinean Shield of the West Africa craton hosted over an Archean basement. It is recognized as being middle Precabrian in age, having been deposited between 1900 to 2100 m. y (Asihene and Barning, 1975). The older beds are overlain by late Proterozoic to Paleozoic rocks of the voltain system. The Birimian has undergone intense folding and shattering with dips commonly in the range of 30º-90º along NE-SW axis. Steeper dips are in the range of 70º-90º and are however most common (Leube *et al*., 1990).

Within formation, lithological units are subdivided into meta-volcanic, meta-sedimentary series and some intrusives. The series comprises an entire stratotype of lithologic associations or rock assemblages. The metasedimentary units include, phyllites, metagreywackes, and schist (Amanor and Gyapong, 1988). The phyllites are mostly lustrous and occasionally interbedded with the greywackes. It is largely politic in origin comprising mud, silt and coarse sediments. This unit represents flyschoid facies made up of 55% of the area occupied by the Birimian (Kesse, 1985). The metavolcanic series contain pyroclastic rocks and felsic lavas (Milesi, 1991). A little hornstone, generally accompanied by epidorite, occurs in isolated places.

The Birimian has been metamorphosed, and partly been assimilated by granitoids. Metamorphism has generally been observed as *low grade* greenschist facies. However, pockets of *amphibolite* to *granulite* facies are present (Senger, 1973). The beds are tightly folded with their axes plunging 30º to 60º towards mine north. Cleavage strike 070º and dip 60º NW is generally parallel to the fold axis. Faulting where prevalent follows the strike of the fold and jointings have several orientations.

Mineralisation is concentrated in extensive shear zones, often associated with graphitic and carbonaceous schist. The fissured zones persist laterally and vertically (Fig. 1). Four types of auriferous orebodies may be identified:They include disseminated sulphide type (DST type 1), regarded as either lithofacies controlled; or

associated with the selvage of quartz veins and epigenetic (DST subtype 2). The Quartz Vein Type (QVT) of local gold concentration is exclusively structurally controlled and epigenetic in origin (Milesi, 1991; Eisenlohr, 1989). The quartz veins are often developed in shear zones which trend parallel to the belt with dip at slightly flatter angles than the host rocks and parallel to the axial plane cleavage.

**Issues governing rock stress behaviour:** As depth increases so do stress levels with a concomitant increase in stress fracturing and mining- induced seismicity. The *in-situ* or virgin stresses existing in the rock mass prior to mining is measurable in the field though the techniques involved are onerous and prone to measurement errors The stresses acting on an element of rock at depth '*h*' (m) below the surface consists of vertical and horizontal components $q_v$ and $q_h$, respectively.

The vertical component ($q_v$) of the virgin stress tends to increase according to the deadweight of the overburden (Jager and Ryder, 1999). This value is estimated from the relationship:

$$q_v = \rho g h \quad (3.1)$$

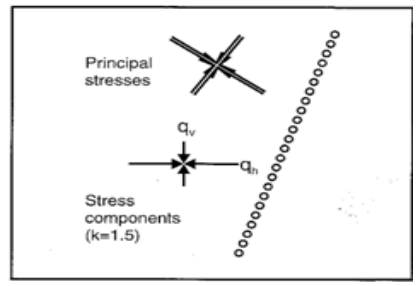
where ρ is the average rock density, g is gravitational acceleration (9.81 m/s$^2$), h is the depth below surface in metres.

The horizontal virgin stress component ($q_h$) is a little difficult to measure and is subject to considerable scatter (Fig. 2). It shows an average constant stress value of about 10MPa. $q_h$ indicates an approximately value of 10+0.01h, thus, varying with small linear increase with depth. The ratio of the average horizontal stress to the vertical stress is denoted by the letter '*k*', (usually called the *k*-ratio) is given by:

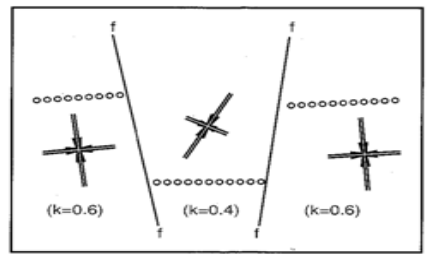
$$K = q_h/q_v \quad (3.2)$$

This figure however tends to decrease with depth. At greater depth however, *k* approaches unity, a condition called *hydrostatic equilibrium*. As a result of the prevalence of tectonic stresses in the earth crust, the major principal in-situ stresses can sometimes be oriented subnormal to stratification. Hence, in deep steeply dipping orebodies, the *k*-ratio may exceed an absolute value of one (Fig. 2).

Using set of catesesian global reference axes, established by orienting the *x*-axis towards the mine north, *y* towards mine east and *z* vertically downward, if the ambient stress component are expressed relative to the axes and denoted the symbol $P_{xx}$, $P_{yy}$ and $P_{zz}$. Then, for elastic rock behaviour the horizontal stress component may be expressed as:




(a)




(b)

Fig. 2: Signatures of virgin stresses of (a) steeply dipping reefs and (b) faulted ground conditions (Arjang, 1996)

$$P_{xx} = p_{yy} = (v/1\text{-}v)\, p_{xx}$$

where *v* is Poisson's ratio for the rockmass.

Within geologically disturbed structures, in which locked-up slippage may have taken place in the past, the stress tensors could be inclined resulting in peculiar stress levels and *k*-ratios. Therefore, the prevailing stress tensors and appropriate estimate of the prevailing *k*-ratio is critical in reliable numerical modeling.

**Stress regime assessment:** Based on the measured stress data at elevations of 26, 32 and 50 levels (i.e., 1500m below sea level) from overcoring technique in the deepest mine in the Birimian formation (i.e., Ashanti Mines) Affam and Archibold, (2010) established that the average measured lithostatic stress observed are ($\sigma_3$) = 34.9MPa, the intermediate stress ($\sigma_2$) = 55 MP*a* while the maximum compressive stress ($\sigma_1$) = 75.5 MPa .

The calculated stress ratios indicate a wide variation. However, from stability consideration, the average stress gradients, following the pre-mining vertical stress as well as the horizontal stresses perpendicular/parallel to the ore-bearing structure, are estimated to be:

Vertical stress → 0.026 MPa/mHorizontal stress (perpendicular to reef) → 1.64 × Vertical stress Horizontal stress (parallel to reef) → 1.13 × Vertical stress

The vertical stresses ($\sigma_v$) and average horizontal stresses ($\sigma_{Ha}$) gradient from the estimation are given as follows:

$\sigma_v$ = 026 MPa/m (obtained from overburden weight)
$\sigma_{Ha}$ = 4.30 MPa + 0.0321 MPa/m (750-1500 m depth below surface) Obuasi
$\sigma_{Ha/\sigma v}$ = 5.15/D=1.24

where D is the depth of excavation in meters Obuasi

The nature of the processes responsible for these complex stress dynamics is not fully understood yet but it predictability of rockmass response to mining can be aided only by observational approach, numerical modeling or seismic monitoring techniques.

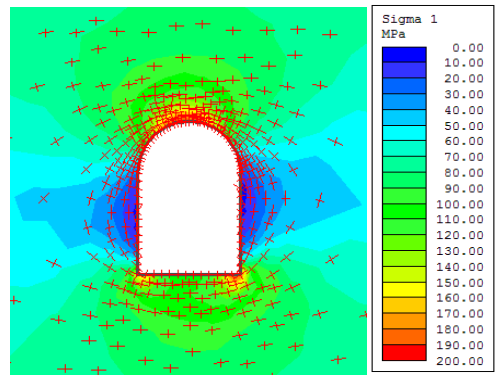
**Geomechanical numerical modeling:** Commercially available finite element software, Phase-2, was used to analyse symmetrically the increasing stress response around the excavations. The rock material was assumed to be linearly elastic and perfectly plastic with failure surfaces defined by the Mohr-Coulomb and Hoek-Brown criterions. Both the associated (dilatancy = friction angle) and non-associated (dilatancy = 0) flow rules were applied. However, for the Hoek-Brown criterion, non-linear stress dependent strength properties were used.

From the model of a horse-shaped tunnel opening, with surface parallel interface extending over 30º at 10 mm from the surface of the opening, the radius of the opening was taken as 4m. Far field stresses were assumed to be homogeneous, linearly elastic and extending to infinity and the rockmass was considered to be *elastic-brittle-plastic*.

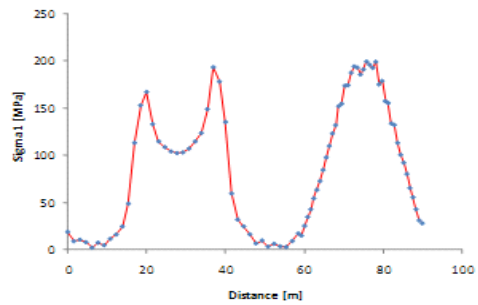
**Elastic analysis:** The rockmass was initially assumed to be governed by the Mohr-Coulomb failure criterion and the physico-mechanical properties were given as; E = 51 GPa and $v$ = 0.22, $c$ = 22 MPa and $\varphi$ = 35. The in-situ stress $\sigma_1$ = 75 MPa and $\sigma_3$ = 34 MPa were assumed to be acting in the horizontal and vertical directions, respectively.

Figure 3 presents variations of the maximum horizontal stress ($\sigma_1$) distribution of the final model representing the post mining stress level. High stress concentrations at the upper roof and floor of the excavation were easily observed . Stresses rose from 120 MPa to a maximum of 200 MPa in the crown pillar and corners of the floor. Theoretically, these stress levels are high enough to easily induce rockbursting (Mitri *et al.*, 2001).

**Plastic analysis with graphitic shear band:** To investigate plastic condition, a graphitic schist band (a weak rock) that possesses much lower physico-mechanical




(a)




(b)

Fig. 3: (a) Stress flow trajectories of the elastic model; (b) post mining stress distribution

properties than the country rock was superimposed on the country rock (phylitic–greywacke hosted rockmass) as pertains within the formation.

The presence of graphitic and phyllitic shear bands act as distressing zones surrounding the excavation. These weak rocks created a yield zones around the stope with high displacement. The high stresses thus reduced within the crown due to yielding of the plastic rocks (Fig. 4).

**Support requirement:** Since horizontal stresses are already higher than the vertical stresses in the formation, it pre-supposes that roof failure and ground heave could be more prominent and therefore require support units. Rocks will naturally prefer to migrate from high stress states to low stress states, it is imperative therefore that mine support systems or excavation design be planned in such a way as to reduce high stress concentrations and stabilise the rockmass immediately surrounding stoping excavations or zones of weakness. With regard to this, the ratio of horizontal to vertical stress $k$ therefore has greater effect on the stability of the underground structures.

From Fig 5a, plastic analysis of unsupported excavations indicates that maximum displacement of 0.096 and yield elements of 583 is observed. The

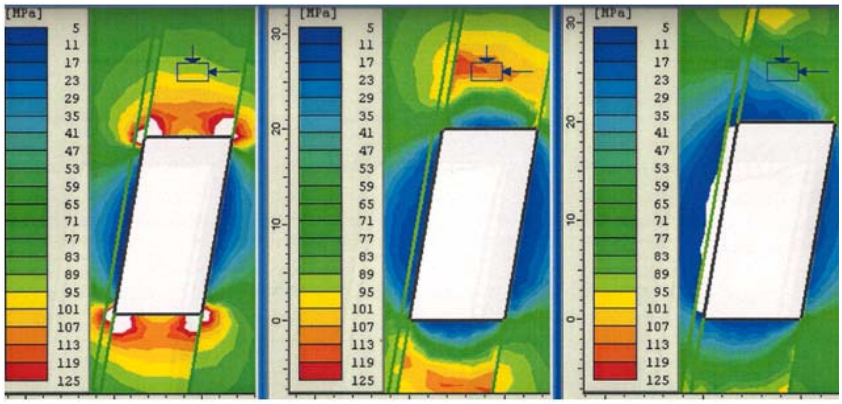
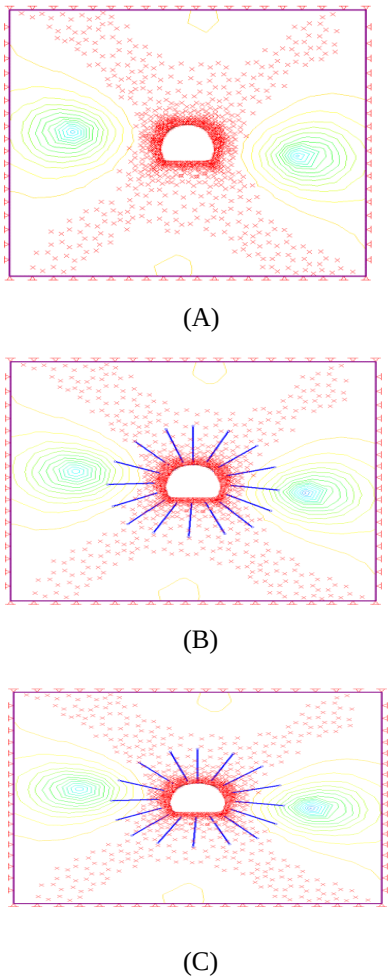



Fig. 4: Plastic model showing low stress regime within the graphitic shear zone



(A)

(B)

(C)

Fig. 5: Strength factor contours and yielded element after plastic analysis of unsupported excavation

maximum deformation is towards the roof and the floor of the tunnel. If K≤1, failure will occur in the ribs or the mid-walls but not the at floor or the roof. As *k* increases the failure zone extends into the roof and the floor, but reduces significantly in the pillar. For K≤1, a tensile failure (zone) which indicates spalling is introduced at the wall and could be observed also at the roof. If *k* increases further, (i.e., K = 4 )extensive failure sometimes involving the second layer in the floor or levels below the floor can occur resulting in devastating consequence.

From Fig. 5b as rockbolts are introduced as support, it seen that all the bolts appear to have yielded as the rockmass around them appear deformed (i.e., highlighted in red). The yielded bolts elements are 237 in number and the displacement reduces to 0.080. This however does not indicate failure of the bolts, the bolts elements are firm but the rockmass around them have failed. Compared to the unsupported excavation, the displacement has reduced from 0.096 to 0.080, but not enough to avert failure.

A liner (shotcrete) will have to be added to the tunnel support the roof. Upon addition of shotcrete, drastic drop in the displacement of the rockmass reduction is observed (Fig. 5c). The number of yielded elements in the bolts is seen to have reduced from 237 to 204.

**Mitigation strategies:** The condition for geotechnical measurement and monitoring should be directed towards assessing field stress regime, rock deformation and fracturing, load support elements, spacing and conditions of orientation of rock joints, and bedding as well as other undesirable discontinuities. De-stressing or pre-conditioning can be used as a safety measure to mitigate potential rockburst incidence. This technique has been used effectively in rockburst prone zones in several mines across the world, in South Africa, Canada, etc., with significant success The technique of rapid blasting sequencing in which explosives are fired simultaneously or at very short intervals can also be used to regulate rockburst time intervals so that the event can be induced to trigger earlier than later. This slows down the number of events scheduled to occur as well as reduces the intensity of bursts.

It is imperative to have early warning signals of any form to alert unfavourable deformations or prompt quick action. As excavation goes deeper, routine monitoring of mining layout and survey plans can timely identify potential areas of rockburst threats. Typical monitoring activities for the deep level mine must therefore concentrate on stopes, drives, shafts and service excavations. The use of Portable Seismic Systems (PSS) and commercially available Rockburst Monitoring systems (RBM) which operate over low frequency ranges are desirable. High frequency prediction systems capable of monitoring rockburst events earlier before the event actually occurs can also be sourced to aid burst prediction. Measuring the deformation or closure monitoring can warn of impending rockmass collapse.

## DISCUSSION

It has however been quite strange as to why with such a high stress regime, damage probably associated with microseismic events with wide ranges of moment magnitudes has not taken place in the underground workings.

**Interpretation of results relating to the roof:** It is observed that as *k* increases, the destresses zone in the roof comes closer downwards while the disturbed zone in the pillar extends further into the rib side. A vertical tensile zone develops on th rib side. It implies that there is a considerable increase in stress concentration parttern over the rib line resulting possible shearing along the bedding planes or slabbing. The vertical displacement in the floor also has a very rapid change under the rib line, a mechanism which can lead to toe failure in the pillars Vertical displacement in the roof strata was not too significant.

**Interpretation of results relating to the floor:** The behaviour of the floor was studied by looking at the vertical displacement at various depths into the floor strata. In assessing the floor, it was found that maximum floor heave occurs at the centre line and its value decreases as the ratio of horizontal to vertical stress (*k*) increases. Although the floor may not seem to be as important as the roof and ribs from the view point of stability, on occasions of floor heave, it can cause serious problems for the mining operations. Besides, instability of the floor may affect the stability of the whole structure indirectly.

Assesment of the strength of the rockmass to the induced stresss and displacement were also made after plastic analysis of the unsupported excavation. It was observed that, rockmass within the tunnel has a strength to stress ratio greater than one (*1*), thus indicating no failure (i.e., high scaled strength)

A strength factor in excess of *1*, although currently stable could either induce a zone of instability around the tunnel, or could generate damage occurring in the rockmass with time.

**Interpretation of results relating to graphitic shear band:** The maximum induced stress immediately surrounding the opening is observed to be between 10-25 MPa. This is considered drastically lower than the 200 MPa observed in the elastic regime and this results in reduced excavation boundary responses. The graphitic schist properties have a significant effect on the response of the whole structure, as it impedes high stress penetration. Comparing the results for all loading conditions, it is observed that there is a de-stressed zone with respect to the second rockmass as depicted from stress magnitudes at the mid-height of the pillar.

**Support measures:** As mentioned before, the primary factors which control support requirements are the stratigraphy of the immediate hangingwall/footwall, the minor geological structure, mining depth and the presence or lack of seismicity. The nature and the extent of the rock to be supported, the deformation to which the support system will be subjected and the generated load characteristics must be designed in such a way that the support system can be able to hold, retain and reinforce the ground.

Considering combined efforts of rockbolting and shortcrete liners which reduced yield element from 583 to 204, the approach appears appropriate enhances stability. The application of enhanced strength through the use of higher rockbolting density or tougher mesh together with shortcrete can improve stability better. If the support requirements are designed in such a manner that a combination of different reinforcing, retaining and holding structures are positioned in appropriate order, the support system will function to resist variable deformational conditions. If however a major rockburst is to be expected, the displacement capacity of the holding element must be improved additionally.

This must be done in such a way that the role of the support will be to absorb excess load and maintain the integrity of the excavation. Under block ejection conditions, the support system must possess the ability to absorb greater portions of the excess energy. It is however preferable to provide excavation design which results in stress reduction and provide self-support rather than to endeavour to heavily support the rocks externally.

**Mitigation effort:** In whatever condition, as excavation deepens it becomes increasingly important to have early warning signals to preempt response to any unfavourable deformations or threat to stsbility. In this regard, microseismic coverage of the site could be used to aid prediction or improve adoption of appropriate mitigation strategies.

## CONCLUSION

The fundamental studies of failure behaviour of the rockmass have shown that elevated stress regime poses great potential for eminent rock bursting in deep mines within the Birimian. Elevate horizontal pre-mining stress level of 75.5 MPa with correspondent post-mining stress of 200 MPa could trigger rockburst.

Destressing or preconditioning can therefore be utilised to extend the normal zone of stress induced, fractured rock to a greater depth ahead of the excavation face. The argument for this is based on the concept that if holes drilled at right angles into the face are blasted, they would advance the depth of fracturing and shift the burst location ahead of the working face.

Support could be improved further by adding enhanced strength or higher rockbolting density and tougher mesh together with shortcrete. If the excavation becomes prone to moderate rockbursting, provision of appropriate support structure can also be made either to limit the bulking process or excessive rock deformation. Microseismic coverage of the deep mines within the Birimian can be used to aid prediction and improve adoption of appropriate mitigation strategies.

## RECOMMENDATION

The following recommendations are being raised for consideration:

- As excavation goes deeper, routine monitoring of mining layout and stopes must be done to identify potential areas of rockburst threats.

## ACKNOWLEDGMENT

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