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Selection of a Mining Method for the C. Anticline of the Synclinorium ore body, SOB shaft, Nkana Mine, Mopani Copper Mines

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Abstract: ***The upper part of the C. Anticline (from 1005m to 1025m) of the Synclinorium ore body has been mined out using sublevel caving. However, the hanging wall has not collapsed. This condition has led to delaying hanging wall exposure which affects the collapsing of the hanging wall, creating a huge void prior to hanging collapse, potential dynamic hanging wall collapse and reduced initial material extraction leaving material to cushion any unexpected dynamic hanging wall failure. The current mining method was studied and the cavability assessment was carried out. The results of the cavability assessment showed that the probability of hanging wall caving is minimal when mining with the current sublevel caving as mining progresses. Therefore, a new mining method needed to be selected. A combination of longitudinal retreat and transverse sublevel caving was proposed as a suitable mining method for C. Anticline. The cavability assessment for the proposed sublevel caving showed an increased probability of hanging wall caving as mining progresses. The proposed mining method was found to be economically viable. Therefore, a trial mining was recommended.***

Key words: **Cavability Assessment, Hydraulic Radius, Mine method selection, Proposed Sub level caving.**

I. INTRODUCTION

Nkana mine, owned by Mopani Copper Mines is located in Zambian city of Kitwe. The Synclinorium ore body is found between Central and South ore body (SOB) shaft of Nkana mine from 941m level going downwards. The Synclinorium ore body can easily be accessed via the SOB shaft.

The geology of the Synclinorium ore body is complex and the structure is highly folded. The four main lithologies of the Synclinorium are, South ore body Shales (SOBS) including the ore, the Hanging Wall Argillite (HWA), the Near Water Sediments (NWS) and the Upper quartzite. Mineralogy is mainly Charcoal Pyrite and Bonite. The C. Anticline of the Synclinorium is of particular interest to this project .It is approximately 150 m in thickness and 150 m in width, it has gradational distribution, and has sharp formational contacts and plunges at 10 degree south to north. The upper part of the Synclinorium C. Anticline (from 1005m to 1025m) has been mined out using the modified sublevel caving. However, the hanging wall has not collapsed.

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This condition has led to; (a) delaying hanging wall exposure, affecting the collapsing of the hanging wall since hanging wall collapsing is function of footprint and is measured in terms of hydraulic radius. (b) Creating a huge void prior to hanging collapse (c) Potential dynamic hanging wall collapse that might cause an air blast; and (d) Reduced initial material extraction leaving material to cushion any unexpected dynamic hanging wall failure

These implications affect the mining method negatively. Hence, there is need to select a mining method suitable for the safe and economic exploitation of the C, Anticline of the Synclinorium ore body. The transverse section of the current state is shown in Figure 1.

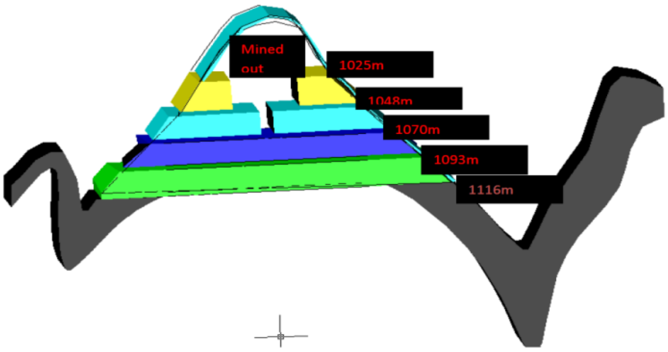

Fig 1: Transverse section of the C. Anticline mined using modified sublevel caving

II. LITERATURE REVIEW

Mining method selection involves comparison of the characteristics of the deposit with those required for each method. The methods that best matches are technically feasible, and should be evaluated economically. The selection techniques discussed in this study deal the physical and geological characteristics of the deposit; and the ground condition of the hanging wall, footwall and the ore zone (Nicholas, 1992). Critical to this study is the cavability of the hanging of the exploited Synclinorium C. Anticline. Empirical and Numerical methods were both used to analyze the cavability of the Synclinorium C. Anticline.

The use of empirical methods to estimate cave behavior have been and are still in widespread use. The most commonly used approach for estimating cavability was developed by Laubscher (Diering&Laubscher1987, Laubscher 1990, 1994, 2000) and is based on a

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compilation of rock mass geotechnical characteristics and caving case histories largely derived from low strength kimberlitic deposits in South Africa. Laubscher’s chart (Figure 2a) defines, three possible caving states that include; “no caving”, “transitional” whereby the cave initiates, but propagation is minimal and “caving” whereby self-sustained propagation occurs.

Many mines still use Laubscher’s chart to estimate the undercut dimensions required to induce continuous caving. In most cases, good agreement is achieved. However Lorig et al. (1995), van As& Jeffrey (2000), De Nicola Escobar & Fishwick Tapia (2000) have previously reported on instances where significant differences were observed. A detailed review of these cases by Trueman&Mawdesley (2003) showed that the biggest difference in actual outcome versus prediction was associated with strong (MRMR greater than 50) rock masses and misinterpretation of the application of adjustments in the MRMR rating scheme. As a result of this review, Trueman & Mawdesley proposed an alternate method for the prediction of continuous caving conditions through an extension of the Mathews stope stability chart (Mathews et al. 1981) that included data from non-caving operations. Their extended stability chart is provided in Figure 2b.

Brown (2003), in his review of cave mining practices, observed that numerical modelling enables a more fundamental and rigorous assessment of cave initiation and propagation behavior than empirical methods, since it may have advantages in cases were current experience is lacking.

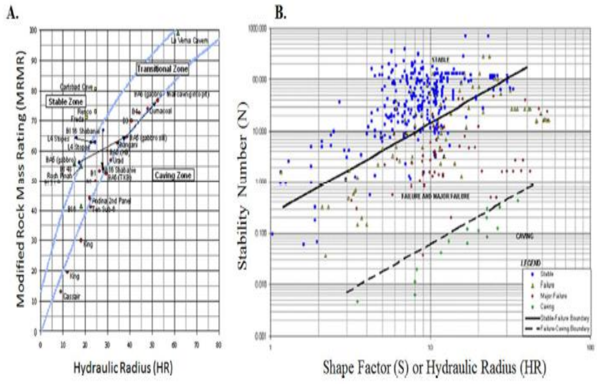


Fig 2: (A) Laubscher’s stability chart and (B) Extended Mathews Stability Chart

There are numerous numerical modelling methods (Boundary Element, Finite Element, Finite Difference, Distinct Element, hybrid based) and approaches available for performing stress and deformation analysis in geomechanics. The important aspect of cave modeling is not necessarily the numerical program itself, but the methodology for simulating the caving process, and the estimation of input material models and properties.

FLAC3D (Itasca, 2006) is a commercially available three-dimensional explicit finite-difference program or software that is capable of modelling in three dimensions. Finite-difference is a domain method where the problem domain (or rock mass) is divided into geometrically simple subdomains or elements. FLAC3D is widely used numerical software for stress and deformation analysis around surface and underground structures opened in both soil and rock. The software is based on the finite difference numerical method with Lagrangian calculation. The finite difference method is applied better to modelling stress distribution around underground mining excavations in comparison to other numerical techniques.

III. METHODOLOGY

The cavability assessment of current sublevel caving was carried out using both the empirical method and Numerical stress modeling using FLAC3D. The standard empirical method for assessing cavability developed by Laubscher 1990, 2000 was used to assess the cavability of the Synclinorium C. Anticline under the current mining geometry. This method requires the determination of the modified rock mass rating (MRMR) and the hydraulic radius (HR) of the undercut. To determine the MRMR, the rock mass rating after Bienwaski (1976) RMR-B was determined from geological mapping of the rock mass and rock testing of the rock samples. This was done by separating the rock mass into a number of rock types and each region is classified separately. The MRMR value was determined by taking the basic RMR value, as defined by Bieniawski, and adjusting it to account for in situ and induced stresses, stress changes and the effects of blasting and weathering. The hydraulic radius of the undercut was calculated by dividing the area of area of the undercut by its perimeter.

The numerical modelling procedure consisted of steps; (1) Determination of boundaries and material properties (2) Formation of the model geometry and meshing (3) Determination of the model behavior (4) Determination of the boundary and initial conditions (5) Initial running of the program and monitoring of the model response (6) Re-evaluation of the model and necessary modifications (7) Obtaining the results. Following the results of the cavability assessment, the mining method selection techniques such as Hartman (1987), Boshkov and Wright (1973), Nicholas (1981), University of British Columbia (UBC), Laubscher (1981) and Morrison (1976). The six mining methods that were consistently selected by various selection schemes were analysed further in terms of safety, productivity, productivity etc. to select the most feasible mining method. The cavability assessment of the most feasible mining method was carried out to establish if the hanging of the C. Anticline would cave as mining progresses.

IV. RESULTS AND DISCUSSION

The caving at Synclinorium C. Anticline is initiated in Southern ore body Shales (SOBS), propagates to the HWA and finally will reach the NWA. The hydraulic radius required in SOBS is in the range of 26 to 29 and to propagate through HWA requires a hydraulic radius between 28 and 37. The hydraulic radius of 19 to 23 is required for caving to occur in NWA.The average hydraulic radius for SOBS, HWA and NWS are indicated in Table 1. If these values are compared with the hydraulic radius on 1048m level (Figure 3), it is concluded that the potential for caving is marginal. It is important to note that the calculations done using empirical are based on average values.

Table 1: The results of the empirical cavability assessment

Rock Type	RMR-B	RMR-L	MRMR	HR(m)
NWS	55	39[35-42]	35[32-38]	21[19-23]
HWA	68	51[46-56]	51[46-56]	32[28-37]
SOBS	66	49[46-52]	44[41-47]	27[26-29]

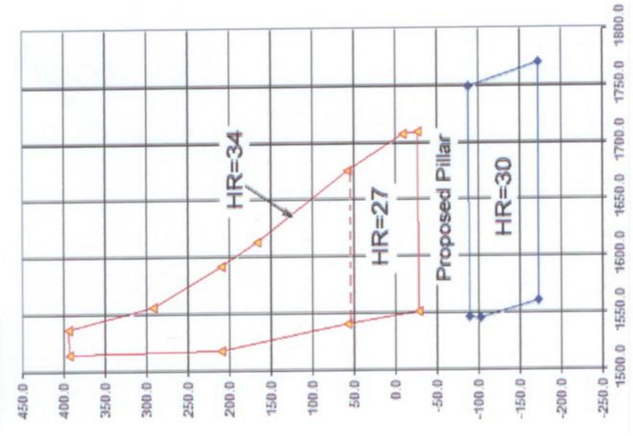


Fig 3: Hydraulic Radius of 1048m level

Numerical stress modelling was done use FLAC3D to simulate cave propagation at levels 1005m, 1025m and 1048m. The modelling was done in the following three phases; (1) Mining of consecutive blocks at 1005m level (2) Mining of consecutive blocks at 1025m level (3) Mining of consecutive blocks at 1048m level. The stages are shown in Figure 4. The physical and Mechanical properties used for modeling are presented in Table 2.

Table 2: Physical and Mechanical properties of SOBS, NWA and HWA

Formation	**Unity weight (MN/m^3)**	**UCS (MPa)**	**Tensile Strength (MPa)**	**Internal frictional angle (*ϕ*)**	**Cohesion *C* (MPa)**	**Modulus of elasticity E (MPa)**	**Poisson's ratio *v***
NWS	**0.21**	**97**	**0.2**	**31**	**2.39**	**11500**	**0.31**
HWA	**0.023**	**130**	**1.07**	**35**	**3.4**	**30000**	**0.33**
SOBS	**0.197**	**96**	**0.63**	**34**	**2.97**	**29500**	**0.29**

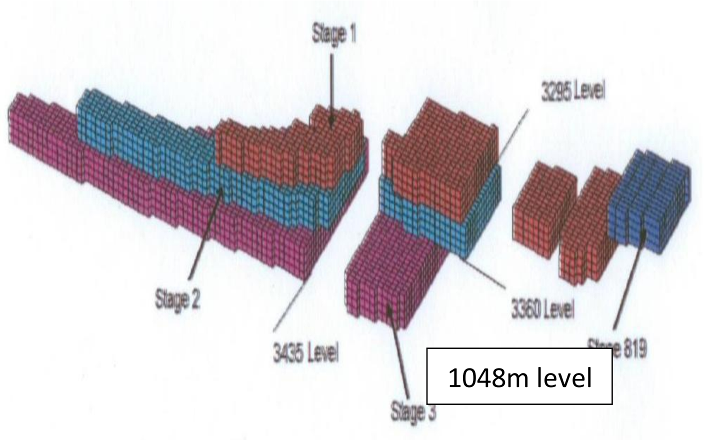
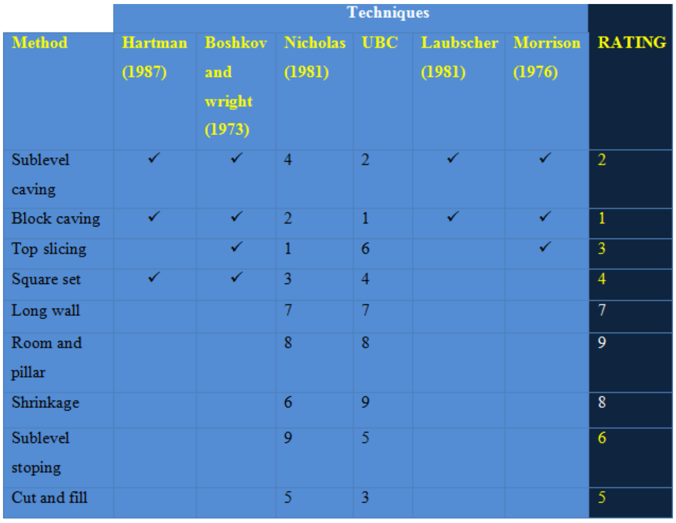


Fig 3: Modeling stages in FLAC3D

The results of the model also showed that a large footprint is required to induce caving and that caving is likely to stall with the current geometry being considered for mining. The results of the cavability assessment using both empirical and Numerical analysis showed that the probability of hanging wall caving is minimal as mining progresses using the same mining method. Hence, a new process of mine method selection was initiated.

The mining methods selection techniques and the summary of the results are presented in Table 3. The six mining methods that were consistently selected by various selection schemes were considered for further analysis. The remaining three methods were labelled not feasible based on the orebody characteristics. Further analysis of the selected methods was based on mining cost, flexibility, productivity, safety etc. The results of the further analysis showed that sub level caving was the most feasible mining method for the exploitation of C. anticline.

Table 3: Summary of the results of all mining method selection techniques and the ratings of the respective mining methods



	Techniques						
Method	**Hartman (1987)**	**Boshkov and wright (1973)**	**Nicholas (1981)**	**UBC**	**Laubscher (1981)**	**Morrison (1976)**	**RATING**
Sublevel caving	✓	✓	4	2	✓	✓	2
Block caving	✓	✓	2	1	✓	✓	1
Top slicing		✓	1	6		✓	3
Square set	✓	✓	3	4			4
Long wall			7	7			7
Room and pillar			8	8			9
Shrinkage			6	9			8
Sublevel stoping			9	5			6
Cut and fill			5	3			5

This is so because of the following reasons; (1) Ground adjacent to the ore reasonably incompetent (2)It will be more cost effective than block or panel caving because of the irregular nature of the ore body (3) Sublevel caving does not tie up ore in the pillars (4) A high degree of mechanization would be employed. However, the proposed sublevel caving should have different approach compared to the approach currently being used. The proposed sublevel caving has not been tried before at the Synclinorium to prove its viability, therefore a trial mining has been suggested as will be seen in following sections.

V. PROPOSED SEQUENCE OF MINING

Mining will be done in the following phases. It will begin with back filling of the void created by the current sublevel caving to avoid the potential air blast that might be caused by the catastrophic caving of the hanging wall. Some of the recommended back fill materials include waste development rock, cemented hydraulic fill and Cemented rock fill. Following back filling, access decline will have to be mined from 1025m to 1208m level (primary development). Then the mining of sublevels and slot drives along the eastern limb hanging wall will follow (secondary development). The production of the ore will be done in two phases;

Longitudinal retreat from hanging wall slot drives (Phase 1)

Longitudinal retreat sublevel caving is used to create a limited opening along the hanging wall. This exposes the hanging wall and completely undercuts the hanging wall. This also increases the hydraulic radius created. This process will be done in five stages; (1) eastern limb hanging wall exposure on 1005m level (2) eastern limb hanging wall exposure on 1025m level (3) eastern limb hanging wall exposure on 1048m level (4) eastern limb hanging wall exposure on 1005m level (5) eastern limb hanging wall exposure below 1093m level to 1185m level.

Transverse mining (Phase 2)

The C. Anticline will be mined using transverse multiple retreat sublevel caving from the sublevels. This will involve drilling charging and blasting of the ore. Bogging and Tramming is the last stage and involves transportation of ore from production faces to surface. At Nkana mine, SOB Shaft, ore is lushed using mechanical loaders from stopes and development ends. The mechanical loader transports the lushed ore to the dump trucks which transports the ore to the section tip. Ore from the section tips is collected from the chute box into locomotives. The locomotives transport the ore to the main tip where grizzly bars are installed to regulate the size of ore rocks going down the main tip. The main tip has a mechanism to collect and load ore into skips which transport the ore to the surface.

VI. PRACTICAL DESIGN APPROACH AND DESIGN RECOMMENDATION

Sub haulages and access declines at Nkana mine, SOB Shaft, are 5 x 4.5 m. These haulages are wide enough to allow movement of large equipment such as dump trucks since the mining method is mechanised. The sublevels and hanging wall slot drives have been designed to about 4 x 4 m. The spacing between the sublevels and hanging wall slot drives is about 7.6m. Figure 4 shows the design recommendations.

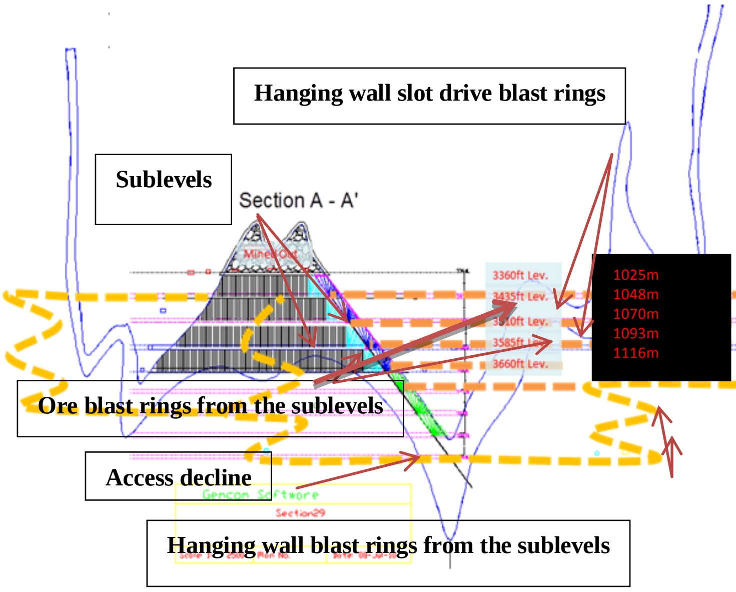
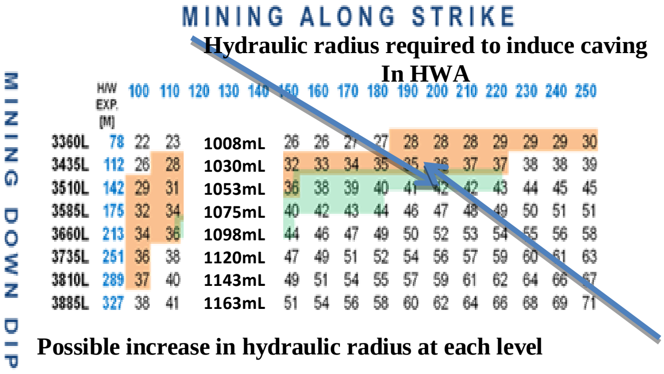


Fig 4: Design recommendation for the C. Anticline

Cavability assessment for the proposed SLC

The success of the proposed sublevel caving depends on the caving of the hanging wall. Empirical analysis is used to determine the cavability of the hanging wall. The values used in this analysis are average values of the specified rock types. The hydraulic radius required for the Hanging Wall Argillite (HWA) to cave ranges between 28 and 37 m while it's between 26 and 29 m for SOB. Figure 5 shows the hydraulic radius matrix that shows the expected hydraulic radii generated when the hanging wall has been exposed by various meters along dip and strike.



	H/W EXP. (M)	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250
3360L	78	22	23	1008mL			26	26	27	27	28	28	28	29	29	29	30
3435L	112	26	28	1030mL			32	33	34	35	35	36	37	37	38	38	39
3510L	142	29	31	1053mL			36	38	39	40	41	42	42	43	44	45	45
3585L	175	32	34	1075mL			40	42	43	44	46	47	48	49	50	51	51
3660L	213	34	36	1098mL			44	46	47	49	50	52	53	54	55	56	58
3735L	251	36	38	1120mL			47	49	51	52	54	56	57	59	60	61	63
3810L	289	37	40	1143mL			49	51	54	55	57	59	61	62	64	66	67
3885L	327	38	41	1163mL			51	54	56	58	60	62	64	66	68	69	71

Fig 5: Hydraulic radius matrix showing the hydraulic radius generated when mining along the strike and down dip in Synclinorium C. Anticline

The hydraulic radius matrix shows that when the hanging wall has been exposed by over 190 m along strike and by 78 m down dip a hydraulic radius of above 28 m and above will be generated. Also, when the hanging has been exposed by over 142 m down dip and by 100 m along strike, a hydraulic radius of over 29 m is generated. Comparing the highlighted values in Figure 5 and those required for the caving of the hanging wall, it can be concluded that sufficient hydraulic radius will be generated as mining progresses and the hanging should be able to cave. This is illustrated in Figure 6. Laubscher's stability curve shows that generated hydraulic radii fall in the curved zone.

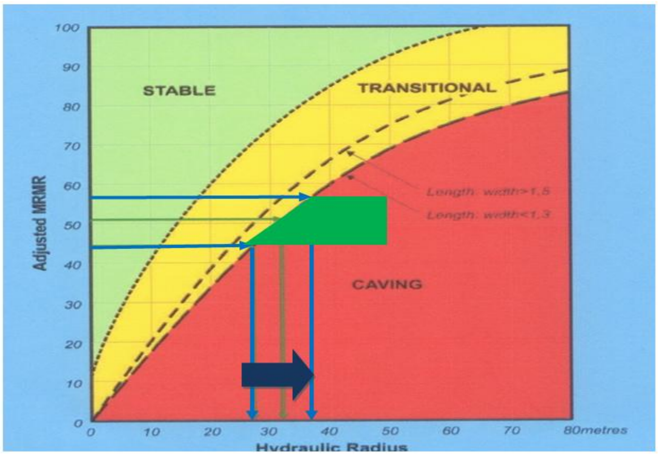


Fig 6: illustration of change in HR on the Laubscher's stability graph

Cave Monitoring

Installation of seismic network within the Synclinorium is required to monitor initiation and propagation of cave. It may also be done by the installation of deep hole cave extensometers. New boreholes may be required or geological boreholes if available may be used. Visual inspection from a hanging wall monitoring drive may also be used to monitor caving. Cave monitoring must also be allowed from surface.

Other Considerations for the Proposed SLC

Support requirement for the Synclinorium C. anticline were determined based on the stresses and ground conditions. Other elements of underground mine design such as drill and blast, Ventilation, Production tonnage and equipment selection for the proposed sublevel caving were considered.

Economic Appraisal

Economic factors govern mining method selection because they affect output, investment, cash flow, payback period and the profit of the project. The costs expected to be incurred include development costs, mining costs, metallurgical costs and other costs such as divisional overheads, corporate overheads and realization costs. A rough estimation on the costs of several units of mining has been made based on the design recommendations in order to have a realistic economic analysis of this project. The long term equilibrium price of copper has been estimated to be $5000 per tone from anode and cathode recoveries. The estimated cost to recovery the mineral commodity included major costs such as extraction costs, development costs and metallurgical costs. The expected revenue was the product of the expected amount minerals commodity to be produced (in tonnes) and long term commodity equilibrium price. Total costs were calculated as the sum of extraction costs, development costs and metallurgical costs. The total revenue was estimated as the product of expected copper recovered from the smelter and long term equilibrium price of copper. The profit was calculated as the difference between the total estimated revenue and the total costs. The summary of the results is presented in Figure 7. The summary of economic analysis results shows that the proposed design is economically feasible.

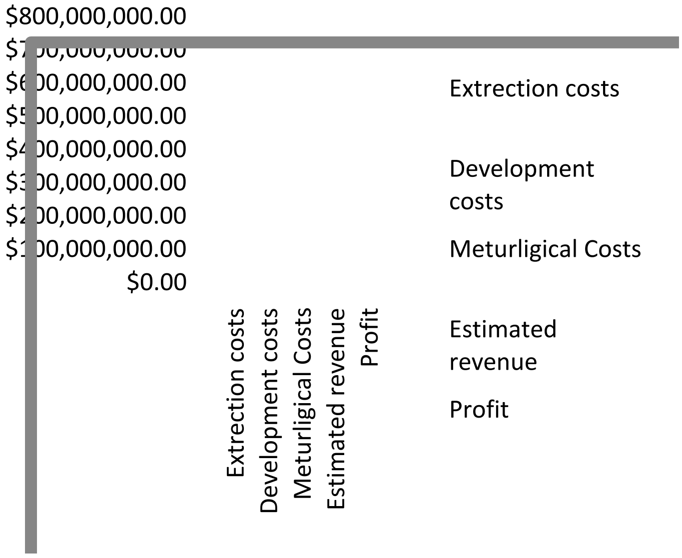


Fig 7: Summary of economical appraisal results

VII. CONCLUSION

After an intensive review of the Nkana underground mine, SOB Shaft, it has been found that sublevel caving is still applicable to the Synclinorium C. Anticline. However, a modification or different approach from the current sublevel caving is to be used for the extraction of the remaining part of the C. Anticline. The proposed sublevel caving which is the combination of transverse and longitudinal sublevel caving is the optimal way of mining the unexploited part of the Synclinorium C. Anticline. The proposed mining method is stable, has good work organization and has high production potential because of mechanization.

VIII. RECOMMENDATIONS

A trial mining for proposed sublevel caving (transverse and longitudinal) should be carried out at the Synclinorium C. Anticline. The extraction pattern of ore will be caving by multiple retreats.

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