Where to Drill
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Abstract

This paper looks at methods to best target resource definition infill drilling for an open pit using Whittle Programming's Four-D package. In the first case, a single mineralized zone (a vein) is intersected by widely spaced exploration holes. A set of infill holes are then simulated to show the desired drilling density and a two dimensional grade/thickness model is constructed in long projection. This can be exported to Four-D and optimized. Sensitivity to grade and thickness of the mineralized zone is tested by modifying the simulated intersection and re-optimising. The final depth of the optimum pit, where it intersects the mineralized plane, can then be contoured for each case.

In the second case a full three dimensional model is produced using a more complex example, with more than one mineralized zone and expected plunging high grade shoots. Rather than running a full set of sensitivities, just pessimistic and optimistic intersections are simulated. The mineralized targets between the two shells are the zone of priority for in-fill drilling.

Introduction

An important question early in the discovery of any new project and particularly in the resource definition drill phase is, "where is it necessary to drill ?". Frequently the solution is to pattern drill the entire mineralized body, but this can be very expensive. Aurora Gold are faced with such a task in developing the many Mt. Muro deposits in Central Kalimantan and want to spend their drilling budget wisely on the most cost effective drill holes.

In this paper we will investigate the physical characteristics of an elongated gold body, and how they control the depth of a pit. In particular, we are looking for a strategy to focus drill targeting.

A simple thin tabular zone

To investigate what controls the ultimate depth of a pit we shall begin with a single simple tabular zone that resembles a mineralized vein. We can model this zone in two dimensions as a thickness and a grade. This can be achieved using the geostatistical program GEO-EAS (Table 1). To represent a high grade "shoot" we can model the central area of this tabular body to have higher grade and increased thickness with both grade and thickness tailing off along strike but with good continuity up and down dip, (which is also the plunge of the shoot).

These simulated mineralized bodies can then be "dropped" onto a digital terrain model (DTM) of a simple dipping surface, and the horizontal thickness computed according to the dip of the zone. This produces a simple three dimensional representation of a mineralized zone. These three dimensional resource models can then be directly exported to the Four-D format using a simple Quick Basic program that preserves the thin zones as sub-parcels within the desired block size. Surprisingly this step will be difficult to reproduce with most of the current general mining packages that cannot handle partial blocks of variable thickness and/or a non-incremental centroid spacing.

These models can now be optimized using very simple costs without cost adjustment factors and all round 45° average pit slopes.

Variable	Nugget	Sill	Along Strike Range
Thickness	0	2.7	250
Gold (Au)	0	1.4	270

Table 1 Example of geostatistical modelling parameters used to construct our prototype models.

Bench (RL)		Four-D	45° Dip		60° Dip		75° Dip	
Floor	**Crest**	**Bench No.**	**Tonnes**	**Grade**	**Tonnes**	**Grade**	**Tonnes**	**Grade**
290	300	20	74,295	2.12	61,722	2.06	54,480	2.08
280	290	19	73,898	2.16	61,422	2.10	54,205	2.12
270	280	18	73,642	2.15	61,243	2.13	54,025	2.15
260	270	17	73,347	2.16	60,988	2.14	53,806	2.16
250	260	16	73,152	2.17	60,834	2.15	53,682	2.17
240	250	15	72,999	2.18	60,691	2.16	53,530	2.18
230	240	14	72,914	2.19	60,634	2.16	53,446	2.18
220	230	13	72,853	2.19	60,577	2.17	53,455	2.19
210	220	12	72,851	2.19	60,540	2.16	53,375	2.19
200	210	11	72,820	2.19	60,515	2.16	53,308	2.19
190	200	10	72,840	2.19	60,546	2.16	53,308	2.19
180	190	9	72,832	2.19	60,551	2.17	53,430	2.19
170	180	8	72,874	2.19	60,583	2.16	53,435	2.19
160	170	7	72,956	2.18	60,645	2.16	53,508	2.18
150	160	6	73,080	2.18	60,823	2.15	53,576	2.18
140	150	5	73,235	2.17	60,896	2.14	53,709	2.17
130	140	4	73,529	2.15	61,100	2.14	53,928	2.16
120	130	3	73,720	2.16	61,335	2.11	54,087	2.13
110	120	2	74,077	2.14	61,584	2.08	54,337	2.10
100	110	1	75,353	2.10	61,952	2.04	54,593	2.06
		Total	**1,467,267**	**2.17**	**1,219,181**	**2.13**	**1,075,223**	**2.16**

Table 2 Summary of resources in prototype models

Which physical characteristics of the mineralization affect the pit shape?

Firstly three base cases were constructed to simulate ore zones dipping at 45 degrees, 60 degrees and 75 degrees. We can gauge the changes to the pit design by recording final depth of pit, stripping ratio and tonnes mined.

Where only the dip of the mineralized zone varies, the depth of the pit increases as the dip of the ore zone steepens as summarised in Table 3. When either the grade or the thickness of the mineralized zone are increased, the depth of the pit can be shown to increase by between 50 and 70 metres, depending on the dip of the ore zone. Next we can increase the grade by 100%. The pit deepens to 150 metres for all three models. Finally we can increase the thickness of the ore zone by 100%. This does not draw the pit down as far, only extending to 140 metres for all three models.

The stripping ratio increases with an increase in dip for all of the cases, as illustrated in Figure 1. When the grade is increased, the stripping ratio increases by 45%, as compared with the base cases. Where the ore zone is wider, the stripping ratio only increases by between 7% and 14% as compared with the base cases. This means that, on average, the stripping ratio is 38% less for the wider ore zone than the higher grade ore zone.

	Deposit Dip	Pit Floor (RL)	Pit Depth (m)	Stripping Ratio	Tonnes Mined	Metal (grams)	Feed Grade
Base Cases	45°	210	90	14.65	3,938,376	921,909	3.66
	60°	210	90	15.95	3,221,816	719,933	3.79
	75°	220	80	16.35	2,532,296	570,202	3.91
Grade increased 100%	45°	150	150	26.85	13,260,416	2,676,244	5.62
	60°	150	150	28.95	10,863,320	2,107,376	5.81
	75°	150	150	29.46	9,623,536	1,808,197	5.72
Thickness increased 100%	45°	160	140	16.63	11,099,920	2,463,240	3.91
	60°	160	140	17.23	8,828,560	1,929,069	3.98
	75°	160	140	18.97	8,593,312	1,734,753	4.03

Table 3 Summary of variations to pit design for each of the nine models.

Increasing the grade of the mineralization has the effect of deepening the pit design, as already explained, thus accounting for the increased stripping ratio. Increasing the width of the ore zone also deepens the pit, however, less material is stripped in this case. These results are significant as they show that for thicker ore bodies, the waste to ore ratio is much lower. Also, for more steeply dipping orebodies more waste material needs to be removed to access the ore, which is common sense.

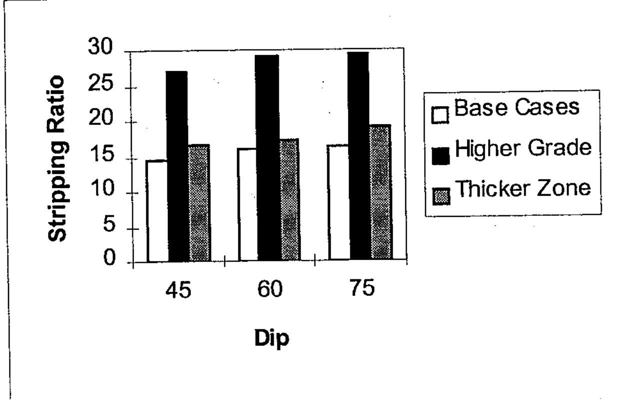

Figure 1 Stripping ratio compared to dip, grade and thickness.

The tonnes of rock mined for each of the scenarios in all cases show that, as the dip of the ore zone increases, the amount of material mined is less (Figure 2). This is coincident with a decline in the amount of product recovered as shown in Table 3. Even though the tonnes decrease, the grade remains relatively unchanged. (An example of this is shown in Table 2, where a breakdown of tonnes and grade mined from each bench is given for the base case scenarios). With higher grade there is a 70% increase in the tonnes mined as compared with the base cases. With a thicker ore zone between 64% and 70% more material is mined than in the base cases, and between 11% and 19% less than the higher grade cases, depending on dip. This is understandable considering that the stripping ratio with wider zones is lower. More product is recovered from the high grade models, (~65% more than the base cases and 4-8% more than the thicker ore zones).

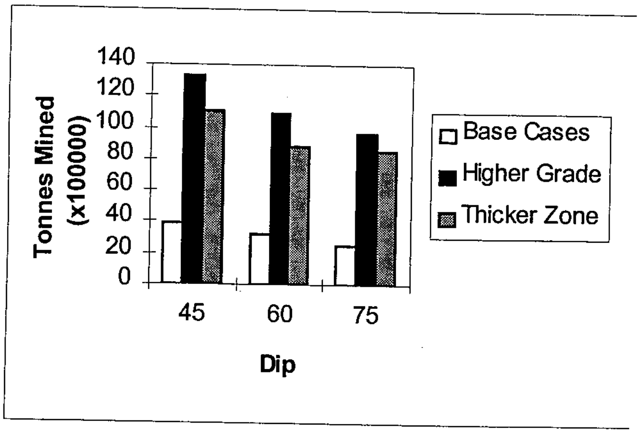

Figure 2 Tonnes mined for the various cases.

Obviously, if the grade of mineralization encountered in the ore zone increases, then the Net Present Value (NPV) of the operation will increase. However, it is interesting to note the decline in NPV as the dip of the ore zone increases, (Figure 3). This can be attributed in part to increased stripping ratio and a decline in the amount of product recovered.

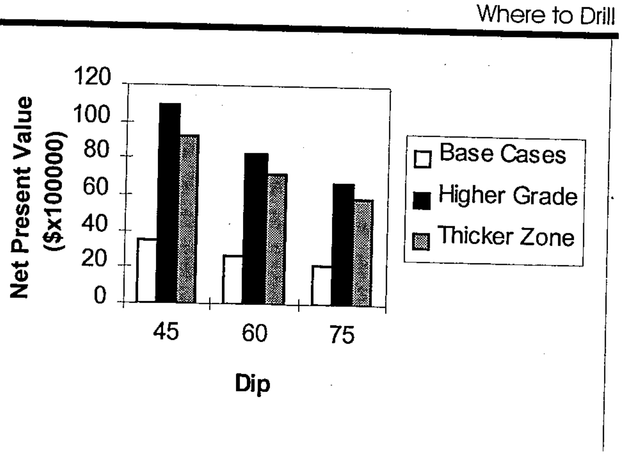

Figure 3 Variation of NPV for different ore zone geometries.

The variable with most influence on the final depth of any pit studied in this paper has been found to be grade. Whilst the thickness of the mineralized zone has also been shown to draw the pit deeper, its effect on the pit shape is not substantially different from that of grade. It will however affect the stripping ratio (thicker ore zone means lower stripping ratio), and influence the tonnes mined accordingly (fewer tonnes mined for not much less recovery in product).

Controls on the depth of drilling

As demonstrated in these simple cases, the proposed final depth of the optimal pit design depends on the three things we have tested. Roughly in order of significance, they are:

- grade
- thickness of mineralisation, and
- dip of the mineralisation.

If we wish to change these variables, we can re-model the resources and export a new "what if" scenario. Even in our very simple examples this will be easy but very time consuming. We need a better strategy to test the different possibilities that control pit depth.

The changes in grade and thickness have much higher influence on the depth of the final pit than changing the dip. Further, the dip of a mineralized zone is generally understood before variations in grade and thickness are well defined. We therefore feel that changing the model to reflect different dips of the mineralized zone is a low priority compared with looking at the impact of thickness and grade.

Consider a pit design based on limited drilling and our degree of confidence in the amount of ore that exists quite low (eg ±25%). This situation can be simulated in Four-D by assigning a recovery of 75% in the parameter file during optimisation studies. The pit outline generated by Four-D will reflect a fairly pessimistic scenario. This pit extends to 260 metres RL and a total of only 10,457,720 tonnes of material are mined yielding 2,325,159 grams of metal.

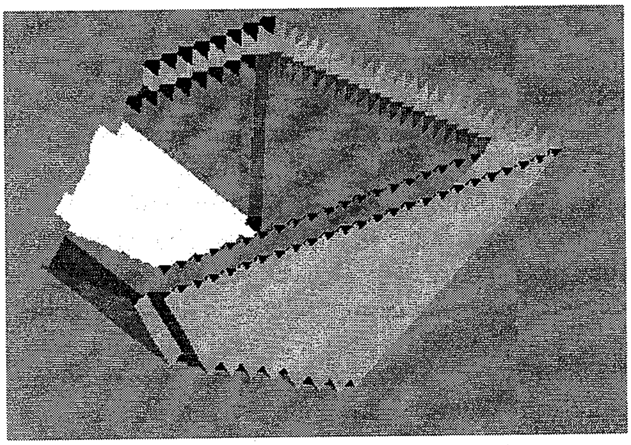

Figure 4 View of 45 degree model looking from south west showing pessimistic (75% recovery) and opimistic (125% recovery) pit designs. (Note: pits share footwall of mineralized zone.)

Imagine we now adopt a more optimistic view, and assign a recovery of 125% to our model during optimisation. This suggests that we might actually encounter more mineralized material than initially assumed. The pit outline generated by Four-D is substantially deeper. This pit extends to 230 metres RL, from which 19,536,400 tonnes of material are mined, yielding 3,266,183 grams of product. This optimistic pit outline is 30 metres deeper than the pessimistic outline, and adds nearly 30% to the amount of metal produced. The pit outlines are compared in Figure 4.

Somewhere between these pessimistic and optimistic outlines lies a pit design that will more accurately reflect the actual mineralization that exists in the project area. To solve this problem we have used the "resource confidence approach", as explained below.

Resource confidence approach

When infill drilling a deposit, the objective is to continually improve the confidence in the resource. This can be achieved by pattern drilling everything to the desired drill density. Unfortunately a lot of drill holes in such a pattern will be wasted as they are either "dead holes" or well outside a potentially economic pit, and thus pattern drilling can be expensive and time consuming. A better strategy is to firstly infill those areas of uncertainty within or adjacent to a potential pit. Since the JORC resource categories are used to qualify the degree of certainty or confidence in the mineralization, it is worthwhile to use this classification during our pessimistic and optimistic optimizations to help select areas of least confidence at the same time as those which have most influence on the final pit shape.

JORC Category	Code	Variation in Recovery (respresenting grade)
Measured Resource	MSD	±5%
Indicated Resource	IND	±10%
Inferred Resource	INF	±25%
Pre-Resource Mineralization [1]	PRM	±50%

Table 4 Varying recovery with JORC Category

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[1] JORC Committee have eliminated the Pre-Resource Mineralization Category from their reporting guideline (see section: A Warning - Do not publish details of Pre-Resource Mineralization.)

By varying the recovery of each category by a reasonable range to reflect the confidence in that mineralization (Table 4), the resulting pit designs will show most variation where the mineralization is least defined.

Any areas of inferred or pre-resource category mineralization within and bordering this zone are naturally the positions of highest priority. As drilling within this zone continues and the level of confidence in the mineralization increases, these pit outlines will gradually converge towards the final design.

We would like to demonstrate this "resource confidence approach" using an actual example based on the Serujan North Pit at Aurora Gold's Mount Muro Operations in Kalimantan, Indonesia. The Serujan North Pit is a very small pit developed early in the operations because it was close to the mill and provided a good place to dump waste from the Serujan Central pit.

During Ashton Gold's resource definition phase leading up to their feasibility study in 1992, there was not sufficient time to undertake all the drilling desired. Priority was given to the larger resources in the Mt Muro area, and the Serujan North deposit was not drilled by Ashton. So resource estimates were based on 21 diamond drill holes (approximately 2,150m of drilling) drilled by the previous owners Penzoil/Duval. There were multiple intersections in some holes and the mineralization was difficult to interpret. The simplest possible interpretation of two intersecting zones was used, and the estimated Measured and Indicated resources of approximately 100,000 tonnes at 4.9% Au[2], 230 g/t Ag and in-pit reserves of around 64,000 tonnes meant it was the smallest deposit defined for the feasibility study and little priority was given to infill drilling, despite the reasonable grade.

In the period leading up to the construction and commissioning of the mill, the Serujan North area was eventually drilled with some very encouraging intersections. With a revised interpretation it was clear the pit could go a lot deeper, possibly well below the majority of the existing drilling intersections. With only one drill available and delays bringing in other rigs it became a race between drilling, pre-stripping and stockpiling ore for the commissioning of the mill.

The original pit design was used as a preliminary pushback and several holes were actually drilled from within this pit to test extensions at depth. The improved knowledge gained from grade control and in-pit mapping helped refine the interpretation further and produced a better resource model. The story ended happily because a second drill arrived on site, and drilling, resource modelling and optimization beat the final production deadline with a day or so to spare. With a revised Indicated and Measured resource of approximately 410,000 tonnes at 3.3 g/t Au and 240 g/t Ag, around 240,000 tonnes at 3.7 g/t Au and 270 g/t Ag were within the ultimate pit design. Figure 5 shows the ultimate pit together with significant drilling intersections.

Whilst the additional 4,100 metres of RC and diamond drill in-fill resource definition drilling were clearly cost effective in this case, any delays in production could have been at significant cost to the company. With a large number of other pits and potential resources also to be drilled, it was considered wise to find a better strategy to economically target drilling.

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[2] For simplicity, all resources and reserves in this paper are quoted to a simple 1 g/t Au cut-off. Aurora gold use a gold equivalent cut-off which gives them higher tonnes and slightly lower grades.

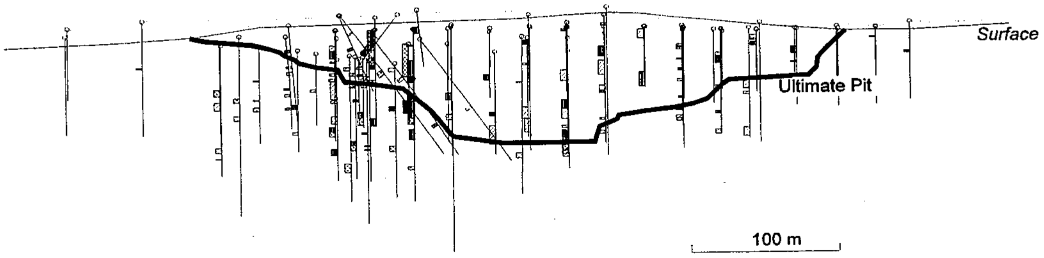

Figure 5 Long projection of Serujan North showing ultimate pit and significant drilling intersections.

The Serujan North data is an ideal example to test out the proposed "resource confidence approach". To do this the drill hole information has been grouped into three phases and three models prepared to represent confidence in the resource definitions in line with the JORC code.[3]

Phase I corresponds with the Ashton feasibility study, where only limited drilling information was available, and thus a very conservative pit is designed (Figure 6). Phase II represents the early infill time frame with pre-stripping and limited ore mining to feed the commissioning of the mill (Figure 7). Phase III represents the final pit and infill drilling to bring the pit into full production (Figure 8). The long section in Figure 9 shows optimizations for the available models in each phase. This was run using only Measured and Indicated mineral resources to represent best practice in defining ore reserves, and provides use with desirable pit limits against which to judge the appropriateness of the target zone.

The proposed "resource confidence approach" can be simply broken into three steps. The first step is to run optimizations on each model using only Measured and Indicated mineral resources. Next a target pit is generated by including the Measured and Pre-resource mineralization categories. Finally pessimistic and optimistic pits are designed by changing the mining recoveries of different categories of resources for each of the three phases.

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[3] The resource models in this study include inferred and pre-resource mineralization categories, whereas the original Ashton/Aurora Gold pit optimizations were based on measured and indicated resources only.

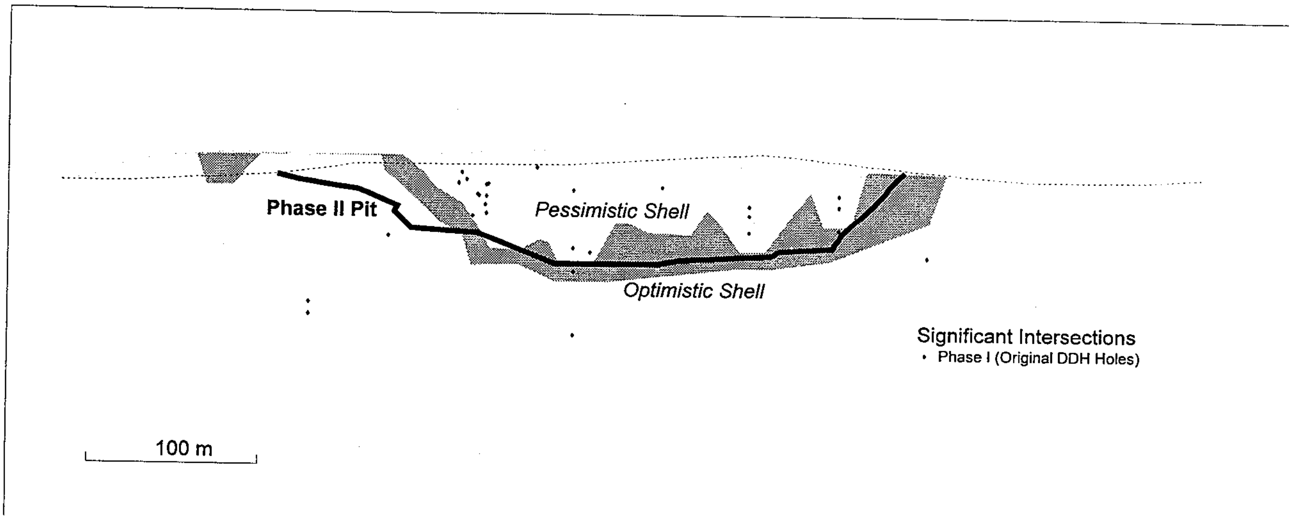

Figure 6 Phase I - Optimizations based on original DDH holes. (Shaded area in these figures represents target for in-fill drilling.)

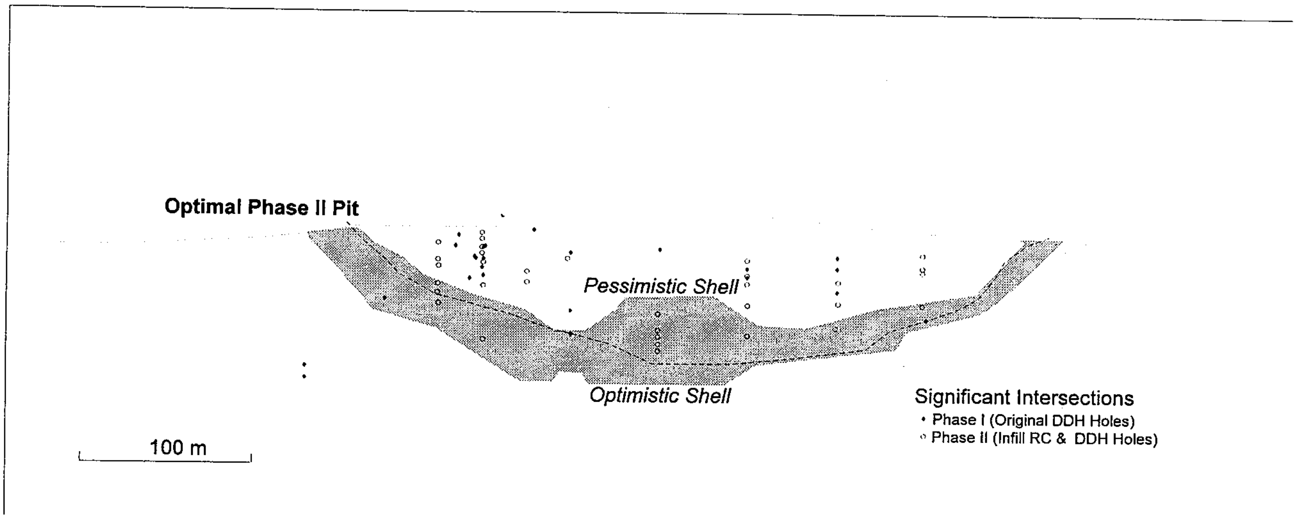

Figure 7 Phase II - Optimizations based on initial infill RC & DDH holes.

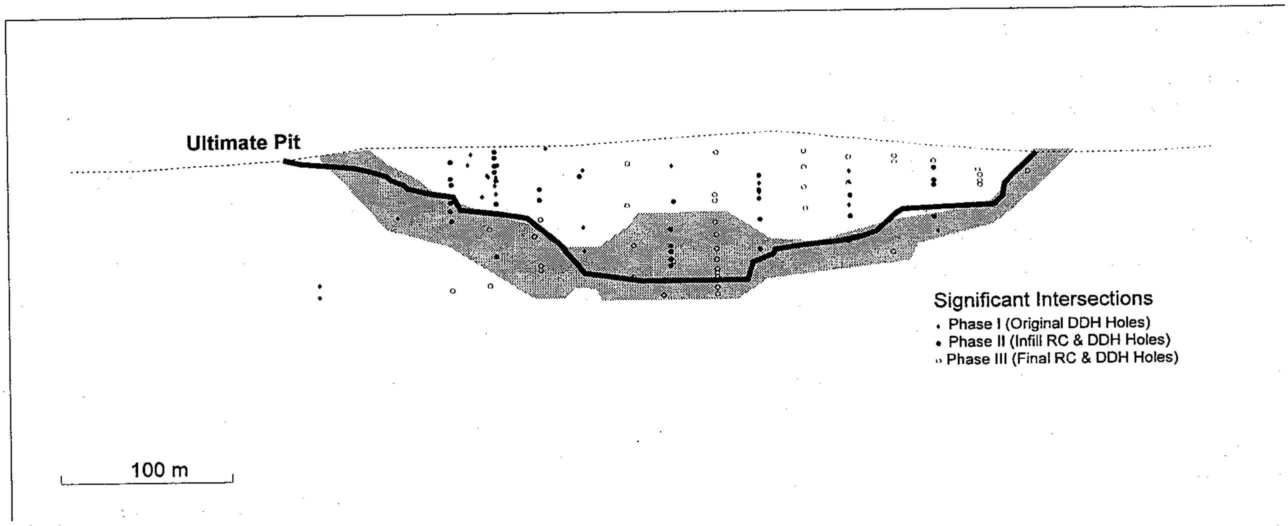

Figure 8 Phase III - Final optimization based on all drilling.

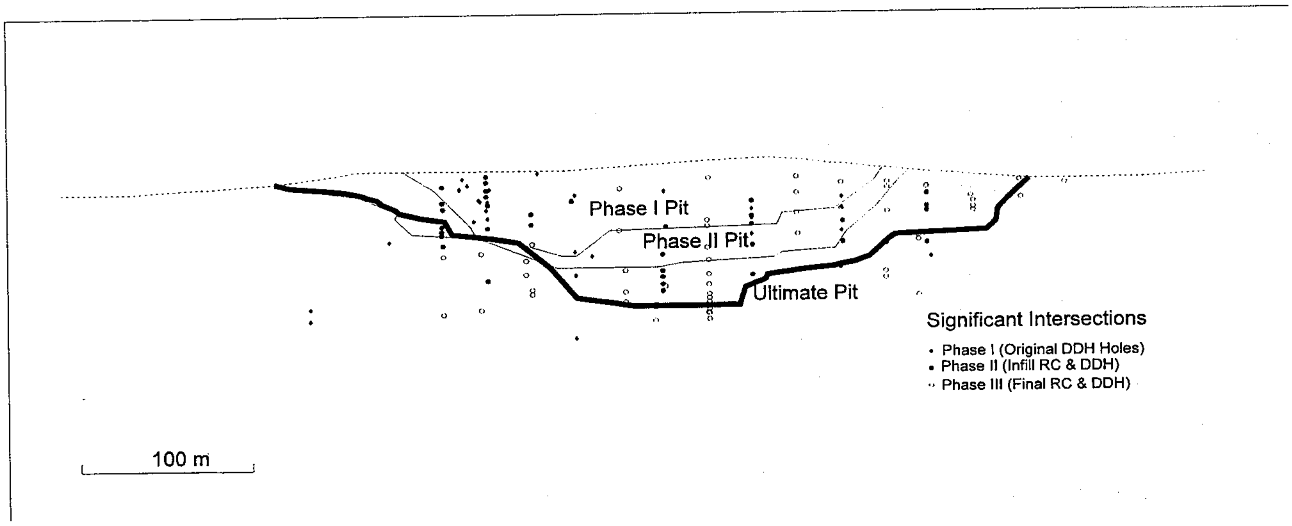

Figure 9 Showing optimisations for the models in each Phase.

The long projection now shows how the pessimistic and optimistic pit outlines do provide a good guide within which to target drilling. The envelope they form has collapsed onto the ultimate pit.

A Warning - Do not publish details of Pre-Resource Mineralization !

The Australasian Joint Ore Reserves Committee (JORC)[4] have recently updated the code for resource reporting and they have now eliminated the term Pre-Resource Mineralization from the JORC Code (1996). So resources considered in this category must not be published. This should not, however, discourage you from using this or a similar category as a means to qualify geological hunches regarding the continuation of mineral zones. Providing everyone clearly understands that this category is the mineralization in which there is least confidence, it can be useful in defining the best drill targets. Leaving out this mineralization just to be conservative will lead to significantly smaller initial pit designs. When an optimistic pit finishes in, or contains significant quantities of, such a Pre-Resource category then drilling is certainly warranted. It is, however, important to remember that the details of these optimizations are for internal company use only and should not be published.

Conclusion

Determining the ultimate depth of an open pit is a complex problem. For a thin elongated mineralized zone the thickness and grade are more significant than the dip of the zone, and both these physical parameters are difficult to quantify in detail early in the drilling campaign.

It can be seen that there are two mechanisms by which variations to the ore body in terms of grade and thickness can be simulated in Four-D. The first is changing the mining recovery (to represent changes in mineralization thickness), and the second is altering the metallurgical recovery (to represent changes in grade). This can be done in stages according to the level of confidence in the resource block model, and is a quick way to generate some pessimistic and optimistic pit designs.

Selecting drill targets to improve confidence in mineralization between these two shells is recommended as a safe and cost effective approach to the selection of in-fill drilling during resource definition.

References

Australasian Code for Reporting of Identified Mineral Resources and Ore Reserves (the "JORC Code" 1996 revision), by The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and the Minerals Council of Australia.

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[4] JORC is the common abbreviation used to describe the Joint Ore Reserve Committee of The Australasian Institute of Mining and Metallurgy, Australian Institute of Geoscientists and Minerals Council of Australia.