A FEASIBILITY STUDY OF A DEEP EXPLORATION PROJECT FOR MASSIVE SULPHIDES IN AN OLD MINING DISTRICT

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ABSTRACT

Simulation technique has been used for a feasibility study of a deep exploration project for massive sulphides in an old mining district, the Skellefte field. The outcome under very different conditions has been studied. Under the specific conditions of the well known Skellefte field it is found to be possible to even calibrate the mathematical model.

It is found that when the geology is not known in detail, an outcome of the order of 50 tons per meter drillhole is to be expected under a simple drilling strategy.

When a certain knowledge about the general structures down to around 1000 m is established, it is possible to improve the outcome by a factor of 2 through an optimization of the depth of investigation. The optimal depth of investigation is in the order of 500 m.

On the other hand, when a minimum ore value is introduced as a function of depth, the expected outcome will again decrease with a factor of about 3.

It must be underlined, that these results are average values in a mathematical model and do not say anything about the outcome in the single exploration case. However, in exploration campaigns of the order of 40 drillholes to a depth of 1000 m an analysis shows that at least one deep seated large body was found in 25% of the exploration campaigns.

Faced with the problem whether to go or not to go into a deep exploration phase, this technique can headlight the problem and it can give an estimate about the order of costs and benefits.
Mineral exploration has up to the present generally been limited to very shallow parts of the earth crust. However, the amount of near surface ore bodies within a certain area is naturally limited. Prospecting for deep seated sulphide ore bodies is a great investment and means a considerable risk. The high costs depend on the demand for extensive drilling. Therefore the order of the expected outcome and the expenditures in a prospecting project is of importance. Faced to the decision whether to start a large deep prospecting project or not, this question should be studied as far as possible theoretically.

Considerable efforts have been made to find optimal strategies, for example grids, for drilling against horizontally layered economic targets. This question is of great economic importance in, for example, the search for oil and gas.

Based on knowledge of the target size and shape, an approach is to study the influence zone of an exploration hole analytically. In a paper by Singer et. al (1976) the concept, "degree of physical exhaustion", is introduced. Another approach is taken by Shurygin (1976) who also includes the value of the target and the costs for exploration in an algorithm for optimal search grids.

The drawback of these methods is the limited possibilities to take the statistical variation of the different geological parameters into consideration. Also the possibilities to handle more complicated geometries and to use knowledge of different characters like geophysics and geochemistry are limited.
One way to improve the possibilities of handling complicated situations is to make use of mathematical simulation technique. This was used by Koch et. al (1974) to guide exploration from the Coeur D'Alene Lead-Silver Mine. This approach made it possible to study the cost effectiveness of various layouts.

In a paper, K Malmqvist et. al (1979), a preliminary study based on a simplified mathematical model of the bedrock is presented. The results from this study show that simulation technique should be a good guide for deep prospecting projects.

The simplified bedrock model used in the preliminary study assumes that nothing about the geological structures are known. The results therefore should be regarded as a lower limit of the expected outcome of a prospecting campaign.

In order to make the simulation technique to a flexible tool in a more realistic planning situation, the mathematical model has been improved to handle more complex geological features. In a paper by K Malmqvist (1979) a developed mathematical model and simulation procedure are presented.

The present paper presents results from the application of this mathematical technique on more sophisticated models in three dimensions. The objective is to investigate the influence on the expected outcome when more information of geological character is introduced into the model. Of importance is also to study the outcome as a function of different parameters as the depth of investigation or under different restrictions like changing minimum accepted ore values.
1. BASIC CONCEPTS

In this study two basic assumptions have been made. The first assumption is that all deposits which reach the bedrock surface are known and the second that the horizontally projected area of all ore bodies is independent of depth.

To give the simulation work as close ties as possible to real conditions the geological situation in a certain part of the Skellefte field - the Udden-Åsen area - has served as a model for a 18 x 5 x 1 km³ large investigation block.

A simulation experiment consists of 100 simulated drilling campaigns on an ore model with a specific set of parameters. The drilling pattern is fixed. A new set of ore bodies is drawn randomly from the set of parameters before every new drilling campaign. The result of an experiment is the average outcome of struck ore from these simulated drillings. The errors given in the diagrams are the standard deviation of the mean in the repeated simulation campaigns. The figure 100 is chosen from experience in order to get the standard error of the mean at a reasonably low level. In some situations 300 simulations are used in order to improve the accuracy. When this is the case, it is specified in the description of the simulation experiment. It is important to remember that when 100 simulations are used, the standard deviation of the outcome from repeated drilling campaigns is 10 times larger than the standard error in the mean that is marked in the diagrams.

The drilling is organized in drilling campaigns consisting of 40 boreholes located in a grid pattern and to various depths of investigation. The maximum depth is 1 000 meters. Every borehole has a northern direction, perpendicular to the main strike of the geological formation. The dip angle is in most cases 75°. Some simulation experiments make use of other dip angles. In these cases the dip angle will be specially stated.

A hole that is drilled to a vertical depth of 1 000 meters and with a dip angle of 75° has a length of 1 350 meters and it reaches about 800 meters in y-direction. If the starting point has the coordinates (x, y, 0) the end point of the borehole has the coordinates (x, y + 800, 1 000) approximately.
2. DESCRIPTION OF THREE SPECIFIC BEDROCK MODELS

It is of large interest to study the influence on the expected outcome caused by adding more information about known properties of the bedrock to the model.

To realize such a study, three specific bedrock models have been constructed according to the possibilities described in a paper by K Malmqvist (1979). The three models represent successively increasing knowledge about the bedrock geology. The objective is not to reproduce the geological situation in detail but to preserve the relations between different rock types and the general tectonical structures.

The first model is a simple model, which means that the centres of the ore bodies are uniformly distributed in the investigation block. The implication of this model is that nothing about the geological structure is known beside the fact that you consider the area to be of certain interest for exploration. This model is called the uniform model.

The second model has a vertical layer of shale which intersects the block composed by volcanics. The thickness of the layer is 300 meters. In this model we presume that the shale has had a certain impact on the ore genesis. Therefore it is assumed that the relative intensity of ore bodies varies with the distance to the shale. The intensity of ore bodies in the shale is zero. This model is called the shale model.

The third model is called the shale-granite model. This model has the same layer of shale as the shale model. Additional, a contact parallel to the shale between a granite and volcanics is introduced. The distance between the granite and the shale is 200 meters. The relative intensity of ore bodies within the granite can be given any value but is chosen as zero. The relative intensity function of ore bodies in the volcanics outside the shale is modified compared to the shale model.
The three models and the ore intensity functions are sketched in Figure 1. In the first model it is assumed that nothing is known about the geological structures. In this case we have chosen a drilling pattern which constitutes a rectangular grid covering the whole surface area of the investigation block.

If something about the geological structures and the probability for ore occurrences are known, it is reasonable to make use of this knowledge in the choice of a drilling pattern. In a drilling campaign on the shale model or on the shale-granite model the boreholes are located at equidistant points along lines parallel to the shale. The distances from the shale are chosen in order to make the drillbit to pass a long way through rocks with high ore intensity at reasonable depths.

The three different drilling patterns are given in Figure 1 where the three models are sketched.
3. VALIDATION AND CALIBRATION OF THE SIMULATION MODEL AND SIMULATION PROCEDURE

Before starting a mathematical study by use of simulation technique, one should validate the simulation model and the simulation procedure. The best way is to make a comparison between a simulated situation and a real situation. Another way is to compare results from some simulation experiments with results from theoretical calculations under the same conditions. In this way you can check that the technical construction of the model and the simulation procedure works properly.

In this study we have a possibility to test the model and to calibrate it with respect to the parameter which gives the amount of ore within the investigation block. One basic assumption is that all ore bodies in the Skellefte field which intersect the bedrock surface are known. There are 8 surface ore bodies in the Udden-Åsen area which served as a rough model for the construction of the bedrock models. Two of them are greater than 4 Mton.

Sets of ore bodies are simulated for different total amount of ore put into the block. Then the amount of ore which is part of outcropping bodies can be recorded. By comparing the observed distributions and the simulated distributions of outcropping bodies as a function of total ore content we can get a rough estimate of the amount of ore within the block. The result of such a calibration is shown in Figure 2. The best estimate of the total ore content is 80 Mton. The average number of big (>4Mton) ore bodies within the block is 7 if the total amount of ore is 80 Mton. The 95% tolerance interval is 7±3.

It is important to remember that this estimate is based on the preassumptions inherent in the model i.e. that all deposits which reach the bedrock surface are known and that the horizontally projected area of all ore bodies is independent of depth.
It is also possible to determine the average number of ore bodies corresponding to 40, 60, 80, 100 and 120 Mton of total ore content. The simulation gave the result that the number of ore bodies were 32, 43, 57, 67 and 91 respectively. In a previous theoretical study based on probability theory by Rhodin, L. (1975) it is shown that we should expect 54 bodies within the investigation block under as close preassumptions as possible to those applied in the simulation.

Rhodin also studied the probability of hitting one ore body. To make a comparison possible with the results of a simulation, the conditions for the simulation should be arranged as close as possible to those applied in the probability calculation. In both studies the ore bodies were uniformly distributed in the investigated block. The amount of ore was given as numbers of ore bodies and varied from 24 to 72 stepped by 12. The drilling was carried out in a rectangular grid and every drilling campaign consisted of 40 boreholes. Every borehole had a length of 1 000 meters, an initial dip angle of 80° and was directed to the north. This means that the drilling was carried out to a depth level of 822 meters.

The result is shown in Figure 3. The graphs show the probability of hitting one deep seated ore body when drilling 1 hole and the probability of hitting one deep seated ore body larger than 4 Mton when drilling 1 hole.

It is worth noticing that the probabilities from the simulation systematically are somewhat lower than the theoretically calculated probabilities. The difference is approximately 10 %. One explanation can be the fact that Rhodin has used an E-W strike direction for all ore bodies. The simulation model permits 40 % of the ore bodies to have a strike direction uniformly distributed in the interval ± 30° from the E-W direction. The probability of hitting an ore body when drilling in a northern direction depends of the projected area of the ore body perpendicular to the borehole. In the simulation case we have an average projected area that is smaller than in the case of theoretically calculated probabilities. This difference is, however, less than 5 %.
4. THE RELATION BETWEEN THE EXPECTED OUTCOME OF A DRILLING CAMPAIGN AND THE AMOUNT OF ORE WITHIN THE INVESTIGATION BLOCK

For each one of the three bedrock models the following simulation experiments are carried out. The amount of ore within the investigation block is assumed to be 40, 60, 80 and 100 Mton respectively. The first model is also run for 120 and 140 Mton. The reason for not to run the shale model and the shale-granite model at these high ore intensities is the risk for interference between single ore bodies.

The outcome of a drilling campaign expressed as the amount of struck ore per drillhole is shown in Figure 4 and the outcome expressed as the probability to find at least one ore body when drilling one hole is shown in Figure 5. For each one of the models two lines are presented, the dashed line represents the outcome of big (> 4 Mton) deep seated ore bodies and the full line represents the total outcome.

These results show that the outcome is a linear function of the amount of ore within the investigation block. They also show that the outcome of ore of possible economical interest, i.e. deep seated deposits bigger than 4 Mton, is approximately half the total outcome.

Furthermore, we find that the possibility of finding an ore body depends both on the bedrock geology and on the knowledge of the bedrock geology. This aspect is discussed later on.
5. THE RELATION BETWEEN THE EXPECTED OUTCOME OF A DRILLING CAMPAIGN AND THE MAXIMUM DEPTH OF INVESTIGATION

Of certain interest is to study the possible change in outcome as a function of bedrock model complexity. For each one of the three bedrock models, the uniform model, the shale model and the shale-granite model, a serie of drilling campaigns were simulated with varying maximum vertical depths stepped by 100 meters from 200 to 1 000 meters. The tonnage of distributed ore was 80 Mton, the number of boreholes was 40 and the drilling was carried out in a northern direction with a dip angle of 75°. The drilling pattern used for the three different bedrock models is described in Chapter 2.

The uniform model

The results from the simulation experiments in the uniform bedrock model have been discussed in detail in a previous paper, K Malmqvist e. al (1979). However, it is given in Figure 6 to make a comparison with the results from the more advanced models possible. All results are based on 300 simulated drilling campaigns each one of 40 boreholes.

In Figure 6 the full line describes the outcome of hit amount of ore per borehole and the dashed line the amount of deep seated ore in bodies > 4 Mton.

These basic experimental results are smoothed and then transformed to hit tons per meter borehole and to the amount of ore per unit cost for drilling. The results after these transformations are shown in Figure 7. The calculation is based on the cost-depth relation for core drilling given by R Johansson (Boliden Metall AB, per. comm) Figure 8.
The shale model

The results from simulation in the shale model are shown in Figure 9. The drilling pattern described in Chapter 2 is applied. It clearly appears that an optimal depth of investigation is around 600 meters. At that depth very few additional finds are made.

Analyzing this effect on the outcome compared to the outcome in the uniform model it is found that not only the depth level of investigation but also the lateral extent of the drillhole influence the result. When the borehole has reached the depth of 600 meters it has also moved about 400 meters to the north and most of the boreholes have passed through the volumes of highest ore intensities.

In Figure 10 these effects from the model of the bedrock geology is even more pronounced. In this figure the transformations to ore per unit borehole length and ore per unit borehole cost is performed. In Figure 10a the outcome in tons per meter borehole shows a clear maximum around a level of 600 meters. There is a tendency for big deep seated deposits to have a somewhat deeper maximum than what the total amount of hit ore has.

When transformed to tons per drilling costs the maximum still remains but is marginally shifted to more shallow depth, Figure 10b.

The shale-granite model

The result from simulation in the shale-granite model are shown in Figure 11. The drilling pattern applied is described in Chapter 2. At a depth of investigation around 500 meters, the additional ore finds are decreased compared to the situation for depths less than 500 meters. By comparison we see that this effect is less pronounced than in the shale model, where the volumes of high ore intensities around the shale are larger.
In the shale-granite model some boreholes pass through both a block of high ore intensity and the layer of shale and thereafter manage to reach the block of high ore intensity at the other side of the shale.

In Figure 12 transformations to ore per unit borehole length and ore per unit borehole cost have been performed. There is a clear maximum at a level of 500 meters for the total amount of hit ore. For big deep seated deposits there is a slight maximum at 500 meters when regarding hit ore per unit borehole cost.

In the last figure in this serie, Figure 13, the relations between found deep seated ore and total found ore as parts of large bodies $> 0.5$ Mton have been put together for all three bedrock models. The figure gives no reason to assume any difference between the three different models in this respect. This is reasonable, since the result only reflects the basic assumption made that the ore area in the bedrock surface is the same at any depth.
6. THE RELATION BETWEEN THE EXPECTED OUTCOME OF A DRILLING CAMPAIGN AND THE MINIMUM ACCEPTED ORE VALUE

The ore value is a factor of great importance for the possibility to mine an ore body. It depends on the grades of valuable metals in the mineralization. The minimum ore value necessary to mine a deposit with profit can vary within a wide range. The difference depends on the size, depth, the mining method and on the demand for environmental protection for example.

Therefore it is of great interest to study how the expected outcome of a drilling campaign varies as a function of minimum accepted ore values of the struck bodies.

Series of simulation experiments have been performed where the minimum accepted ore value varies from 60 to 180 S. kr/ton stepped by 20 S. kr/ton. For each one of the three bedrock models, two series of simulation experiments are carried out. The amount of ore in the investigation block is assumed to be 60 and 100 Mton respectively. The results are shown in Figure 14-16.

When interpreting these results it is necessary to have the frequency and distribution functions for the ore value parameter in mind. These are shown in Figure 17.

The results from these experiments should in some way be mappings of the ore value distribution function. The frequency of ore bodies is highest for ore values between 60 and 120 S. kr/ton. This means that when the minimum accepted ore value is changed from 60 to 120 S. kr/ton the amount of hitte ore will decrease faster than when the minimum value is changed from 120 to 180 S. kr/ton. This qualitative estimate is confirmed by the simulation results.
7. THE RELATION BETWEEN THE EXPECTED OUTCOME OF A DRILLING CAMPAIGN AND THE MINIMUM ACCEPTED ORE VALUE AS A FUNCTION OF DEPTH

In reality one has to demand higher ore values with increasing depth of the deposits caused by the more expensive investments needed to put a deep ore body into production.

Two series of simulation experiments have been performed with different minimum accepted ore values for different depths to the tops of the deposits. The two series start with 80 and 100 S. kr. respectively when the tops of the deposits are located between 0 and 200 meters and is then stepped up by 20 S. kr. for every interval of 200 meters of increasing depth.

This study is performed at the uniform and the shale model with the same conditions as described in Chapter 5. The results concerning deep seated ore bodies > 4 Mton are shown in Figure 18-21. In these figures also the results from Chapter 5 with no restriction in ore values are repeated in order to make an easier comparison. For the shale model restriction I and II gave approximately the same result.

From the results we see that a restriction on the ore values depending on the depths of the deposits has an important influence on the outcome of a drilling campaign and on the optimal drilling level.
8. THE RELATION BETWEEN THE EXPECTED OUTCOME OF A DRILLING CAMPAIGN AND THE DIP ANGLE OF THE BOREHOLE

The average curvature for boreholes as a function of dip angle is shown in Figure 22. The result is based on holes drilled in steep geological structures. The pathway of a 45° borehole differs a lot from the pathway of a drillhole with a dip angle of 90°. Low dip angles imply at the end almost horizontal boreholes. Since boreholes with different initial inclinations penetrate very different rock volumes it is of interest to study the outcome as a function of the initial dip angle of the borehole.

In order to study this situation the following simulation experiments have been carried out. The dip angle is varied from 60° to 90° stepped by 5°. The drilling direction is to the north. The amount of ore in the investigation block is fixed to 80 Mton. The simulation experiments have been performed both in the uniform model and in the shale model with the corresponding drilling patterns described in Chapter 2.

The maximum depth of investigation is fixed to 1 000 meters. This means that a borehole with a flat dip angle is much longer than a borehole with a steep dip angle. For 60° and 90° the lengths of the boreholes are 2 150 and 1 050 meters respectively. This is taken into consideration when the outcome per drilled meter is calculated.

The results are shown in Figure 23 and 24. In the uniform model the dip angle of the borehole has no effect on the average amount of hit ore per drilled meter. There is, however, a slight increase for a dip angle of 60° which is hard to explain.

In the shale model the average amount of hit ore per drilled meter increases with increasing dip angle of the borehole. An explanation of this phenomenon might be that the steep borehole passes a longer way through the limited rock volumes of high ore intensity compared to a flatter hole which soon has passed through the zone of highest ore intensity.
9. THE RELATION BETWEEN THE EXPECTED OUTCOME OF A DRILLING CAMPAIGN AND THE SIZE DISTRIBUTION OF ORE BODIES

One basic assumption in this study is that all outcropping ore bodies in the Skellefte field are known. The distributions of the different geometric ore parameters have been calculated from all these known deposits. This is described in more detail in a previous paper K Malmqvist, (1979).

However, there is a risk that there still exist some unknown outcropping ore bodies in the Skellefte field. If these unknown bodies are systematically small or large they bias our assumptions. It is reasonable that small occurrences can be unknown or neglected in the exploration of the good old days. From this point of view it can be of interest to study the expected outcome of deep seated deposits from a drilling campaign if we have a greater share of small ore bodies.

To study this question, the distributions of the length of big and short axes of the ore ellipsoid were modified. These two distribution functions control the size of ore bodies. The length of the medium axis is obtained from that of the big axis via the distribution of the quotient between the two axes. This distribution is not changed. Figure 25 shows the distribution functions for the Skellefte field distribution, A, and the two modifications, B and C, that have been studied.

The modifications imply that the share of small ore bodies is increased. The first modified distribution is described in detail in a previous paper, K Malmqvist, (1979) and has a moderate increase of small deposits. The second modification is designed with an extremely increased number of small ore bodies. Figure 26 shows the frequencies of tonnage for the three size distributions defined. The share of big (> 4 Mton) ore bodies is 8.4%, 7.4% and 3.1% respectively.
The simulation experiments were repeated under the variation of distributed ore from 40 to 100 Mton stepped by 20 Mtons. This study was performed at the uniform model only. The drilling pattern was the rectangular grid of 40 holes with an initial dip angle of 75°. All the holes were drilled in a northern direction to a vertical depth of 1 000 meters.

The least square fitted lines from the three experiments are shown in Figure 27. The amount of hit ore from big deep seated deposits should decrease slightly with increasing share of small ore bodies. Unfortunately, the errors are too large to allow any conclusion from the experimental results. On the contrary, the amount of total hit ore increases with increasing share of small deposits. This result is statistical significant and seems reasonable. The reason is that the total projected area becomes larger when the share of small deposits increases since the average thickness of the bodies is smaller.

Figure 28 shows the result expressed as the probability for hitting one ore body when drilling one hole to a depth level of 1 000 meters. In this figure the tendency from Figure 27 is even more pronounced.

In Figure 29, finally, the quotient between the number of hit small deep seated deposits and the total number of hit deposits is presented for the three distributions. Here we see that the probability of hitting a small, uneconomic deposit with a borehole increases with increasing share of small deposits.

The variation in the amount of struck ore in repeated simulations depends on two things. The first thing is the random process that is used when the ore bodies are located in the block and the other thing is the random size distribution for a set of ore bodies. To study this problem the following simulation experiment was performed. The results from 500 simulated drilling campaigns were grouped according to the number of big ore bodies that was distributed in each simulation. The mean value and standard deviation of the number of struck ore bodies and of the amount of struck ore
were calculated for each group. The total amount of distributed ore was 80 Mton, the number of drillholes was 40 and the depth of investigation was 1 000 m.

The average number of struck bodies was 1 with a standard deviation of 1 body and the average amount of struck ore was about 3.5 Mton with a standard deviation of about 4 Mton. This was valid for all groups and independent of the number of big ore bodies distributed in the block.

This study also gave as a result, that in exploration campaigns of the order of 40 drillholes to a depth of 1000 m performed on the uniform bedrock model, at least one deep seated large body should be found in 25% of the exploration campaigns.
10. THE EFFECT OF CLUSTERING TENDENCY

A detailed study of the locations of ore body centres in the Skellefte field indicates that there exists a tendency of clustering. In order to study if such a clustering tendency would have any significant effect on the expected outcome, the uniform bedrock model is modified to handle this situation. The model is called the cluster model.

The clustering tendency parameters in the bedrock model is described in a previous paper, K Malmqvist, (1979). They are the angle ($\beta$) between the x-axis of the investigation block and the main u-axis of the cluster, the standard deviation ($\sigma_u, \sigma_v, \sigma_z$), of the multivariate normal distribution of the cluster members, the maximum number of ore bodies ($q$) in a cluster and finally the frequency of clusters ($f_{c_1}, ..., f_{c_q}$) containing 1,..., $q$ ore bodies.

In this particular cluster model we have chosen the following parameter values: $\beta = 15^\circ$, ($\sigma_u, \sigma_v, \sigma_z$) = (1000, 500, 300), $q = 4$ and ($f_{c_1}, ..., f_{c_4}$) = (0.2, 0.4, 0.2, 0.2).

The following series of simulation experiments were carried out. In each of them the amount of ore within the investigation block was varied from 40 to 140 Mton stepped by 20 Mton.

The first serie uses grid drilling as defined before. The second uses "cluster-drilling" campaigns. This is a grid-drilling with the additional rule that when you get a hit, you relocate 2 holes from the "end" of the drilling pattern to each side of the successful hole. The coordinates of the starting points of the new holes are $(x_{\pm} \sigma_u/2, y - \sigma_v \cdot 2/5)$ where $x$ and $y$ correspond to the successful hole. This can be regarded as an evolution of the grid drilling pattern in such a way, that you make use of your knowledge of the clustering tendency.
The result in Figure 30 shows that, if cluster-drilling is used, the expected outcome is somewhat increased for low ore intensities, but obviously decreased for high ore intensities within the investigation block. A possible explanation might be, that with high ore intensity, also the number of ore bodies is high, so the location procedure overrides the tendency of clustering. In this case there probably are several hits in every drilling campaign. With the cluster-drilling strategy each hit means 2 less holes at the end of the drilling campaign, which in turn means that a big area remains un-investigated.
11. DISCUSSION

The objective of this method is to extrapolate the knowledge about the mineralizations and the geology in a mining district under certain assumptions to a deeper bedrock block than that, which is possible to explore with traditional exploration methods. From this model of the bedrock block it is then possible to perform simulations of exploration campaigns and study the outcome for different strategies, under different assumptions about the bedrock geology and about the statistical properties of the economical targets distributed in the block.

It must be underlined that the results which comes out from the simulation experiments only reflect the preassumptions given to the model. It is a mapping of various knowledge in terms of exploration results, the outcome. Consequently, a result is neither better than the quality of the original data, nor better than the degree of good judgement with which the data have been applied to the problem.

The method has to be used by experienced prospectors as a guidance in the very complex situations coming up in future exploration for deep seated massive sulphides.

In a first paper, K Malmqvist et al (1976, 1979), we introduced the concepts of the method and gave some examples from the application of the method to a certain block in the Skellefte field. To simplify the situation a uniform bedrock model was chosen. It was concluded that the flexibility of the model must be increased to permit a better fit to true geological conditions.

The uniform model means that the possibility to find an ore center is the same all over the block. This is obviously not true. From the prospectors point of view the outcome from such a model can be regarded as a lower limit of a reasonable result, since no knowledge about the ore potential in different rock types of the block has been used.
In a mining district there often are good geological models of the ore genesis and the ore potential of different rock types. In the case of stratabound mineralizations, predictions about the spatial ore potential can be done which anyhow certainly is closer to reality than the assumption of a uniform ore potential.

The purpose of these simulation experiments is to study the influence on the outcome when more absolute information about the bedrock geology is introduced to the model. In this paper two more complex models have been studied.

The most advanced model represents absolute knowledge, which certainly is an overestimate of the reality. From the prospectors point of view the outcome, in some sense, can be regarded as an upper limit of a probable outcome. In this way it should also be possible to put reasonable limits of the outcome, based on the prospectors subjective conception of the geological situation.

The calibration of the models

If the simulation is performed with a very wellknown mining area as the object, there is a possibility to calibrate the model to the known properties in the bedrock surface as given in Chapter 3.

In the Udden-Åsen area there are 2 large surficial ore bodies and another 6 smaller deposits. The simulation down to 1 000 meters depth predicts a total ore content of around 80 Mton in the block. At that ore intensity the simulation model gave 13 outcropping bodies, 2 of them greater than 4 Mton.

Of greater interest is, however, that the block then from the statistical point of view, gives room for another 5 deep seated bodies bigger than 4 Mton. It is of interest to notice that 2 of them should on the average have an ore value exceeding 150 S.kr./ton. It must again be underlined that this outcome is of statistical
character and does not guarantee anything in the single case. An investigation of the statistical distribution shows, however, that the probability is 0.95 that the number of big ore bodies in the block lies between 4 and 10 if the total amount of ore in the block is 80 Mton.

The outcome as a function of ore intensity and the bedrock model

As found from the results given in Figure 4, there exists a good linearity between ore intensities and outcome for all bedrock models.

Of certain interest is, however, to study the outcome as a function of the bedrock model. In Figure 31 the amount of struck deep seated ore greater than 4 Mton per drilled meter and the number of them are plotted for the different bedrock models. The plot has been made for an ore intensity of 80 Mton total tonnage and for 1 350 m long drillholes down to 1 000 m depth level.

From the result it is seen that the outcome in tonnage is doubled from the uniform model to the shale-granite model. In the shale-granite model the areas of high ore potential is very much restricted. In spite of that the outcome is only doubled. The possible reason is that the long deep boreholes physically exhaust a large volume of rock especially from the point of view of large tabular bodies.

It can also be noted that a possible outcome with unrestricted ore value is of the order of 50 tons per meter drillhole. The possible variation with respect to lack of knowledge of bedrock geology lies in the order of ± 25 Mton. That is the case in the mean, if the desired large targets are hit.

From these results it is obvious that the outcome is only little influenced by an increased knowledge of the details in the 3-dimensional geology. Consequently, detailed geological
mapping is of less importance. The efforts should be focused on the large structures of the block.

It can also be of interest to consider the number of hit large deep seated bodies, which gives an idea of the possibilities to hit one target. This is also shown in Figure 31.

The possibility to find one target is also doubled, approximately, between bedrock model I and III. The consequence, with all the reservations from the last paragraph, is that you have in the mean to drill about 100 boreholes to be able to hit one deep seated deposit larger than 4 Mton. Also in this case a detailed knowledge of the geology has only a marginal effect on the outcome.

**The outcome as a function of optimum depth of investigation**

In Chapter 5 the relation between the expected outcome and the optimum depth of investigation has been presented for the three different bedrock models.

The average amount of ore per unit cost of drilling for the three bedrock models is shown in Figure 32. These curves are quite different for the three models. It is obvious that the comparison between the average outcome per meter borehole for full length holes, Figure 31, disregards the fact that outcome per unit cost has a maximum for the more advanced models.

If we use the knowledge of the optimal depth of investigation and stop drilling at that depth, the optimal average outcome per unit cost for large deep seated bodies is much improved compared to the cost-efficiency for drilling down to the level of 1 000 m, as shown in Figure 31.
The dependence on the model is from this optimal cost-efficiency point of view significant. Compared to the outcome from the two specified bedrock models II and III a decrease of outcome happens in the uniform model I. The outcome seems to be very similar in the two specified models.

One conclusion from this optimization is, that if you are able to get a general idea of the large structures down to say a depth of 1000 m, it is possible to optimize the depth of investigation. This is an important step in a deep exploration project, since it can improve the cost-benefit relation by a factor of 2.

Of some interest can be to compare the contributions from large surficial and large deep seated bodies as a function of depth. In Figure 13 this has been done for all three bedrock models. In this case no differences occur between the different models. This is reasonable since this basically is a consequence of the assumption that ore content is independent of depth. The different bedrock models only take into account lateral changes in the ore intensity.

However, if these assumptions are accepted, it is obvious from Figure 13 that the share of new deep deposits successively increases with increasing depth. This is a consequence of the fact that the surficial deposits attenuate with depth and the fact that deep seated deposits in the mean are larger than surficial bodies, since surficial bodies are more or less decaputated by erosion.

From Figure 13 it is also clear, that exploration for large deep seated deposits between the ground and a depth of around 200 m is inefficient, since there is very little to find. The depth interval of 500-700 m which appears from other simulation experiments as optimal, seems to be reasonable also from this point of view.
The influence from different minimum ore value criteria

In a real situation we only have to consider an optimal depth of investigation but also the fact, that the expenditures for exploration and mining increase with depth.

To investigate the impact of different requirements on the ore value at different depth of the top of the body, three simulation experiments have been carried out. In the Figure 18 the results are given for the uniform bedrock model.

In Figure 33 the average amounts of ore per unit cost (S. kr.) as a function of depth are put together. The three curves represent no restriction on the ore value and two different restrictions with increasing minimum ore value.

When these restrictions have been applied, also the uniform model gives a maximum in outcome as a function of depth around the 800 m level.

At the top of Figure 33 the average outcomes for the three ore value profiles are plotted. The increased requirements on ore value decrease the average outcome considerably. For the uniform model with no restriction this experiment gives about 110 kg ore per S. kr, which however decreases to 30 kg ore per S. kr for the hardest requirements on the ore value.

However, the situation can be somewhat improved as shown in Figure 33 if the holes are interrupted at the depth of maximum outcome. The improvements are around 50 %. With the hardest restriction on the ore value the expected outcome is 50 kg ore per S. kr.

The same experiments are performed on the shale model. The results are given in Figure 34. Compared to the uniform model, the restriction on the minimum accepted ore value influences the result somewhat harder. The expected outcome decreases from 280 kg ore per S. kr to 120 kg ore per S. kr with optimal depth of investigation.
The influence from the size distribution of ore bodies

Often the parameters which are parts of the model are not fully known. In that situation it can be of interest to study the influence on the outcome from changes in the distribution function of that parameter.

In deep exploration projects large expenditures must be reserved for follow up work of ore occurrences. It is paradoxically very expensive to prove that a body is of no interest for mining operation. The more ore hits of no interest done the higher exploration costs.

One important factor from this point of view is the relative number of small mineralizations. In the observational material from which the distribution functions are calculated these small bodies might have been underrepresented. To investigate the effect from an underestimation of the number of small bodies three simulation experiments were performed under modified size-distribution functions. The results are shown in Figures 27 and 28.

From these results the relative number of hit small deep seated bodies to the total number of hit deep seated bodies were calculated. The result is shown in Figure 29. We find that 66% of all hit deep seated bodies are smaller than 4 Mton when the originally calculated Skellefte field size distribution was applied. This share increases to 76% for the moderate modification and to 82% for an extreme unlikely modification.

The conclusion is that even under great geological mistake about the share of small bodies the change in the number of potential follow up cases is moderate and less than 25%.
12. CONCLUSIONS

Simulations technique to guide exploration decisions can be a new tool for the operating prospector. The outcome under very different conditions can be studied. Under the specific conditions of the well known Skellefte field we have found that it should be possible to even calibrate the mathematical model.

As a base it is found that also under conditions when we do not know the geology in details an outcome of the order of 50 tons per meter drillhole should be hit under very simple drilling strategies.

If a certain knowledge about the general structures down to around 1 000 m can be established, it seems possible to improve the drilling strategy and to optimize the depth of investigation. This lies in the range 500-600 m below ground. The improvements seem to be able to increase the outcome with a factor of about 2.

However, all large deep seated bodies can not be mined because their low grades. If a certain criteria of mining minimum ore values is introduced as a function of depth, the outcome will again decrease by a factor of about 3. But if carefully treated, this can be marginally improved by choosing a reasonable optimum depth of investigation.

We have to underline that these results have a statistical character and do not say anything about the outcome in the single exploration case. However, faced to the problem whether to go or not to go into the deep exploration phase, this kind of technique helps to analyze the problems and can give a general idea about the order of costs and benefits.

Going into a deep exploration project means a great economical risk in the single case. However, if the risk seems be at a reasonable level the financing of a whole program must be worked out. If so, then only the personal courage of the prospectors remains to be mobilized.
ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

1a The uniform bedrock model with drilling pattern.

b The shale bedrock model with relative ore intensity function and drilling pattern

c The shale - granite bedrock model with relative ore intensity function and drilling pattern

Calibration of the simulation model by comparison with reality

3 Validation of the simulation model by comparison with theoretically calculations of probability

Expected outcome as amount of struck ore per drillhole as a function of both the amount of ore in the bedrock block and of the bedrock model. The depth of investigation is 1 000 m.

Same as 4, but the expected outcome is expressed as number of struck ore bodies per drillhole

Expected outcome per drillhole as a function of the depth of investigation. The uniform model with the total amount of ore in the bedrock block = 80 Mton

Expected outcome per drilled meter and per unit cost as a function of the depth of investigation. The uniform model with a total amount of ore = 80 Mton

Average cost per drilled meter as a function of the depth of investigation. Dip angle = 75°

Same as 6 and 7 but for the shale model

Same as 6 and 7 but for the shale-granite model
13 The quotient between struck deep seated ores > 4 Mton and struck ores > 4 Mton as a function of the depth of investigation

14 Expected outcome per drillhole as a function of minimum accepted ore value. The uniform model with the total amount of ore = 60 Mton and 100 Mton respectively. The depth of investigation = 1 000 m

15 Same as 14 but for the shale model

16 Same as 14 but for the shale-granite model

17 Frequency and distribution functions for ore value

18 Expected outcome per drillhole with restrictions on ore value depending on depth as a function of depth of investigation. The uniform model with the total amount of ore = 80 Mton

19 The expected outcome in Figure 18 is expressed per drilled meter and per unit cost

20 Same as 18 and 19 for the shale model

21 Average curvature of drillholes for different dip angles

22 Expected outcome per drillhole and per drilled meter as a function of dip angle of boreholes. The uniform model. Total amount of ore = 80 Mton. Depth of investigation = 1 000 m

23 Same as 22 but for the shale model

24 Modified distribution functions for the lengths of big and shortest axes of ore ellipsoid
26 Frequencies of size of ore bodies for the three different size distributions defined

27 Expected outcome as amount of struck ore per drillhole as a function of total amount of ore in the bedrock block for the three size distributions. Depth of investigation $= 1000$ m

28 The expressed outcome in Figure 27 is expressed as probability of hitting at least one ore body when drilling 1 hole

29 The quotient between small deep seated ores and all deep seated ores as a function of total amount of ore in the bedrock block for the three different size distributions

30 Expected outcome per drillhole as a function of total amount of ore in the uniform bedrock model with a tendency for clustering

31 Comparison between the expected outcome for different bedrock models. Total amount of ore $= 80$ Mton. Depth of investigation $= 1000$ m

32 Increase in expected outcome when optimizing the depth of investigation for different bedrock models. Total amount of ore $= 80$ Mton

33 Effect of ore value restrictions and optimization of depth of investigation. The uniform model. Total amount of ore $= 80$ Mton

34 Same as 33 but for the shale model
Figure 1a. The uniform bedrock model
Figure 1b. The shale model.
Figure 1c. The shale-granite model.
<table>
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<tr>
<th>Amount of ore (Mton)</th>
<th>Average number of all deposits</th>
<th>Average number of outcropping deposits</th>
<th>Av. number of deep seated</th>
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<tr>
<td></td>
<td>&gt; 4 Mton</td>
<td>&gt; 0 Mton</td>
<td>&gt; 4 Mton</td>
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<td>reality</td>
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</tbody>
</table>

Figure 2. Calibration of the bedrock model.
Figure 3. Validation of the bedrock model.
Figure 5.
Figure 6. Uniform model.
Figure 7. Uniform model.
Figure 8.
Figure 9. Shale model.
Figure 10. Shale model.
Figure 11. Shale-granite model.
Figure 12. Shale-granite model.
Figure 13.
Figure 14. Uniform model.
Figure 15. Shale model.
Figure 16. Shale-granite model.
Figure 17. Frequency and distribution functions for ore value.
Figure 18. Uniform model with restriction on ore value depending on depth.
Figure 19. Uniform model with restriction on ore value depending on depth.
Figure 20. Shale model with restriction on ore value depending on depth.
Figure 21. Shale model with restriction on ore value depending on depth.
Figure 22. Average curvature of drillholes.
Figure 23. Uniform model.
Figure 24. Shale model.
Figure 25. Distribution functions.
Figure 26.
Figure 27.
Figure 28. Probability of striking one ore body when drilling one hole.
Figure 29.
Figure 30. Cluster model.
Figure 31. Comparison between different bedrock models.
Figure 32. Increase in expected outcome when optimizing the drilling depth for different bedrock models.
Figure 33. Effect of ore value restriction and drilling depth optimization. Uniform model.
Figure 34. Effect of ore value restriction and drilling depth optimization. Shale model.