SOME PRACTICAL ASPECTS OF ORE RESERVE ESTIMATION AT CHUQUICAMATA COPPER MINE, CHILE

Prof.D.G.KRIGE and MR.P.G.DUNN

ABSTRACT

The copper ore reserves at the Chuquicamata mine were re-estimated during March to June 1994, as part of a comprehensive audit of the mine's overall short- and long-term planning. The basic principles essential to all ore reserve estimates were implemented ,viz.:

(i) A detailed study of the geology, in this case particularly of the orientations of structural features of copper mineralisation and the subdivision of the ore body into geologically homogeneous sections,

(ii) the use of both drill- and blast-hole data sets,

(iii) statistical and geostatistical analyses of both data sets to model anisotropic spatial structures for.all the geologically homogeneous sections,

(iv) block kriging using both data sets individually, and

(v) a comprehensive validation of the block valuations to confirm ***the absence of global and conditional biases and to quantify the actual improvement achieved in the overall quality of the estimates*** compared to those executed on earlier techniques.

INTRODUCTION

The world famous Chuquicamata porphyry copper deposit is in northern Chile, roughly 1300 kilometers north of Santiago and 240 kilometers from the coast at Antofagasta as shown on ***Figure 1***. It is in the Atacama desert at an elevation of 2800 meters.

Open pit mining started at Chuquicamata in 1915 with the exploitation of high grade oxide copper ore which formed through oxidation of an earlier

supergene enrichment blanket. Current production comes principally from enriched sulphide ore at a daily rate of l54000 tons of ore. The present pit is oval in shape with a long N-S axis of some 4.5kms, a short E-W axis of 2.5kms and a depth of about 800m.

The average head grades have been declining rapidly for the past few years as a result of an increasing proportion of primary sulphide ore. This has not only caused the estimation of ore reserves to be more difficult, but also required that those estimates be more accurate. *A detailed geologic model of the deposit is required to provide better short term mine planning, to allow better exploration within the deposit and to ensure a higher standard of ore reserve estimates*.

The mine's previous ore reserves (1991), were based on geostatistical techniques but did not incorporate anisotropical spatial features associated with the structural geological model now developed for the copper mineralisation. The search routine for the block valuations on ordinary kriging was also somewhat restricted and resulted in some remaining conditional biases. Furthermore, in line with all previous ore reserve estimates, only drill-hole data were used. A preliminary ore reserve update on the same general basis was carried out by the mine early in 1994 but, in view of the comprehensive mine audit which highlighted the need for a re-examination of the ore reserve techniques used, the whole ore reserve framework was reviewed. This led to a request for a recalculation of the ore reserves and the incorporation of all available geological and geostatistical information and models.

GEOLOGICAL

General: As with all ore reserve estimations, *a thorough understanding of the geology is essential, including a practical model of the mineralisation structures, and the definition of the various ore types present*. This will ensure that the geostatistical analyses and valuations are carried out within defined geologically homogeneous zones , so as to avoid obvious nonstationarity , and that significant mineralisation structures are modelled

geostatistically and used in the valuation process. The serious dangers of ignoring relevant geological information are wellknown but were again stressed in a recent paper (Krige,1994).

The entire Chuquicamata orebody occurs in an intrusive Tertiary granodiorite complex known as the Chuquicamata porphyries. This lithologic unit has been divided into three different rock types on the basis of *texture*, but there appears to be no significant change in copper grades, at least in the supergene zone, related to these textural changes.

The ***mineralisation*** is abruptly terminated to the west by the West Fault, which juxtaposes the Chuquicamata porphyries with the barren Fortuna granodiorite, the latter being similar in age and composition to the mineralised intrusive. The West Fault is part of a major regional structural feature that can be easily traced for at least 600 kilometers north and south of Chuquicamata from 20°S to 26°S latitude. It appears to have controlled the emplacement of many of the porphyry deposits in northern Chile such as Escondida and Zaldivar to the south, and El Abra and the Quebrada Blanca-Collahuasi district to the north of Chuquicamata.

The West Fault has had a complicated structural history***. A detailed structural analysis*** indicates that the early displacement along the fault was right-lateral, with subsequent left-lateral displacement. The total amount of displacement is unknown, but the recent discovery of the Mansa Mina deposit south of the present pit and west of the fault suggests that approx. 12 kms. of left-lateral displacement occurred since the early period of mineralisation. This tectonic deformation has been an important factor in the formation of the Chuquicamata deposit.

An early stage of mineralisation formed typical disseminated pyrite, chalcopyrite and bornite associated with potassic and propylitic silicate alteration. A series of late stage veins was then superimposed on this typical porphyry copper mineralisation. These range from early quartz-molybdenite veins to late enargite veins that contributed a great deal of the copper that was subsequently leached and redeposited as chalcocite and covelite in the supergene enrichment blanket. These late-stage veins occur within a zone of

strong sericite alteration.immediately east of the West Fault. This zone strikes roughly parallel to the fault and is up to 500m. wide.

Movement in this zone along the West Fault occurred during this late stage of mineralisation and resulted in a complicated fault pattern within the Chuquicamata porphyries. Two sets of prominent faults formed; one set strikes N10°E to N20°E, roughly parallel to the West Fault, and the other has strikes ranging between N60°E and N90°E . Movement along these faults, in turn, formed numerous smaller structures resulting in the complicated overall fault pattern shown in a simplified form.on ***Fig.2***.

These structures were important in controlling not only the emplacement of the late-stage veins, but also the channels of the subsequent supergene solutions. *The orientation of these structures and the location of the strong late-stage veins, marked by the sericite alteration zone, therefore are the principal geologic factors that needed to be considered in the geostatistical treatment of the assay data used for the reserve estimates*.

Geological Coding: The ore body is divided primarily into leached, oxidised, secondary and primary ores with subdivisions of the latter two into sericitic, potassic and propylitic ores. In the secondary ore there are further subdivisions into chalcocite, chalcocite-covelite and covelite for sericitic, potassic and propylitic ores. A total of 14 ore types are listed and the analytical data as well as all the standard ore blocks are coded accordingly. For the ore blocks the boundaries of the different codes are interpolated from regular E-W sections through the ore body. These estimated boundaries have to be updated regularly as more information becomes available so as to avoid misclassification and hence biased valuations of ore blocks at or near these boundaries.

Structural Geology: The geostatistical estimation of the copper ore reserves depends primarily on the mathematical definition of a model of the structure of the mineralisation, i.e. mainly the continuity of grades in various directions. It is obvious that this process can be assisted substantially by first modelling on a geological basis the structures correlated with the mineralisation. The proposed structural model based on the analyses outlined above is depicted in ***Fig. 3.*** The ore body is subdivided into 3 main

zones. Zone 1 corresponds essentially to the strong sericite alteration zone. Zones 2 and 3 cover both potassic and propylitic ores. Zones 1 and 2 have strong vertical structural features striking N10°E to N20°E , particularly in the primary ores, whereas structural directions in Zone 3 are not as clearly orientated. For structural purposes the potassic and propylitic ores have been combined because of a somewhat vague border between them and no significant differences in main structures. The geostatistical modelling of the mineralisation was consequently effected on the basis of this geological model. ***The results validated this geological model remarkably well.***

GEOSTATISTICAL MODELLING:

Drill-hole Data: The present data base covers 13 meter composites. Detailed semivariogram analyses were effected for each of the three structural zones and for each of the main geological codes, i.e. primary ore (sericitic, potassic and propylitic), secondary ore (sericitic, potassic and propylitic), oxidised ore and leached ore. Composites of less than 6.5m in length were omitted for this analysis.

Previous ore reserve schemes used subdivisions based on geological codes, but did not consider the structural zones and the anisotropies were not modelled. For the new analysis, exponential semivariograms were modelled for the individual geological codes within each of the three structural zones. The final models provided firstly, better fits to the data than the spherical models used in the earlier reserve schemes and, secondly, better definitions of the strong anisotropies associated with the geological structures.

The anisotropies defined on drill-hole composites for zones 1 and 2 agreed in direction exactly with the structural geological model suggested and were observed for all the main ore types. In zone 3 most of the models were isotropic with a few weak anisotropies not consistent in direction.

Blasthole Data: The blasthole data base covers results generally from 26m holes and ,for practical reasons, these have been averaged into 20m x 20m blocks for every bench. These block values can all be used for valuation purposes, but for semivariogram analyses only those blocks with at least 4

holes were used. The results of these variogram analyses complement the drill-hole analyses covered above. On the whole, the blasthole data show somewhat lower nugget effects (i.e. variability at zero lag distance) and longer ranges.

A typical set of blasthole variograms for secondary sericitic ore in Zone 1 is shown in ***Fig. 4*** *The blasthole data confirmed exactly the anisotropical directions shown by the drillhole data for zones 1 and. 2*,as well as no obvious preferred direction within the vertical structures of mineralisation .For zone 3 the blasthole variograms differed from those based on the drillholes in that ***the N20°E direction of mineralisation so pertinent in zones 1 and 2 was found to extend into zone 3 as well***.Furthermore this was found to apply to the primary, secondary and leached ores as well, the data for oxidised ore being inadequate. The difference between drill- and blast-hole anisotopies for zone 3 is probably due to the difference in sizes of the data supports, i.e. between small drill-hole cores and the much larger blasthole blocks of 20mx20mx26m. The latter can be expected to eliminate small scale noise and to yield more reliable estimates of anisotropical features on a scale relevant for selective mining purposes. ***The overall geostatistical evidence is that of strong directional mineralisation along vertical structures striking about N15°E and confirm that the structural geological model.for zones 1 and 2 appears to be more regional, as it also extends into zone 3 and applies to all the ore types***.

BLOCK VALUATIONS

Integrating Drillhole and Blasthole Data: *The practice of not using blasthole data for routine ore reserve valuations cannot be justified*. The blasthole database is very extensive and is in any case used in practice for final selective mining purposes between and within mining blocks. The

valuation of blocks on and close to the pit face can obviously be improved significantly by using blasthole data from nearby drilled and mined-out blocks in addition to the widely spaced drillhole data used exclusively in the past. The ideal basis on which to integrate blast- and drill-hole data is via ***co-kriging,*** not catered for in the mine's present software facilities. An interim practical approach was, therefore, proposed on the following basis:

(i) Value all blocks on drillhole data.

(ii) Value the blocks on blasthole data.

(iii) Combine the two estimates on weights inversely proportional to the calculated kriging variances.

Drillhole Estimates: Ordinary kriging was used throughout and only data from the relevant structural zone and geological code was used for a block valuation. Search radii of the order of 400m were used, i.e.substantially longer than in previous estimates and the observed anisotropies were incorporated. The search routine was also changed to allow the access of up to 8 composites from any one borehole (4 previously) and up to a total of 36 composites (16 previously).

Validation of the block estimates is required to confirm the absence of overall and conditional biases and to measure and compare the qualities of alternative estimates. The serious effects of conditional biases on tonnage-grade curves, grade control, mine planning and on potential profits when selective mining is practised, were demonstrated clearly in a recent paper (Krige, 1994).

Comparisons with the 1994 preliminary estimates and validations were effected in respect of all mined out blocks covering the mine's lowest 16 benches. A total of 4666 blocks were available on this basis across all the structural zones and geological codes. The results of the preliminary estimates and of the re-run of the drillhole block valuations on the anisotropic model are shown on ***Figs.5 and 6*** respectively for all zones and codes combined. For reasons of confidentiality the grade scales are coded. The block estimates (Cu%) are plotted on the X-axis and the corresponding follow-up blasthole block values on the Y-axis. The means (Cu %) of the drillhole block estimates (X) and the corresponding blasthole values (Y) are effectively

identical (percentage difference 0.2) indicating ***no global bias*** between drillhole and blasthole values. Ideally, if no conditional biases are evident, the average trend of the follow-up values should plot along the 45° line (i.e. the slope of the regression line of Y on X should be unity). In this case, the trends plot close to the 45° line with slopes of 0.98 and 1.006 respectively.

The block distributions are both skew and hence subject to a proportional effect. This is evident from the spread of data vertically either side of the regression lines with the spread increasing for the higher grade categories. Errors of estimation are, therefore, better assessed with a proper lognormal transformation, in this case to Ln(grade+0.4), as shown on ***Fig. 7***.for the new anisotropic estimates. The proportional effect has been eliminated by the transformation and the error variances of the estimates for the different schemes are, therefore, best compared on this basis.

The results for the preliminary 1994 reserves(Fig.5), which took no account of the geological structures and did not model the associated anisotropies, appear to be similar to the new estimates(Fig. 6). However, the correlation coefficient for the new reserve is higher than for the preliminary estimates. Also, the slopes of the regression lines for the new estimates are closer to unity than for the preliminary estimates with a ***consequential effective absence of conditional biases*** (see ***Table 1***).

The calculated variances of the differences between the estimates (X) and the corresponding follow-up values (Y) provide a measure of ***the observed error variances of the estimates.*** Compared to the preliminary estimates the new estimates show a reduction in error variance of some 14.5%(Table1).

Blasthole Estimates: The same general procedures were used as for the drillhole estimates but to ensure proper validation only blasthole data from mined out ground above the lowest 16 benches were used for this purpose. The search routine was limited to 12 data blocks. This was not ideal as some conditional biases were still evident. However, as the final objective was to combine the blasthole and drillhole estimates for a broad fringe around the present pit face, the combined estimates were calculated and validated against the mined-out blocks covering the 16 lowest benches.

Combined Estimates: The correlation of the combined estimates with the follow-up data is shown in ***Fig. 8*** for the logtransformed values. A significant further improvement is evident compared to the drillhole estimates(Fig. 7). *More than half of the overall improvement relative to the preliminary 1994 estimates is due to the introduction of blasthole data and the balance can be attributed to the introduction of the geological structures,the associated anisotropies and the better search routine. The absence of conditional biases is also clear.*

CONCLUSIONS

The improvements in ore reserve valuations due to:

(i) the introduction of a structural geological model and the corresponding anisotropical variograms as well as an expanded routine for kriging and

(ii) the introduction of blasthole data with anisotropical spatial structures similar to those for the drillhole data,

are summarised in ***Table 1***.

All three criteria used, i.e. the level of correlation between estimates and follow-ups, the observed error variances, and the slopes of the regression lines confirm the significant advantages gained. ***The best measure, i.e. the error variance, shows an average improvement of nearly 30% for all geological codes, which is very significant in the absence of conditional biases.*** Similarly the improvements for the secondary sericitic and potassic codes are about 25% and over 50% respectively. More than half of the overall improvement is due to the introduction of blasthole data and the balance to the structural model and the associated anisotropic geostatistical models. There is still evidence of some conditional biases for secondary potassic ore, and this is likely to be eliminated only after geological recoding and/or further changes to the search routine. The remaining biases are,

however, small and are substantially lower on the combined basis as compared to the preliminary estimates(isotropic) and the new drillhole estimates(anisotropic).

When a ***co-kriging procedure*** is introduced, further overall improvements, but of a relatively lower order, are expected.

Final Selection above a Cut-off: For purposes of selective mining decisions at the stage when a block has been drilled for blasting, similar advantages will be gained by updating:

(i) the combined kriged or co-kriged estimate for the block, and,

(ii) where necessary , effecting combined or co-kriged estimates of subdivisions of the block following semivariogram analyses of the blasthole data for such smaller support sizes.

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REFERENCE

Krige,D G,1994. An analysis of some essential basic tenets of geostatistics not always practised in ore valuations, *Proceedings, First Regional APCOM Symposium, Slovenia, June 1994 ,pp 15/25.*

NB: All 7 figures are to be scanned from the published paper.