MEDIAN INDICATOR KRIGING - A CASE STUDY IN IRON ORE

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Abstract

The iron ore deposits of the Pilbara region in Western Australia have some unique characteristics requiring advanced geological block modelling solutions. Iron ore grade estimation commonly involves a suite of chemical variables. With Hamersley Iron's strong focus on across-site blending to precise customer requirements, it is important that all grade variables are estimated accurately.

In this case study, the 84 East deposit is examined at the Channar mine site, east of Paraburdoo. This deposit was originally estimated by inverse distance techniques. After two years of mining, the deposit has recently been remodelled using ordinary kriging and median indicator kriging.

The grade distributions of Fe and SiO_2 observed in the 84 East deposit are bimodal, as a consequence of the geological nature of iron ore mineralisation. The distributions of the contaminants Al_2O_3, P and LOI are positively skewed. Median indicator kriging was applied, using two medians to represent the ore and BIF populations, to try to improve the estimates of Fe and SiO_2 in the geological block model.

A comparison is made between the results of inverse distance, ordinary kriged and median indicator kriged grade estimates. Each method has a different effect on geological block model grade distributions and local grade estimates.

Key Words: *iron ore, geological block model, geostatistics, grade distributions, non-linear estimation, mining, median indicator kriging, ordinary kriging, bimodal.*

Introduction

Hamersley Iron Pty. Ltd. (Hamersley) currently operates six open cut iron ore mines in the Pilbara region of Western Australia. With the exception of Hamersley's newest development, Yandicoogina, the other five mines plan as one mine to produce blended ore. These include the Mount Tom Price, Paraburdoo, Channar, Marandoo and Brockman mining operations. Two products, lump and fines, are sold to customers at the port of Dampier. Each product must be blended to stringent grade specifications to meet customer requirements. The quality of each product is controlled on six chemical variables - Fe, SiO_2, Al_2O_3, P, Mn and Loss On Ignition (LOI) - and a number of physical ore characteristics.

The geological block models for each deposit are fundamental to good mine planning and sound resource estimation. For the purposes of this paper, the term "geological block model" refers to a computer-generated block model of an ore deposit, in which each block contains information about the geology, grade, tonnage, density and dimensions of that block in space. The aim of these geological block models is to provide estimates of grade and tonnage for mine planning and mineral resource reporting purposes. These estimates are used for different purposes: global resource estimates, strategic mine planning, whole-of-life mine plans, long-term and short-term mine planning and grade control. It is important to use an unbiased estimation method which can provide a cost-effective, fit-for-purpose grade and tonnage estimate. By providing the best estimate, mining costs can be decreased by minimising the need for unplanned digging.

In this case study, the 84 East deposit is examined at the Channar mine site, east of Paraburdoo (Figures 1 and 2). This deposit was originally estimated by inverse distance grade techniques. After two years of mining, the geology was reinterpreted and the orebody remodelled using ordinary kriging and median indicator kriging.

To test the relative success of the three grade estimation methods, a comparison is made between the results of inverse distance, ordinary kriged and median indicator kriged grade estimates. This includes a comparison of input composite grade distributions with the resulting model grade distributions, and local grade estimates in each model with respect to the drillholes. These results are interpreted with a focus on the geological features of the deposit.

Geology

The Channar mining area is situated approximately 20 km southeast of the town of Paraburdoo. The 84 East deposit is one of several deposits in the Channar mining area (Figure 2) with significant identified mineral resources (Table 1).

Table 1: Mineral Resource Statement
Channar mining area deposits as at 31st December 1997.

Million tonnes	Fe %	SiO_2 %	Al_2O_3 %	P %

265	63.0	3.8	2.1	0.098

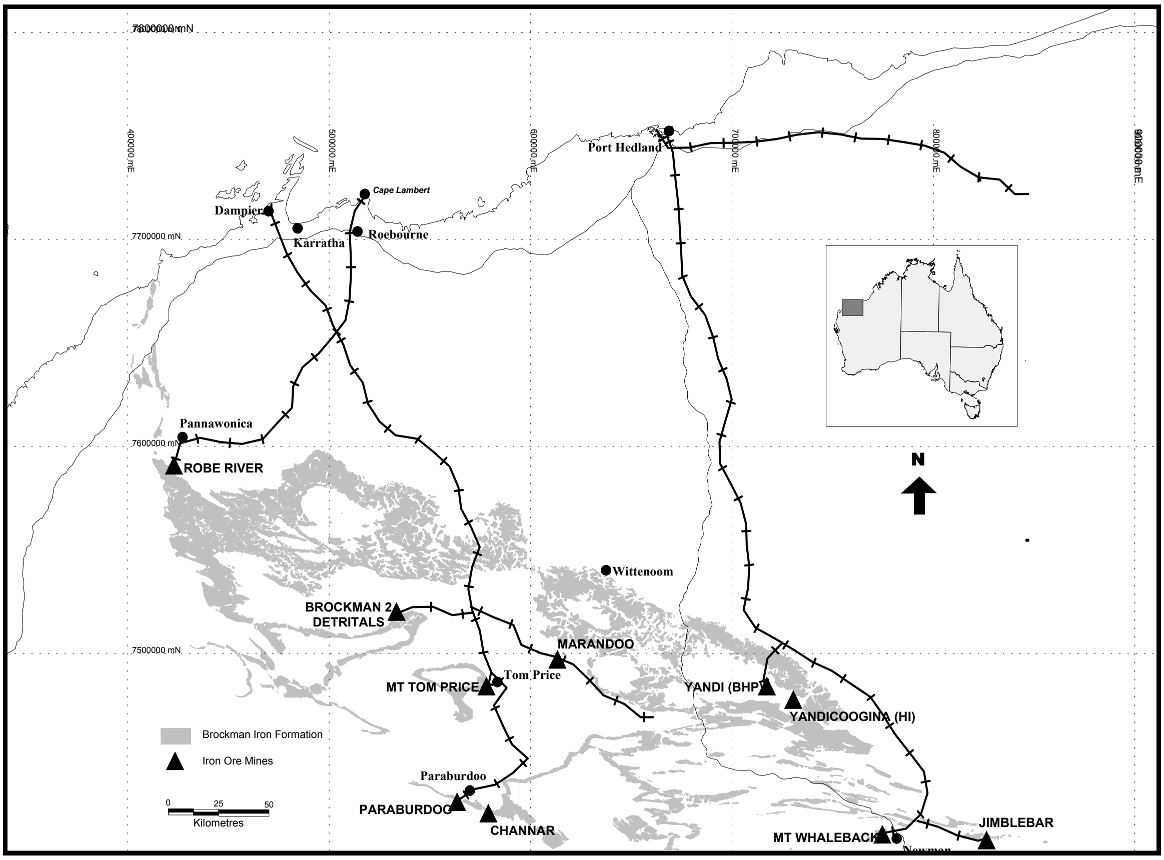


Figure 1. *Location map: Pilbara iron ore mines.*

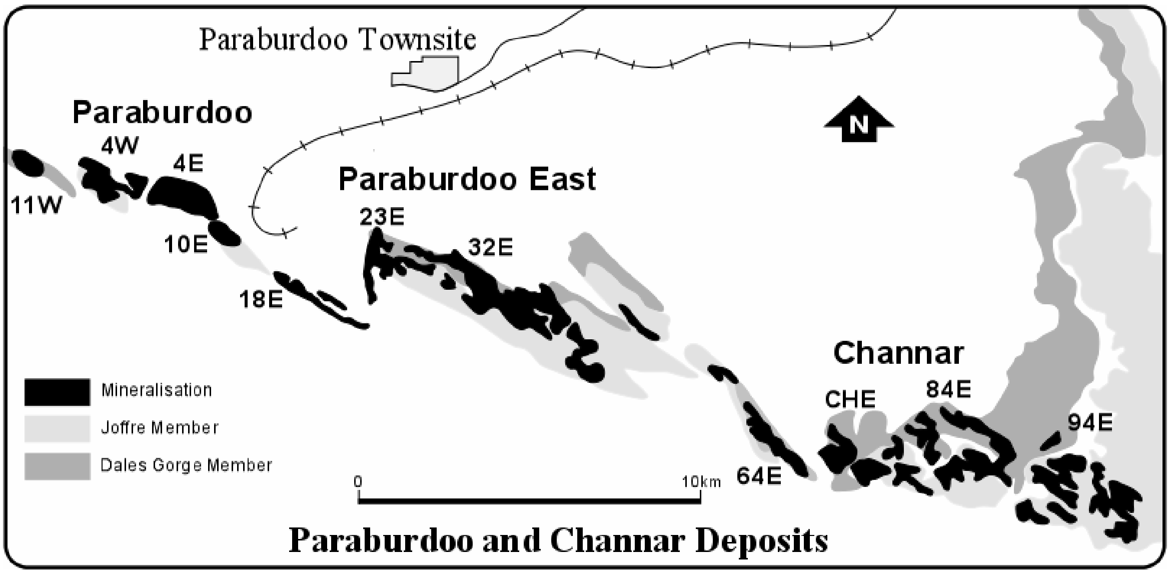


Figure 2. *Location map: Paraburdoo and Channar deposits.*

These bedded iron ore deposits are hosted in the Brockman Iron Formation of the Hamersley Group within Banded Iron Formation (BIF; Figure 3). The Hamersley Group is a sequence of BIF, shale, dolomite and acid volcanics up to 2500 m thick, intruded by dolerite dykes and sills. Geological Members contain consistent thicknesses of layered BIF or ore with continuous marker shale bands. A detailed description of the geology of the Hamersley Province and iron ores is provided in Harmsworth *et al.* (1990) and Blockley (1990). For further background information refer to discussions on iron ore geostatistics by Marechal and Srivastava (1977) and iron ore resources by Pal (1993).

Each deposit has unique grade issues and grade variability related to geology. Iron ore mineralisation occurs where BIF has become relatively enriched in iron and depleted in silica. The transition from ore to unmineralised BIF varies from a sharp contact to being gradational over tens of metres. Within the orebodies, shale bands, dolerite dykes and sills, and near-surface clays and cavities cause local increases in contaminants.

Mineralisation at the 84 East deposit is near-surface. Martite-hematite and martite-goethite ore types are predominant and the ore-BIF boundaries are gradational. Relative to Hamersley Iron's blended ore product grades, the ore is moderate to high in Fe, slightly higher in P and Mn, and moderate in Al_2O_3. Drilling density is 60m x 60m, with 1.5m downhole samples, composited to 1.75m.

The majority of the mineable ore occurs in the Joffre Member, with lesser amounts in the Dales Gorge Member and Colonial Chert Member (Figure 3). Local bedding in these geological Members dips gently (20^o) to the south with open east-west trending fold axes. The dip of the orebodies in 84 East generally reflects the dip of the beds. Minor high-angle faults and dolerites cross-cut these strands.

Each geological Member is subdivided into strands, distinguished by their relative shale content (Figure 3). Mineralisation is typically of higher purity (higher Fe with lower contaminants such as Al_2O_3, P and LOI) in those strands with lower shale content. The Joffre Member contains six strands (J1 to J6), and the Dales Gorge Member three strands (DG1 to DG3; Figure 3). The thickness of each strand is interpreted from drillhole gamma traces (Figure 3) and sample grades. In the 84 East deposit, the 430 drillholes were reinterpreted and section interpretations were compiled from drillhole and mapping information. This provided good geological control for the geological block model.

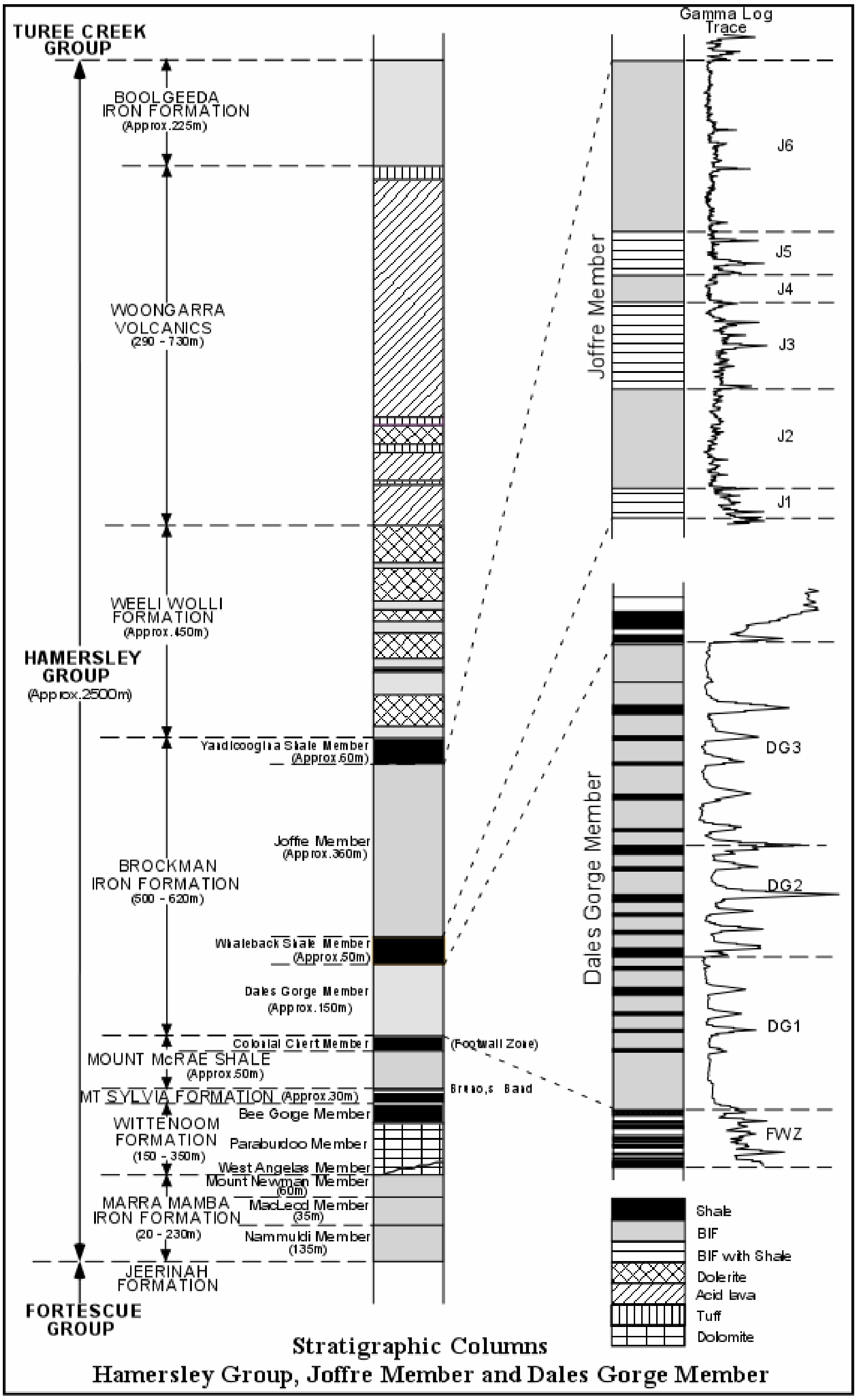


Figure 3. *Stratigraphic Columns - Hamersley Group, Joffre Member and Dales Gorge Member.*

Grade distributions

In the 84 East deposit, the distributions of Fe and SiO_2 are strongly bimodal. This is depicted in Figure 4 in the grade distribution histograms of drillhole composites from the Joffre Member. This bimodality is due to the geological nature of iron ore mineralisation: BIF contains low Fe and high SiO_2 values, whereas ore contains moderate to high Fe and low to moderate SiO_2 values. These two major populations also result in a strong inverse relationship of Fe to SiO_2.

In contrast to the bimodal distributions of Fe and SiO_2, contaminants such as Al_2O_3 and P display a single, positively skewed grade distribution (Figure 4). High Al_2O_3 and P values occur in shaly strands and clay-rich cavities. The distribution of LOI also depends on local geological controls, as LOI increases in shaly strands and in near-surface hydrated ore zones.

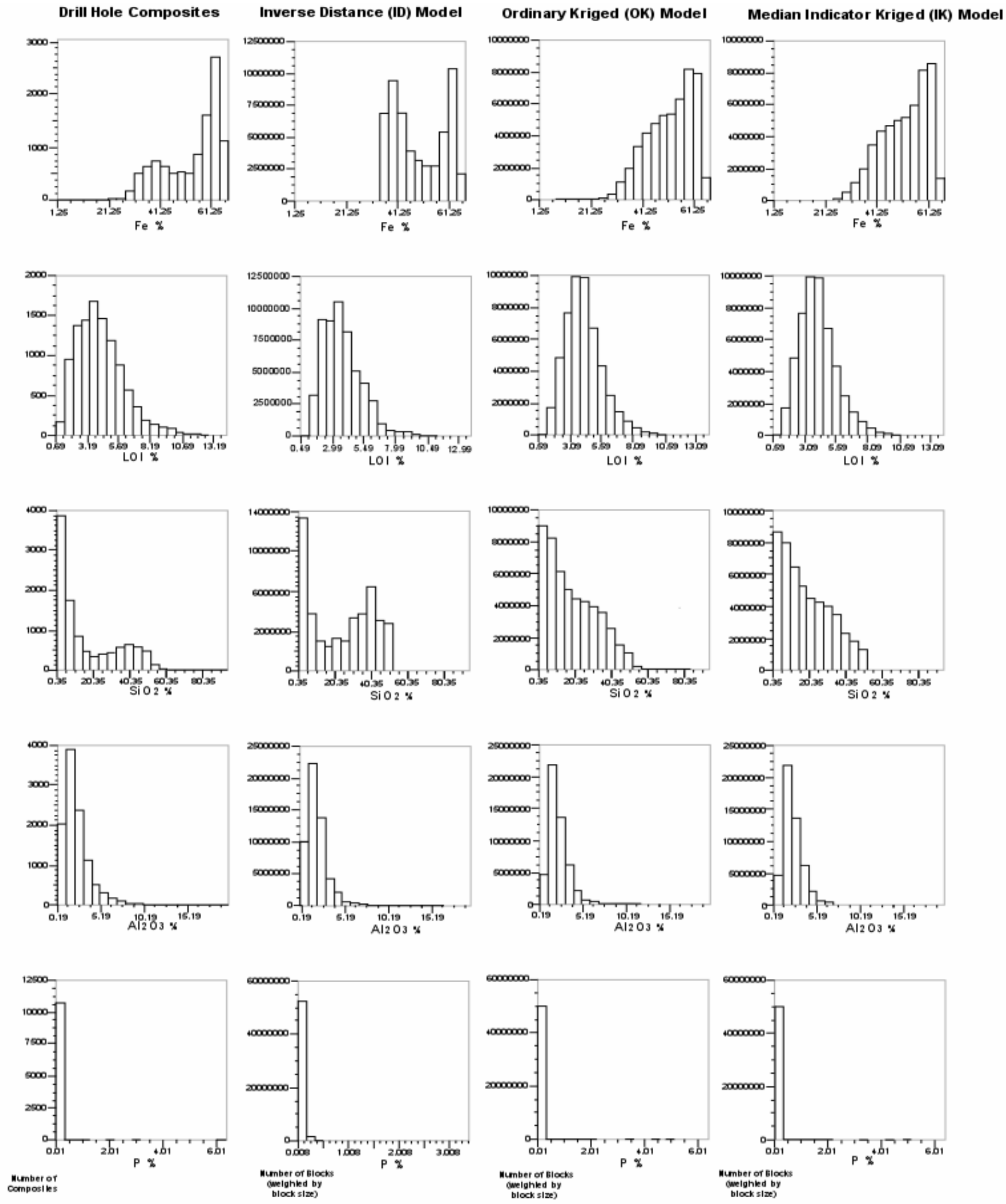
It is important to use an estimation method which deals with the nature of these distributions appropriately. Since none of the grade distributions are normal or log-normal, a non-linear estimator is ideal (Isaaks and Srivastava, 1989).

Variography

Variography was completed using the composites from each geological Member, because the consistent layering results in good continuity within individual members. No further domaining was applied. Grades were estimated into each strand, using only composites from that strand. Variograms employed in kriging within each Member were based on data within the relevant Member. This enabled shaly strands to be estimated separately from non-shaly strands, minimising mixing of populations. Variograms from these Members display no appreciable drift.

Figure 5 shows the Joffre Member Fe variograms for 84 East. For the purposes of the ordinary kriged estimate, one variogram was completed in each direction; downhole (minor axis of continuity), direction 1 (major axis) and direction 2 (semi-major axis).

For the purposes of the median indicator kriged estimate, two variograms were calculated in each direction for both Fe and SiO_2. For Fe, the medians of each population were set at 38% Fe and 62% Fe, with a population boundary (close to an inflection point) at 46% Fe (Figure 6). For SiO_2, the two medians were set at 5% SiO_2 and 38% SiO_2, with a population boundary (close to an inflection point) at 14% SiO_2 (Figure 6). Indicator variograms were calculated for each median. Means were calculated for each indicator class (by decile, with extra classes at the 2.5th, 5th and 95th percentiles). The deciles were then separated into two groups representing the populations of ore above the inflection point and BIF below. The appropriate variogram was used when estimating these deciles. For further discussion on the method of median indicator kriging, refer to Journel (1982), Journel and Huijbregts (1978), Glacken and Blackney (1998) and Vann and Guibal (1998).



84 East Deposit

Joffre Member Histograms

Figure 4. *84 East deposit histograms of Fe, LOI, SiO_2, Al_2O_3 and P in drillhole composites, inverse distance (ID) model, ordinary kriged (OK) model and median indicator kriged (IK) model.*

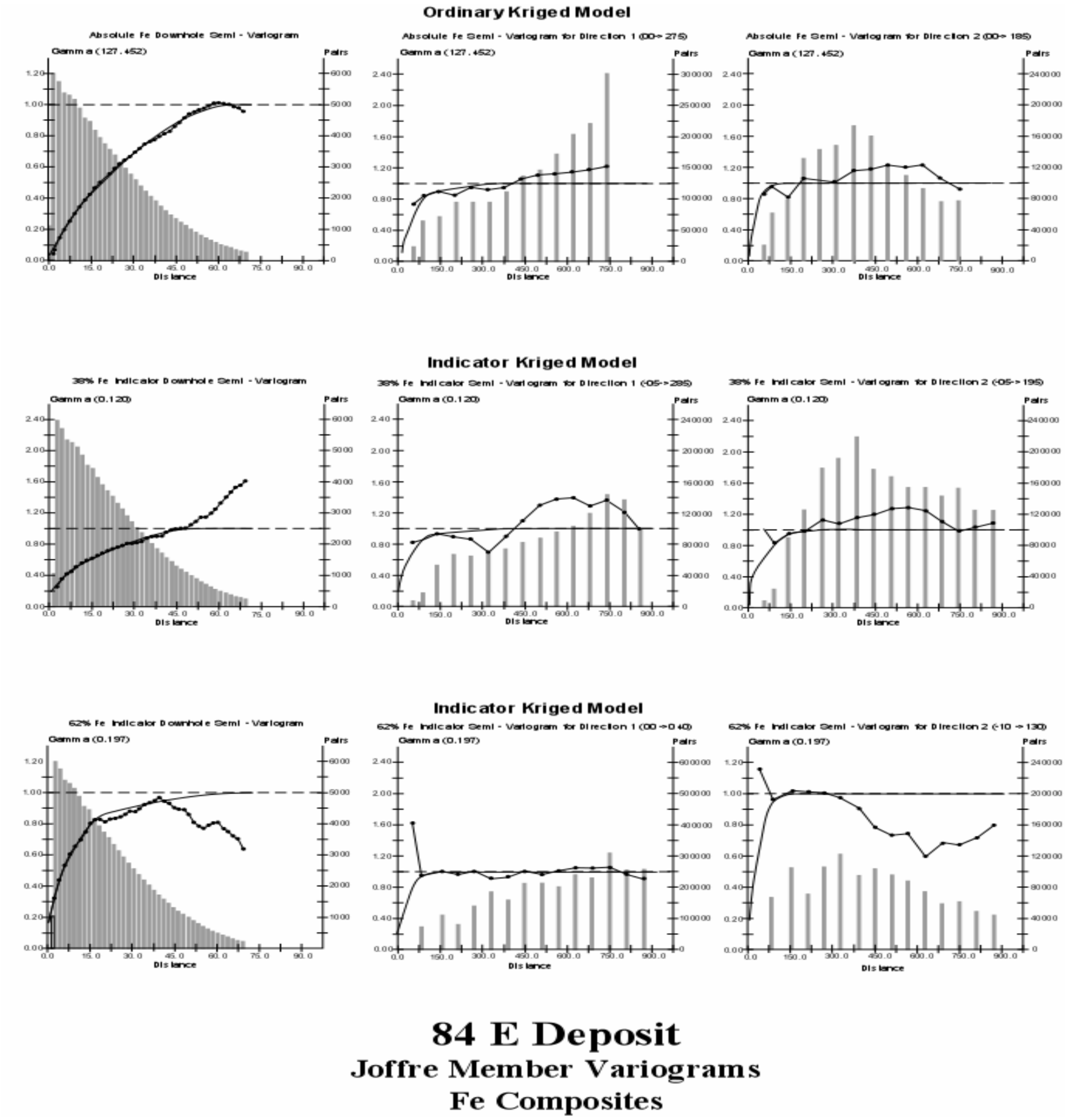


Figure 5. *84 East deposit Joffre Member Variograms of Fe composites.*

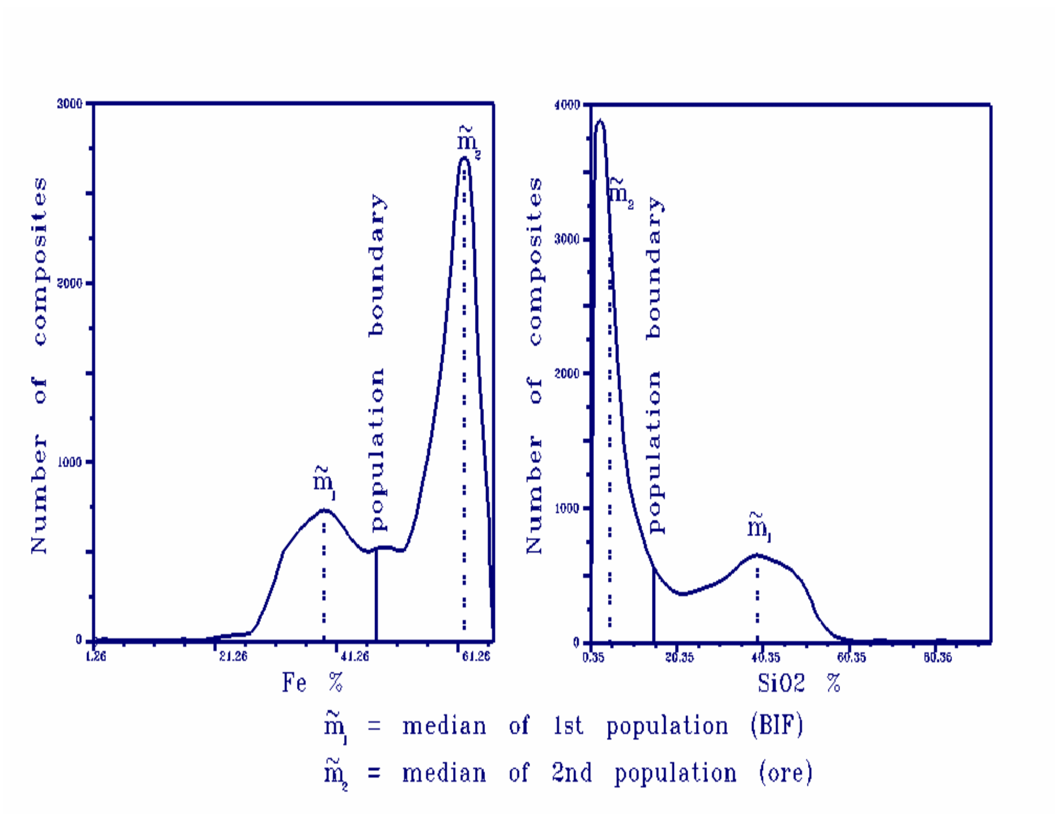


Figure 6. *84 East deposit Fe and SiO_2 composite grade distributions showing population boundaries and medians for Fe and SiO_2 indicator variograms.*

In the Joffre Member at 84 East, the nugget effect is typically 5 - 20 % of the population variance, reflecting the consistent layering and low variability at short ranges. In the maximum continuity directions, ranges are greater than 130m for most elements, and are up to 400m. In less consistent strands, the nugget effect can be up to 60 % of the population variance, although this is quite rare. The two median indicator variograms (Figure 5) display similarly shaped structures, but different ranges and directions, suggesting that the two populations have different continuity. The absolute variograms show similar structures, ranges and directions to the BIF (38%Fe) indicator variograms.

Typical variography shows low nugget effect and long ranges, reflecting good continuity. This drill spacing of 60m is less than half of the minimum range of 130m. While the drill spacing is well within the maximum ranges, there are shorter-scale structures (for example; Figure 5 shows short-scale Fe structures at approximately 75m) which constitute a high proportion of the population variance. Therefore drilling is required at this spacing or closer spacing to define these structures. This suggests that the drill spacing is just adequate for the purposes of grade estimation for long term planning purposes.

Grade estimation

The individual characteristics of each deposit are reviewed before deciding the best approach to producing each geological block model. The method used to build the geological block model and estimate grades is dependent on two major factors: the purpose of the model, mining constraints and the specific characteristics of the geology and grades. Statistics and variography are used to help choose optimal grade estimation parameters.

The method used to estimate the ore-BIF transition will impact on local estimates, resource and reserve figures. Although the estimation of high grade (>60% Fe) areas has the most impact on resource and reserve figures, it is important to estimate transitional categories (for example, 55-60% Fe and 50-55% Fe) well because of the blending nature of the mining and potential for upgrading lower grade ore.

Some of the estimation techniques which may be used include:

- inverse distance (ID);
- ordinary kriging (OK);
- inverse distance estimation of separate ore and BIF domains;
- ordinary kriging within separate ore and BIF domains;
- median indicator kriging (IK);
- full or multiple indicator kriging (FIK).

An improvement was required in the grade estimation of the 84 East deposit, for the purposes of medium to long-term mine planning. The previous geological block model was estimated by inverse distance (ID) methods. This model did not provide adequate local estimates for accurate mine planning. Records showed an inverse distance cubed weighting was applied, with a large search distance of 300 metres. No ore-BIF boundary was used.

Kriging techniques were used to try to improve the inverse distance estimated geological block model. Two models were produced for the 84 East deposit; an ordinary kriged estimate (OK) for all elements and a median indicator kriged estimate (IK) for Fe and SiO_2. The ordinary kriged model and median indicator kriged model differed only in the variogram parameters and estimation method used. All other parameters, such as search distance, search orientation and discretisation, were the same. No ore-BIF boundary was used for either model.

Ordinary kriging was used to estimate Al_2O_3, P, Mn and LOI in both the OK model and IK model. Fe and SiO_2 were estimated by ordinary kriging in the OK model. In the median indicator kriged (IK) model, median indicator kriging methods (using medians to reflect the two populations of BIF and ore) were applied to estimate Fe and SiO_2. The aim was to produce a model which honoured the gradational nature of the ore-BIF boundary, and dealt with the complexity of a bimodal distribution without the constraints of an ore-BIF boundary.

In other deposits, median indicator kriging has been used for some contaminant elements where their distribution is highly skewed, to minimise the impact of outlying values on the estimate. This has been applied where extreme values appear to be less continuous geologically, such as sporadic occurrences of Mn along fault and joint planes. Because ordinary kriging does not perform well for strongly skewed distributions, where data may be sparse, it is possible that the use of ordinary kriging in such cases may assign incorrect weights to key areas in some elements.

Playkrig software was used to help determine the optimal discretisation and search parameters using the modelled variogram structures. Post-indicator kriging steps included dealing with order relation problems and back-calculating grades using the means for each decile weighted by the proportion of samples within each indicator class.

Model comparisons

The median indicator kriged model (IK) and ordinary kriged model (OK) were compared with the previous inverse distance estimated model (ID) for 84 East.

Comparison of local estimates showed an improvement from ID to the kriged models. Specifically, the kriged Fe estimates show ore-BIF grade transitions which reflect the geology observed in drillholes and mine faces. In contrast, the ID Fe estimates display abrupt, vertical changes between drillholes.

The ID model was estimated using inverse distance cubed methods with a search distance of 300 metres. Although local estimates generally closely reflect samples from the nearest drillholes, where two adjacent drillholes differ substantially (eg; ore vs. BIF) the transition is abrupt and in many cases does not reflect the observed geology (Figure 7). Effectively, these grade estimation parameters cause a similar result to that of a polygonal estimation.

Local estimates differ only slightly between the OK model and IK model. Subtle differences are apparent in the ore-BIF transitions, where blending and low grade category blocks occur. The median indicator kriged model also appears to show more continuous high grade (HG) blocks between drillholes which display HG composite values (Figure 7). Estimates appear to be geologically sensible and the block estimates better reflect the input composite values.

The histograms of the ID block model do not reflect the input (composite) data well. Whilst a bimodal distribution is apparent, the shape and range of block values are substantially different. The highest SiO_2 and lowest Fe composite values are non-existent in the block model, resulting in a sharp drop-off at this end of each distribution. The ID method does not adequately reflect the gradational nature of ore-BIF boundaries seen in mine faces. Smoothing has not occurred to an appropriate degree.

The histograms of the kriged geological block models show bimodal Fe and SiO_2 and positively skewed Al_2O_3, P, Mn and LOI distributions (Figure 4). In each case, the block model minimums have increased and maximums have decreased as expected due to smoothing (volume-variance effect). The local estimates of the kriged geological block models reflect the drillholes well, but have also incorporated a degree of smoothing which reflects the observed geology. The Fe and SiO_2 block model distributions display a higher proportion of intermediate values. This suggests an addition of the two smoothed distributions and appears to be a reasonable outcome of smoothing a bimodal distribution.

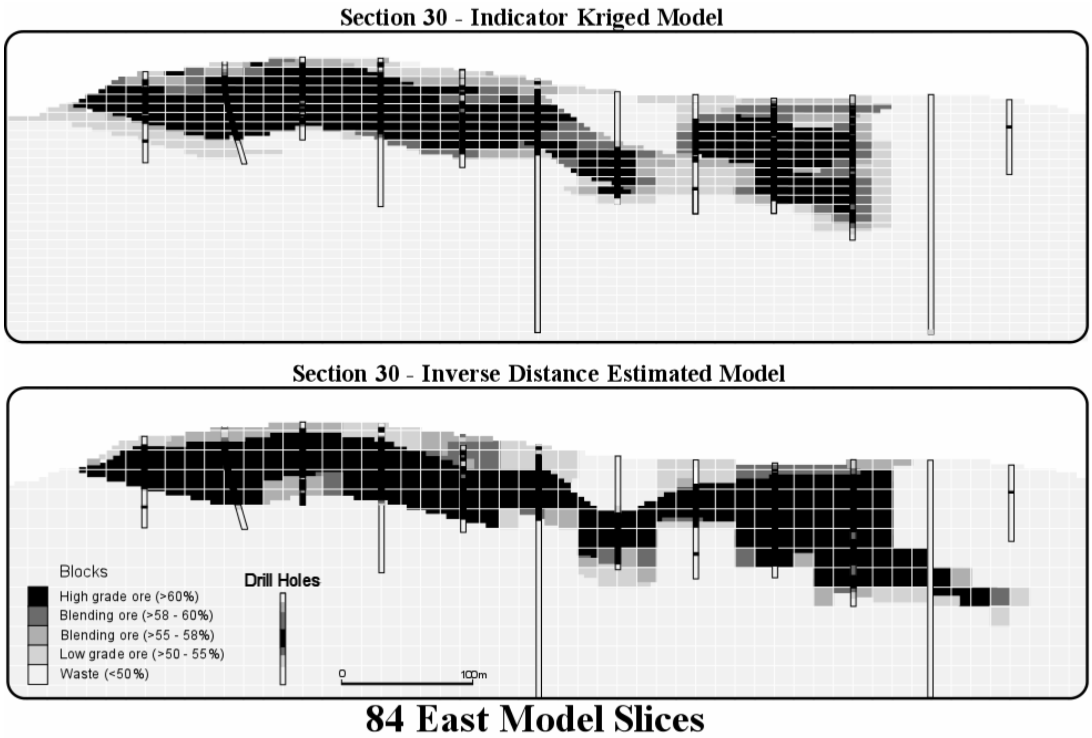


Figure 7. *84 East deposit model slices: Section 30 of Median Indicator Kriged Model and Section 30 of Inverse Distance Estimated Model.*

The OK block model Fe and SiO_2 histograms are similar to the IK block model histograms (Figure 4). While they both show similar shaped distributions, the very low Fe and very high SiO_2 values are only present in the ordinary kriged blocks. This suggests that in the IK model the most extreme values have less influence in the estimation, because the outside percentile bins are treated separately. Outlying values are not generally considered to be part of the same population as the majority of data, as they often reflect different geological genesis: for example, remobilisation of elements along faults or near-surface. Therefore, median indicator kriging is considered to provide a more valid method to estimate an element with a very skewed or bimodal distribution.

To fully test the results of the various grade estimation methods in 84 East, reconciliations must be performed between the models and blasthole production data. Reconciliations are currently in progress. Multiple indicator kriging may serve to define the various distributions even better, and is therefore the next logical step to improve the grade estimation of skewed or bimodal elements in iron ore. The most obvious constraints in using this method are the time required to produce all of the indicator variograms and computing time. Once the results of median indicator kriging are tested, the benefits of applying this method will be examined.

Conclusions

This case study compares the results of inverse distance, ordinary kriging and median indicator kriging estimation in the 84 East iron ore deposit east of Paraburdoo mine. The comparison includes examination of local estimates and data distributions. The kriging methods have improved the estimation compared with the inverse distance method, in the block data distributions and the pattern of local estimates.

Median indicator kriging has been tested on the bimodal distributions of Fe and SiO_2 in iron ore. A decision was made to separate the two main populations of BIF and ore from these distributions and estimate medians for each. The differences between ordinary kriging and median indicator kriging of Fe and SiO_2 are slight. Both methods provide geologically sensible local estimates and an appropriate degree of smoothing.

However, the median indicator kriging method is considered to provide a better way of estimating an element with a bimodal or strongly skewed distribution. Outlying assay values have less influence when using the median indicator kriging method.

Detailed reconciliation work is required to test how well each of these kriging estimates compare with inverse distance estimates for mine planning purposes. Optimal methods of grade estimation will continue to be explored.

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