Resource Estimation and Surpac

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Mining Associates

- Hong Kong and Brisbane based minerals consultancy.
- Specialists in mine geology and resource/reserves estimation.
- Production control and planning.
- Computer and systems experts.
- Environmental and Permitting.
- Personal quality service.
Capability

- Geological Modeling, Exploration Targeting.
- Ore Body Modeling & Resource Estimation.
- Mine Geology & Ore Production Control.
- Project management and systems.
- Geological Systems, Databases, Mining software, Training.
- Due diligence and technical audits.
- Expert witness.
- Technical Reviews & Audits.
- Feasibility Studies, Due Diligence & Valuations.
- Environmental and Permitting.
Recent Laterites Experience

- Abednego, Western Australia, (Ni)*, feasibility study.
- Aurukun, Queensland, Australia. (bauxite)*, geology & resource estimate.
- Cawse, Western Australia. (Ni), in-depth review.
- Cerro Matoso, Colombia. (Ni), reserves audit.
- China Aluminium Corporation (bauxite), IPO.
- Goro Feasibility, New Caledonia. (Ni)*, feasibility study.
- Murrin Murrin, Western Australia, (Ni), in-depth review, feasibility study.
- Ouaco, Noumea (Ni) Mine Planning Services
- Ramu, Papua New Guinea. (Ni)*, feasibility study.
- Siriwo, West Irian, Indonesia, (Ni), project review.
- Sishen, RSA. (Fe), in-house audit and review.
- Tiebaghi Mine, New Caledonia (Ni), production control and planning.
- Udon Potash, Thailand (potash)* scoping and pre-feasibility study.
- Vanua Levu, Fiji, (bauxite)* field program & resources estimate.
- Weipa, Queensland, Australia. (bauxite)* mine geology, resource & reserves.
- Worsley, Western Australia. (bauxite) mine geological review.

* indicates resource/reserves estimates/reviews on these projects.
Geostatistics

► Basic Statistics
  - Measure of central tendency/location
  - Measure of spread
  - Measure of shape

► Plots

► Clustering/Declustering

► Top cuts/Grade capping

► Domaining
GSLib in Surpac

- **KT3D** - 3D kriging (simple & ordinary kriging)
- **IK3D / POSTIK** - indicator kriging
- **NSCORE** - normal score transformation
- **SGSIM / POSTSIM** - Sequential gaussian simulation (Also uses HISTSMTH)
- **SISIM / POSTSIM** - Sequential indicator simulation.
Geostatistics – Basic Statistics

- Measure of central tendency/location
  (Describes the centre of the distribution)
  - Mean
  - Median
  - Mode
  - Min & Max
  - Number of samples
Measure of spread
(Describes the variability of the data)
- Range
- Variance
- Standard Deviation
- Inter-quartile (25th & 75th percentile)
Geostatistics – Basic Statistics

- Measure of shape
  (Describes the shape of the distribution)
  - Skewness
    - Non-skew distribution \((mean \approx mode \approx median)\)
    - Positively skewed distribution \((mode < median < mean)\)
    - Negatively skewed distribution \((mean < median < mode)\)
  - Coefficient of Variation (COV)

\[
\text{Skewness} = \frac{\sum (\text{sample} - \text{mean})^3}{n \cdot \text{std deviation}}
\]
\[
\text{COV} = \frac{\text{std deviation}}{\text{mean}}
\]
Geostatistics – Plots

- **Histogram**
  - Studying a data set
  - X-axis assay values & Y-axis frequency
  - Data are sorted and binned into assay intervals & number of samples in each bin
  - Log-Histogram used where data are skewed
Geostatistics – Plots

- Cumulative Distribution Function (CDF)
  - Accumulated histogram
  - “S” shaped when data is non-skew
Geostatistics – Plots

Probability Plots
- Assessing whether the data are normally distributed
- Normal distribution $\approx$ straight line
- Identify multiple populations
Geostatistics – Plots

- Scatterplot
  - Qualitative measure of how 2 variables are related
  - Sensitive to outliers
  - Compare data from different labs (QA QC)
  - Summary of similarity & precision
  - Measure the correlation coefficient
Geostatistics – Plots

- **Q-Q plots**
  - Percentiles are plotted against each other
  - Straight line indicates similar sample distribution
  - Examples:
    - Exploration vs. grade control data
    - Different drilling types
    - Compare different domains
Box & Whisker Plots
- Summarises the spread and location of the data
- Whiskers defines the range
- Box defines the inter quartile range
Geostatistics – Sichel’s Mean OR Log Estimated Mean

Provide an unbiased estimate of the global mean only when the population is log normally distributed
Geostatistics – Declustering

- **Clustering**
  - Caused by irregular sampling or biased infill drilling of high grade areas
  - It manifest itself as mixed populations in a histogram

- **Declustering** (good indicator of the global mean)
  - By selectively remove clustered drillholes
  - Nearest neighbour declustering/ Gridding
  - Cell weighted declustering
Geostatistics - Declustering

Average = 4.57 g/t

Declustered Average = 4.08 g/t
Top Cuts OR Grade Capping

- Needed where there is extreme grades
- Process of reducing the grade of the outliers to a value that is representative of the surrounding grade distribution
- Min the overestimation

Tools
  - Sichel’s Mean, CV & Probability Plots
Geostatistics – Domaining

- Single orientation of grade continuity
- Geological homogeneous
- Controls used as boundaries include structural, weathering, geological, mineralisation & lithological controls
- Tools
  - Histogram & log probability plot
Geostatistics – Domaining

► Hard vs. Soft domain boundary
  - Hard boundaries – coal seam or gold vein
  - Soft boundaries – porphyry Cu-Au deposits (disseminated)
Estimation Techniques

- Geological Methods
  - Polygonal
  - Nearest Neighbour
  - Inverse Distance
  - Ordinary Kriging
  - Indicator Kriging
- Simulations

- Concepts
  - Search Strategy
  - Discretisation
Geological Methods

► Generating a series of geological cross-sections & plans using a manual interpretation

► Volume = Area x section thickness

► Average grade obtained from the drillholes
Polygonal

- Area is divided into a series of polygons, centered upon a individual point
- Average grade assigned to the polygon that is of the central sample
Nearest Neighbour

Assigns grade values to blocks from the nearest sample point to the block
- 3D search ellipsoid
- Maximum search distance
Inverse Distance

- Samples closer to the point of estimation are more likely to be similar in grade.
- Each sample is weighted according to the inverse of their separation.
- Samples closer gets a higher weighting than samples further away.
Ordinary Kriging

Is an inverse distance weighting technique where weights are selected via the variogram according to the samples distance & direction (anisotropy)
Indicator Kriging

- Used where there is mixed populations and skewed data
- Transforming data to indicators using a selected threshold and ordinary kriged
- Indicators are weighted according to their probabilities that the grade estimate is less than the respective indicator
- Probabilities create a cumulative distribution function (CDF)
## Estimation Techniques – Pros & Cons

<table>
<thead>
<tr>
<th>Technique</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverse Distance</td>
<td>• Quick and easy to use</td>
<td>• Sensitive to data clustering</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Weight is directly related to distance, irrespective of the ranges of influence</td>
</tr>
<tr>
<td>Ordinary Kriging</td>
<td>• Built in declustering</td>
<td>• Time and effort to do variography</td>
</tr>
<tr>
<td></td>
<td>• Uses spatial relationship between samples to weight the samples</td>
<td>• Negative weights needs to be controlled</td>
</tr>
<tr>
<td>Indicator Kriging</td>
<td>• Can handle mixed populations</td>
<td>• Time and effort to do full indicator variography</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Order relation problems needs to be controlled</td>
</tr>
</tbody>
</table>
Model Validation

- It is important to validate the kriging results against the raw data, looking at various parameters:
  - Comparing basic statistics &
  - Conditional bias statistics
    - Kriging Variance
    - Kriging Efficiency
    - Conditional Bias Slope
  - Q-Q plots
  - Grade Tonnage Curve
Model Validation – Conditional Bias

Statistics

- **Kriging Variance (KV)**
  - Relative measure of confidence in each block estimate
  - Good indication if the area has been sampled enough, KV is higher if the sampling density is higher
  - KV is linked to the location and spacing of the samples
Kriging Efficiency (KE)

- Measures the effectiveness of the kriging estimate to accurately reproduce the local block grade
- Range between -1 (very poor estimate) & 1 (very good estimate)
- Low KE indicates a high degree of smoothing & high KE a low degree of smoothing

\[
KE = \frac{\text{Block Variance} - \text{Kriging Variance}}{\text{Block Variance}}
\]
Model Validation – Conditional Bias Statistics

- **Conditional Bias Slope**
  - State the reliability of an estimate
  - Summarises the degree of over smoothing of high & low grades
  - Range between 0 & 1
  - Low values indicates a poor relationship between the estimated and actual block grades
  - Equivalent to the regression slope
Model Validation – Q-Q plots

- Used by plotting the estimated grades against the actual grades.
- It will plot a straight line if the sample distribution is the same.
- If the differences are high it will introduce a large bias.
Grade Tonnage Curve

- Stating the amount of ore that is available at a certain cutoff grade.
- High cutoff grade would correspond to a lower amount of ore tonnes available.
Kriging Neighbourhood Analysis (KNA)

- Objective is to determine the combination of search neighborhood and block size that will result in conditional unbiasedness.

- Criteria to consider:
  - Conditional bias slope
  - Kriging Variance
  - Kriging Efficiency
  - Distribution of kriging weights
Kriging Neighbourhood Analysis

- Pick Trace/Test Blocks to test the search neighbourhood and block sizes
  - Well informed blocks
  - Less informed blocks
  - Poorly informed blocks

- Optimal parameters will result in a slope of 1 & a KE of 100%

- Achievable results: slope > 0.9 & KE 80-90%
Conditional Simulations

- Produces several equally likely resource models
- Each model is a simulation of reality based on:
  - Geological assumptions
  - Input data
  - Variogram parameters
- Generate 3D models for risk analysis
- Simulations have to honour:
  - The sample data at the sample locations
  - Variogram models
  - Statistics of the input data
## Simulation Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turning Bands</td>
<td>Archaic, now discredited, method that has the undesirable side effect of producing models with inherent artificial banding. First method developed.</td>
</tr>
<tr>
<td>Sequential Gaussian</td>
<td>Equivalent to ordinary kriging. Maximise the entropy*. Preferable in for lateritic or oxidised deposits, stockwork or brecciated mineralisation.</td>
</tr>
<tr>
<td>Sequential Indicator</td>
<td>Equivalent to indicator kriging. Minimise the entropy*. Preferable when the geological texture is more “connected” for example vein or shear-zone hosted deposits.</td>
</tr>
<tr>
<td>Probability Field (P-field)</td>
<td>Generates models of probability, conditioned to a supplied variogram, for use in the Monte Carlo process. Fast, but sub-optimal – the sample data variograms are not necessarily honoured.</td>
</tr>
<tr>
<td>Simulated Annealing</td>
<td>Can be used to produce simulations that are conditional to some other, possibility non-spatial, measure. Also useful for post-processing spatial simulations. Powerful, but potentially quite slow.</td>
</tr>
</tbody>
</table>

*entropy factor – describes the disassociation of adjacent simulated grades.
Simulation Techniques

- It depends on:
  - The style of mineralisation
  - Its associated continuity
  - Statistical behaviour of the mineralisation

- No 2 deposits are the same

- Each technique has its own list of desirable features and limitations
The simulated models are validated by comparing the output models to the input data through:

- Visual inspection/comparison of the model to input data in 3D
- Basic statistics, such as the mean and the variance
- Q-Q plots & histograms
- Variograms – conformation of spatial continuity (compare against input model parameters)
- Grade tonnage curve
Simulation - Applications

- Short term planning:
  - Grade control
  - Minimisation of cost of grade control
  - Optimisation of underground ore blocks

- Long term planning:
  - Quantifying resource risk (classification)
  - Quantifying reserves risk within a pit shell underground designs
  - Optimising SMU size or bench height to evaluate likely implications for equipment selection
Aurukun Bauxite Deposit - Example

- Background
- Geology
- Density
- Modelling
- Resource Classification
- Conclusions
Introduction

The Weipa bauxite deposits
- occur along and inland from the western coast of Cape York.
- Are confined to the lateritic unit known as the Weipa Plateau – modified Cretaceous regression surface
- Stretch 350km by 40 km
- Is incised by rivers and alluvial fans

Adapted from Taylor et al. 2008
Profile Composition of bauxite with depth

Typical Mineralogical composition of bauxite profile with depth.

Zone 1 -Soil
- Soil
- Average Zone SG: 1.43

Zone 2
- Average Zone SG: 1.65

Zone 3
- Average Zone SG: 1.63

Zone 4
- Average Zone SG: 1.48

Zone 5
- Average Zone SG: 1.55

Zone 6
- Average Zone SG: 1.77

Hematite
- SG 5.3

Boehmite
- SG 3.0

Gibbsite
- SG 2.4

Kaolinite
- SG 2.6

Quartz
- SG 2.7

Others

Depth from surface (metres)

% Cumulative Minerals

Zone of concretion

Zone of water table fluctuation

Zone of weathered parent rock
Aurukun Bauxite Deposit - Outline

- Background
- Geology
- Density
- Modelling
- Resource Classification
- Conclusions
Modelling Approach

- **Hard / Soft Boundaries**

HARD BOUNDARIES - prevent assay data informing neighbouring domains, the domains are independent.

SOFT BOUNDARIES – permit assay data to inform neighbouring domains, the domains are related.

Aurukun Resource Model used a combination of soft and hard boundaries, determined by the Bauxite profile.
### Aurukun Bauxite Profile

<table>
<thead>
<tr>
<th>ZONE</th>
<th>LITHOLOGY</th>
<th>RECOVERY</th>
<th>Ksi</th>
<th>BOEHMITE</th>
<th>Boundary Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SOIL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>EARTHY PISOLITIC</td>
<td>low</td>
<td></td>
<td>high</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>REWORKED BX</td>
<td>medium</td>
<td></td>
<td></td>
<td>Hard</td>
</tr>
<tr>
<td>4</td>
<td>IN-SITU BX</td>
<td>high</td>
<td></td>
<td>low</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>LOW BOEHMITE</td>
<td></td>
<td></td>
<td>low</td>
<td>Soft</td>
</tr>
<tr>
<td>6</td>
<td>KAOLINITIC</td>
<td>medium</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>KAOLINITE</td>
<td></td>
<td></td>
<td>high</td>
<td>Hard</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The resource estimate was conducted in unfolded space.

This approach:

- Preserves the laterite profile characteristics (both horizontally and vertically) irrespective of thickness or orientation;
- Constrains informing samples for estimation into the zone(s) required and improves stationarity/domaining concerns; and
- Converts real RL to a relative position.
Block Models

Scam Model

Layer A
Layer B

Cell has variable height following Layer B

Block Model

Layer A
Layer B

Cell has fixed height but contains 22% layer A and 78% layer B
Unfolded Block Model

FOLDED

LAYER A
LAYER B
LAYER C

UNFOLDED

LAYER A
LAYER B
LAYER C
Folded Block Model

Unfolded Samples

<table>
<thead>
<tr>
<th>Zone</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>soil</td>
</tr>
<tr>
<td>2</td>
<td>earthy reworked bx</td>
</tr>
<tr>
<td>3</td>
<td>pisolithic reworked bx</td>
</tr>
<tr>
<td>4</td>
<td>hi boehmite bx</td>
</tr>
<tr>
<td>5</td>
<td>low boehmite bx</td>
</tr>
<tr>
<td>6</td>
<td>kaolinitic bx</td>
</tr>
<tr>
<td>7</td>
<td>kaolinite</td>
</tr>
<tr>
<td>8</td>
<td>no sample</td>
</tr>
</tbody>
</table>

Folded Block Model
Resource Estimation - Sequence

1. Bauxite layers were generally above the economic cut-off, as such, the concentration of contaminants were considered more important to model;

2. Experimental variography was undertaken using unfolded data;

3. Modelled variograms were based on total silica, and confirmed as representative of all major elements in all layers;

4. To limit order relation issues a single modelled variogram is preferred;

5. Kriging neighbourhood analysis was carried out using the modelled silica variogram;

6. Estimation was conducted in unfolded space using ordinary kriging;

7. Relative block levels were re-set of original block levels thus re-folding the block model.
Conclusions

- The resource estimation of the Aurukun lateritic deposits presented specific issues related to the lateral changes in thickness and elevation of the various zones within the deposit where the x and y dimensions are orders of magnitude greater than the z dimension.

- The solution was to do the resource estimation in “unfolded” space which maintains the zone layering irrespective of zone thickness or orientation. The block model estimation method was Ordinary Kriging done in unfolded space and then refolded.

- A number of selection criteria, developed in consultation with the project engineers and owners, were applied to the deposit to define resource categories.