Incorporating Mineral Prospectivity Analysis in Quantitative Estimation of Undiscovered Mineral Resources

John Carranza
School of Earth & Environmental Sciences
James Cook University
Townsville, Queensland, Australia
Quantitative mineral resource assessment (QMRA)

- The 3-part quantitative mineral resource assessment of the USGS consists of (Singer, 1993):
  - Delineation of geologically permissive tracts according to type of mineral deposits.
  - Estimation of the number of undiscovered deposits per type per tract.
  - Estimation of amount of undiscovered metals based on grade and tonnage models.
Mineral prospectivity mapping (MPM)

Conceptual model of deposit occurrence

Theoretical relationships between various factors or controls of *how and where* certain deposits occur

Input spatial data

Spatial database

Analysis of predictive model parameters

‘Factor’ or ‘Predictor’ maps

Integration models

Model validation

Predictive map of mineral prospectivity
QMRA vs. MPM

- Both QMRA and MPM have a common goal - to delineate prospective ground for mineral exploration.

- But, MPM has not been a part of QMRA
  - Various researchers have suggested that MPM can be part of QMRA but have not demonstrated how to do it
Proposition

- We should do it this way:

- MPM can be a part of QMRA of undiscovered mineral deposits if the spatial pattern of discovered deposits of the type sought is considered in both predictive modeling processes.
Case study area

Case study area

Spatial analysis of structural controls on mineralization for conceptual modeling of deposit occurrence

- **Fractal analysis** of the spatial pattern of mineral deposits (Carlson, 1991)

![Box-counting method](image)

*Box-counting method* \( n(\delta) = C\delta^{-D_b} \)

- The inflection points at 4 km imply that certain geological controls on gold mineralization in the area operated on at least two spatial scales

![Radial-density method](image)

*Radial-density method* \( pd = Cr^{D_r-2} \)

\( pd = 0.38r^{-1.46} \)

\( R^2 = 1.00 \)

\( SE = 0.0083 \)

\( pd = 0.18r^{-0.88} \)

\( R^2 = 1.00 \)

\( SE = 0.0003 \)
Spatial analysis of structural controls on mineralization for conceptual modeling of deposit occurrence

- **Fractal analysis** of the spatial pattern of mineral deposits (Carlson, 1991)

- The fractal dimensions of 0.20 and 0.54 at \( \leq 4 \text{ km} \) suggest that
  - **gold mines/prospects cluster at scales of \( \leq 4 \text{ km} \)**
  - at scales of \( \leq 4 \text{ km} \), the spatial pattern of the gold mines/prospects is plausibly due to *focusing of hydrothermal fluids toward certain locations in deformations zones*

- The fractal dimensions of 1.16 and 1.12 at \( > 4 \text{ km} \) suggest that
  - **clusters of gold mines/prospects form linear corridors at scales of \( > 4 \text{ km} \)**
  - at scales of \( > 4 \text{ km} \), the spatial pattern of the gold mines/prospects is plausibly due *channeling of hydrothermal fluids along deformation zones*
Spatial analysis of structural controls on mineralization for conceptual modeling of deposit occurrence

- **Fry analysis** of the spatial pattern of mineral deposits (Vearncombe & Vearncombe, 1999)

- Fry points for the 51 gold mines/prospects in the area suggest **structural controls** by NNE-and NW-trending faults
Spatial analysis of structural controls on mineralization for conceptual modeling of deposit occurrence

- **Fry analysis** of the spatial pattern of mineral deposits (Vearncombe & Vearncombe, 1999)

- Pairs of Fry points ≤6.8 km apart suggest that NW-trending faults and intersections of NNE-/NE- and NW-trending faults are plausible local-scale structural controls on gold mineralization in the area.
Case study area

Spatial analysis of structural controls on mineralization for conceptual modeling of deposit occurrence

- **Distance distribution analysis** of spatial association of mineral deposits with structures (Berman, 1977, 1986)

- these results imply that proximity to NNE- and NW-trending faults and proximity to intersections between NNE- and NW-trending faults are likely structural controls on gold mineralization in the area
Predictive mapping of mineral prospectivity

- Spatial recognition criteria of prospectivity for gold deposits in the area:
  - proximity to NNE-trending faults
  - proximity to NW-trending faults
  - proximity to intersections of NNE- and NW-trending faults
Predictive mapping of mineral prospectivity

- Spatial recognition criteria of prospectivity for gold deposits in the area:
  - Stream sediment geochemical anomalies

**PCs (and variance explained in %)**

<table>
<thead>
<tr>
<th></th>
<th>PC1</th>
<th>PC2</th>
<th>PC3</th>
<th>PC4</th>
<th>PC5</th>
<th>PC6</th>
<th>PC7</th>
<th>PC8</th>
<th>PC9</th>
<th>PC10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Au</td>
<td>0.17</td>
<td>0.04</td>
<td><strong>0.72</strong></td>
<td>-0.06</td>
<td>-0.32</td>
<td>0.58</td>
<td>-0.05</td>
<td>0.02</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>As</td>
<td>0.09</td>
<td>-0.13</td>
<td><strong>0.72</strong></td>
<td>0.27</td>
<td>-0.12</td>
<td>-0.61</td>
<td>-0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>-0.02</td>
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<tr>
<td>Cu</td>
<td>0.56</td>
<td>0.58</td>
<td>0.11</td>
<td>-0.26</td>
<td>0.10</td>
<td>-0.08</td>
<td>0.31</td>
<td>0.34</td>
<td>-0.20</td>
<td>0.05</td>
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<tr>
<td>Pb</td>
<td>0.07</td>
<td>0.32</td>
<td>-0.06</td>
<td>0.87</td>
<td>0.25</td>
<td>0.21</td>
<td>-0.03</td>
<td>0.15</td>
<td>0.00</td>
<td>0.05</td>
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<tr>
<td>Zn</td>
<td>0.50</td>
<td>0.70</td>
<td>-0.01</td>
<td>0.13</td>
<td>-0.13</td>
<td>-0.06</td>
<td>0.07</td>
<td>-0.45</td>
<td>-0.09</td>
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<tr>
<td>Cr</td>
<td>0.74</td>
<td>-0.44</td>
<td>-0.07</td>
<td>0.04</td>
<td>0.07</td>
<td>-0.01</td>
<td>-0.39</td>
<td>0.06</td>
<td>-0.18</td>
<td>0.21</td>
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<tr>
<td>Ni</td>
<td>0.83</td>
<td>-0.36</td>
<td>-0.12</td>
<td>0.06</td>
<td>-0.19</td>
<td>0.05</td>
<td>0.03</td>
<td>-0.05</td>
<td>-0.22</td>
<td>-0.28</td>
</tr>
<tr>
<td>Co</td>
<td>0.67</td>
<td>-0.37</td>
<td>-0.26</td>
<td>0.16</td>
<td>-0.31</td>
<td>-0.02</td>
<td>0.33</td>
<td>0.05</td>
<td>0.34</td>
<td>0.10</td>
</tr>
<tr>
<td>V</td>
<td>0.64</td>
<td>0.49</td>
<td>-0.01</td>
<td>-0.23</td>
<td>0.21</td>
<td>-0.07</td>
<td>-0.34</td>
<td>0.05</td>
<td>0.34</td>
<td>-0.11</td>
</tr>
<tr>
<td>Fe</td>
<td>0.31</td>
<td>-0.42</td>
<td><strong>0.31</strong></td>
<td>-0.08</td>
<td>0.72</td>
<td>0.11</td>
<td>0.24</td>
<td>-0.18</td>
<td>0.05</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Predictive mapping of mineral prospectivity

- Application of **evidential belief functions** to calculate and integrate indices of mineral prospectivity (Carranza and Hale, 2003) using 45 prospects for training.
Estimation of undiscovered mineral endowment

- **One-level prediction** (McCammon and Kork 1992; McCammon et al. 1994)

- This involves dividing an area into a grid of equal-area unit cells and assumes that the datasets available are sufficient to assess and model:

  1) a numerical **measure of favourability of mineral deposit occurrence**

  2) **degree/extent of exploration**

  3) the **discovered endowment for the defined grid of unit cells**
Estimation of undiscovered mineral endowment

- **One-level prediction** *(McCammon and Kork 1992; McCammon et al. 1994)*

- **Map of favourability of mineral deposit occurrence** is converted into a binary map (i.e., classification of prospective and non-prospective cells).
Estimation of undiscovered mineral endowment

- **One-level prediction** (McCammon and Kork 1992; McCammon et al. 1994)
- **Modeling of degree/extent of exploration**
  - Degree/extent of exploration must be assessed from location maps of ore-bodies and drill-holes compiled from published and unpublished sources.
  - **But, unpublished data sources are usually inaccessible!**
  - However, we can imagine that degree/extent of exploration or the explored portion ($E$) of every cell in an area decreases with increasing distance from any mine/prospect ($P$).
  - And, based on the notion of mineral deposit density as a tool for estimating undiscovered deposits (Singer et al., 2001, 2005; Singer, 2008), we can estimate $E$ of every cell as mine/prospect density ($PD$) in cumulative increasing areas defined by increasing distances ($r$, in km) from every $P$, thus:

$$E_r \approx PD_r = \frac{N(P)}{(\text{cell count})_r \times (\text{cell size})^2 \times 0.000001}$$
Estimation of undiscovered mineral endowment

- **One-level prediction** (McCammon and Kork 1992; McCammon et al. 1994)
- Modeling of **degree/extent of exploration**
Estimation of undiscovered mineral endowment

- **One-level prediction** (McCammon and Kork 1992; McCammon et al. 1994)

- Modeling of **discovered endowment**
  - calibration in an **explored control region**, whereby a constant of proportionality, $C$ (i.e., ratio of the discovered endowment to the area of explored portion of control region) is estimated
  - $C$ is assumed to be a fixed but unknown endowment per unit cell
    - is then applied to the whole study area in order to estimate undiscovered endowment

- Geology of control region must be representative of the geology associated with mineral deposits of the type sought
Estimation of undiscovered mineral endowment

- **Calibration of one-level prediction** (McCammon and Kork 1992; McCammon et al. 1994)
  - In a study area, there are \( k (=1,2,...,l) \) number of cells, each of which is classified as either *endowed* \((M)\) if containing \(P\) or *unendowed* \((\overline{M})\) if not containing \(P\).
  - Each \(M\) cell is given an endowment score equal to the metal endowment (i.e., product of metal grade and ore tonnage) of \(P\). Each \(\overline{M}\) cell is given an endowment score of zero.
  - If we cross a binary map of metal endowment and a binary map of mineral prospectivity, we have prospective-endowed \((pM)\) cells, prospective-unendowed \((\overline{pM})\) cells, unprospective-endowed \((\overline{pM})\) cells and unprospective-unendowed \((\overline{pM})\) cells.
  - Total metal endowment \([N(TM)]\) is then defined as:

\[
N(TM) = \text{known endowment} + \text{unknown endowment}
\]

\[
= \sum_{k=1}^{l} M_k + \left( C \times \sum_{pM=1}^{q} P_{pM} \left(1 - PD_{pM}\right) \right)
\]
Estimation of undiscovered mineral endowment

- **Calibration of one-level prediction** (McCammon and Kork 1992; McCammon et al. 1994)
  - Known metal endowment is the sum of endowment scores of $c^{th}$ ($c=1,2,...d$ number of) control cells:
    \[
    N(KM_c)_{known} = \sum_{c=1}^{d} M_c
    \]
  - Known metal endowment in control cells can be calculated as a function of $C$, prospectivity ($p$) and explored portions ($PD$) of every control cell:
    \[
    N(KM_c)_{calculated} = C \times \sum_{c=1}^{d} p_c PD_c
    \]
  - By setting $N(KM_c)_{known} = N(KM_c)_{calculated}$, we can derive $C$. 

**OLP of number of undiscovered prospects**

- In the study area, we do not have complete data for grade and tonnage!
- Instead of metal endowment, we assigned each endowed unit cell (i.e., containing a prospect/mine) an endowment score $M = 1$ and each unendowed unit cell an endowment score $M = 0$.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Information/data from the control region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted prospectivity</td>
<td></td>
</tr>
<tr>
<td>Known endowment</td>
<td></td>
</tr>
<tr>
<td>Number of unit cells</td>
<td>15</td>
</tr>
<tr>
<td>Number of prospects</td>
<td>15</td>
</tr>
<tr>
<td>Total number of prospects</td>
<td>16</td>
</tr>
<tr>
<td>$\sum E$ in unit cells</td>
<td>14.400</td>
</tr>
<tr>
<td>Total $\sum E$ in unit cells</td>
<td>851.591</td>
</tr>
<tr>
<td>$\sum p \times E$ in unit cells</td>
<td>14.40</td>
</tr>
<tr>
<td>Total $\sum p \times E$ in unit cells</td>
<td>551.891</td>
</tr>
</tbody>
</table>

- $C \left(= \frac{16}{551.891} \right) = 0.029$
- $Type I$ error $\left(= C \times \frac{537.491}{851.591} \right) = 0.018$
- $Type II$ error $\left(= C \times \frac{0.960}{851.591} \right) = 0.000$
- ANEM $= 0.018$
In the study area, we do not have complete data for grade and tonnage!
Instead of metal endowment, we assigned each endowed unit cell (i.e., containing a prospect/mine) an endowment score $M = 1$ and each unendowed unit cell an endowment score $M = 0$.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Information/data from the SAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predicted prospectivity</td>
<td></td>
</tr>
<tr>
<td>Known endowment</td>
<td></td>
</tr>
<tr>
<td>Number of unit cells</td>
<td>31</td>
</tr>
<tr>
<td>Number of known mines/prospects</td>
<td>31</td>
</tr>
<tr>
<td>Total number of mines/prospects</td>
<td>44</td>
</tr>
<tr>
<td>$\sum p(1-E)$ in $pM$ unit cells</td>
<td>-</td>
</tr>
<tr>
<td>Number of undiscovered prospects</td>
<td></td>
</tr>
<tr>
<td>in $pM$ unit cells $=C\times\sum p(1-E)$</td>
<td>-</td>
</tr>
<tr>
<td>Error $=[ANEM \times (6065 \times 4633.6497)^{1/2}]$</td>
<td>-</td>
</tr>
<tr>
<td>Corrected number of undiscovered</td>
<td></td>
</tr>
<tr>
<td>prospects</td>
<td>37</td>
</tr>
</tbody>
</table>
Estimation of number of undiscovered prospects

- To cross-validate results of OLP, we can apply the radial-density fractal relation (Raines, 2008):

\[ \text{‘degree/extent of exploration’} = \frac{N(P)}{(\text{cell count})_r \times (\text{cell size})^2 \times 0.000001} \]

\[ N(P)_r = Cr^{D_r-2} \times (\text{cell count})_r \times (\text{cell size})^2 \times 0.000001 \]

**NOTE:** \( C \) in OLP is not the same as \( C \) in fractal analysis.
Estimation of number of undiscovered prospects

- To cross-validate results of OLP, we can apply the radial-density fractal relation (Raines, 2008):

$$N(P)_r = Cr^{D_r-2} \times (\text{cell count})_r \times (\text{cell size})^2 \times 0.000001$$

- Results suggest that total number of lode-gold prospects in the SAB is 84.
- Since there are 45 presumed known lode-gold prospects (i.e., used as training data in MPM), the results suggest there are still 39 undiscovered lode-gold prospects in the area.

- OLP = 37; fractal analysis estimate = 39
Case study area where we have grade and tonnage data
Application of **evidential belief functions** to calculate and integrate indices of mineral prospectivity (Carranza and Hale, 2003) using 69 deposits for training.
Case study area where we have grade and tonnage data


- **One-level prediction** (McCammon and Kork 1992; McCammon et al. 1994)
  - Results in the Skellefte district:
    - undiscovered Cu endowment is ca. 709 Kt
    - undiscovered Zn endowment is ca. 3190 Kt
    - undiscovered ore tonnage is ca. 95 Mt
    - number of undiscovered VMS deposits is 48

- **Radial-density fractal analysis** (Raines, 2008):
  - Results in the Skellefte district:
    - undiscovered Cu endowment is ca. 746 Kt
    - undiscovered Zn endowment is ca. 3389 Kt
    - undiscovered ore tonnage is ca. 97 Mt
    - number of undiscovered VMS deposits is 50

- The results of two different methods are remarkably similar!
Remarks

- Estimates of undiscovered mineral resources obtained via OLP are slightly lower than respective estimates obtained via radial-density fractal analysis.

- The main reason for this is that estimates in OLP pertain to predicted prospective cells based on the results of the MPM, whereas estimates in radial-density fractal analysis pertain to all cells.

- Thus, different results obtained via OLP and radial-density fractal analysis suggest the presence of undiscovered deposits in predicted non-prospective areas.
Conclusion

- MPM can be a part of QMRA of undiscovered mineral deposits if the spatial pattern of discovered deposits of the type sought is considered in both predictive modeling processes.
MUITO OBRIGADO...

POR SUA ATENÇÃO!!

John Carranza
Fractal analysis of the spatial pattern of mineral deposits (Carlson, 1991)

Fractal dimensions
Fractal dimensions of simple objects

(a) 

(b) 

\[ y = 10150.25x^{-2.00} \]

\[ y = 223.36x^{-0.94} \]

\[ y = 1.00x^{-0.00} \]
**Fry analysis** of the pattern of deposit occurrences (Fry, 1979)

- Geometrical method of spatial autocorrelation

For \( N \) original points, there are \( N^2 - N \) Fry points.
Fry analysis of the pattern of deposit occurrences (Fry, 1979)

- Geometrical method of spatial autocorrelation

Fry points

Original points

Fry points

Direction analysis

For all pairs of Fry points

Directional diagrams

For pairs of Fry points at certain distances from each other