Undiscovered Resource Modelling: Towards Applying A Systematic Approach To Uranium

Martin Fairclough\textsuperscript{1} and Laz Katona\textsuperscript{2}

\textsuperscript{1}IAEA, \textsuperscript{2}Geological Survey of South Australia
With contributions from the Geological Survey of South Australia

URAM 2014
Or
How much Uranium is left and where might it be found?

Martin Fairclough\textsuperscript{1} and Laz Katona\textsuperscript{2}

\textsuperscript{1}IAEA, \textsuperscript{2}Geological Survey of South Australia

With contributions from Bernd Michaelsen, Geological Survey of South Australia

URAM 2014
Uranium Resource Modelling

“Why do we want to model undiscovered uranium resources?”

If you can’t quantify, you can’t plan for it
“Why don’t we want to model undiscovered uranium resources?”

“lies, damn lies..............and (geo)statistics”
Uranium Resource Modelling

“Aren’t imaginary numbers just geofantasy?”

(But) we use geostatistics everyday to interpolate and extrapolate? (kriging, co-kriging, conditional simulation, gridding of geophysical and geochemical data, best fit curves, regression analysis for geochemical data etc)
But isn’t large scale modelling of unknown resources “fringe geoscience”?

Not at all

1) used routinely in other commodities including base metals, precious metals, hydrocarbons etc

2) geologists do it in their heads everyday (target generation, area selection, begging for money from the board) – we just don’t put a number on it
Uranium Resource Modelling

If you can quantify, you can’t plan for it
But why do we want to plan for it?
Uranium Resource Modelling

But why do we want to plan for it?
Uranium Resource Modelling

Why do we want to plan for it?
Purely from a supply-demand perspective:
1) Current supplies (at mid-range demand scenario) only enough until 2035*
2) Not all uranium will be brought into production
3) Long lead in times (particularly) for U mines
4) Projections to 2060 (beyond IR)e.g IAEA Techdoc

*likely to increase due to reactor shut down/stockpiling
Uranium Resource Modelling

*Why do we want to plan for it?*

From a socio-economic perspective:

1) Need for financial analysis
2) Need for comparison with other land uses
3) Need for comparison with other tracts of land
4) Need for consideration of economic/environmental consequences of possible development
5) Security of supply!!!
Uranium Resource Modelling

*Let's look at a few of these factors*

- Security of supply
Uranium Resource Modelling

13 countries represent approx. 96% of total world U resources

<USD130/kgU

1. Australia (3)
2. Kazakhstan (1)
3. Russian Fed/Canada (2)

Other Countries 4%
52% of world production comes from just ten mines in six countries (of 20 producers), these six providing 85% of the world's total mined uranium.
Lets look at a few of these factors
Not all uranium will be brought into production
Let's look at a few of these factors
Not all uranium will be brought into production

Less than half of all discoveries made in the World since 1950 have been put into production

Note: Based on deposits > 100k oz Au, >100 kt Cu, > 250kt Zn+Pb, >10k ton Ni, >5k ton U3O8
or other other minerals of equivalent size
Excludes Bulk Mineral discoveries and satellite deposits found within existing camps

Source: MinEx Consulting © February 2014
Uranium Resource Modelling

Let's look at a few of these factors

Not all uranium will be brought into production

<table>
<thead>
<tr>
<th>Number of Deposits</th>
<th>Conversion Rate</th>
<th>Contained Metal (Premined Resource)</th>
<th>Conversion Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Discovered</td>
<td>Developed</td>
</tr>
<tr>
<td>Gold</td>
<td>51%</td>
<td>1482</td>
<td>760</td>
</tr>
<tr>
<td>Copper</td>
<td>39%</td>
<td>763</td>
<td>298</td>
</tr>
<tr>
<td>Zinc + Lead</td>
<td>58%</td>
<td>204</td>
<td>118</td>
</tr>
<tr>
<td>Nickel (sulphide)</td>
<td>31%</td>
<td>181</td>
<td>57</td>
</tr>
<tr>
<td>Nickel (laterite)</td>
<td>19%</td>
<td>122</td>
<td>23</td>
</tr>
<tr>
<td><strong>Uranium</strong></td>
<td><strong>46%</strong></td>
<td><strong>282</strong></td>
<td><strong>130</strong></td>
</tr>
<tr>
<td>Other</td>
<td>41%</td>
<td>464</td>
<td>190</td>
</tr>
<tr>
<td>Total / average</td>
<td>45%</td>
<td>349</td>
<td>1576</td>
</tr>
</tbody>
</table>

Less than 1 in 5 NiLat deposits get mined. This is driven by their poor economics.

In terms of the amount of metal found, the conversion rates are higher ... i.e. bigger deposits are more likely to be developed.

This figure is probably skewed for Uranium because of long lead-in times (14.7 years – a problem!)

Source: MinEx Consulting © March 2014
Uranium Resource Modelling

*Let's look at a few of these factors*

Long lead-in times (15-20 years getting longer)

Vance, 2005
Uranium Resource Modelling

*Let's look at a few of these factors*

Long lead-in times average >14 years for Uranium

Another critical factor is the business cycle

Uranium prices and discovery rates: 1945-2013

Partly related to timing and cycles, and partly related to uranium-specific development constraints. Discoveries found in 1 boom are often delayed until the next boom. And the delays are getting longer....

**IAEA**

Note: Analysis based on 295 primary uranium deposits >5 kt U₃O₈ found in the World 1945-2013

Source: MinEx Consulting © March 2014
Uranium Resource Modelling

Projections of supply-demand out to 2060

...........necessarily significantly rely either on Unconventional Resources or on resources yet to be found - or both (due to depletion of identified resources)
Uranium Resource Modelling

Projections of supply-demand out to 2060

………….necessarily significantly rely either on Unconventional Resources or on resources yet to be found - or both (due to depletion of identified resources)

……..but long lead-in times mean we have to assess these now!!
**Uranium Resource Modelling**

(June 2012 : 51$/lb U3O8 = 132 USD/kgU)

<table>
<thead>
<tr>
<th>Identified Resources</th>
<th>Undiscovered Resources</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recoverable at Costs</strong></td>
<td><strong>Decreasing economic attractiveness</strong></td>
</tr>
<tr>
<td>USD &lt;40/ kgU (15/lb)</td>
<td>Reasonably Assured Resources</td>
</tr>
<tr>
<td>USD 40-80/kgU (30/lb)</td>
<td>Reasonably Assured Resources</td>
</tr>
<tr>
<td>USD 80-130/kgU (50/lb)</td>
<td>Reasonably Assured Resources</td>
</tr>
<tr>
<td>USD 130-260/kgU (100/lb)</td>
<td>Reasonably Assured Resources</td>
</tr>
<tr>
<td></td>
<td>Inferred Resources</td>
</tr>
<tr>
<td></td>
<td>Inferred Resources</td>
</tr>
<tr>
<td></td>
<td>Inferred Resources</td>
</tr>
<tr>
<td></td>
<td>Inferred Resources</td>
</tr>
</tbody>
</table>

**Decreasing confidence in estimates**
Uranium Resource Modelling

- Reserves
- Resources (IR + Undiscovered Resources)
- Resource Base ("The World")

Decreasing economic attractiveness

Decreasing confidence in estimates

Modified from Tilton & Lagos 2007
2009 Resources

• At least 7 100 000 tU Conventional identified resources recoverable at for all cost categories
• Plus as yet undiscovered deposits 10400000 tU
• However for the countries that do report to Red Book, most do not report Undiscovered Resources
• And for those that do, we do not know how the numbers were made
So how do we assess undiscovered resources?
Uranium Resource Modelling

Quantitative

Nonspatial

Spatial

Qualitative
Uranium Resource Modelling

Quantitative

Ore Reserve Calculations

nonspatial

Spatial

Qualitative

Exploration Targeting
Uranium Resource Modelling

Statistically Driven or knowledge driver

Quantitative

Qualitative

nonspatial

Spatial
Mineral Potential Modelling is common in other commodities – but not common in Uranium.

So there is a need to transfer expert knowledge from other commodities such as copper, gold, nickel.
Large Scale Quantitative Assessments

Rarely publicly exist for uranium, but several early attempts:

1) Quantitative – NURE (National Uranium Resources Evaluation) 1974-1982 for USA ca 3-4 Mt. Being revisited now by USGS.

A possible modern process....
Uranium Resource Modelling

Three-part Resource Assessments

• General locations of undiscovered deposits are delineated from a deposit type’s geologic setting – permissive tracts within metallogenic provinces

• Frequency distributions of tonnages and grades of well-explored deposits serve as models of grades and tonnages of undiscovered deposits

• Number of undiscovered deposits are estimated probabilistically by type

(and then we can do economic filtering!)
Uranium Resource Modelling

3-Part Mineral Resource Assessment

Part 1
Mineral Resource Map

Part 2
Estimated Number of Undiscovered Deposits

Part 3
Worldwide Data on Grade and Tonnage of Deposits

DEPOSITS
1. PORPHYRY COPPER
2. KUROKO
3. EPITHELIAL

Guidelines for New Research
Land Use Decisions
Exploration and Development Strategy

IAEA
Uranium Mineral Potential Modelling

Part 1

- General locations of undiscovered deposits are delineated from a deposit type’s geologic setting

1) Deposit model (genetic is best)
2) Key ingredients (knowledge of processes)
3) Identify mappable criteria (proxies – the data components)
4) Identify the large datasets that show where are the permission tracts
5) Optionally smaller-scale mineral potential mapping
Knowledge components (Kreuzer et al, 2010)

 Mineral Systems Concept

- Focuses on the critical processes that must occur to form a mineral deposit
- Mineral deposit formation is precluded where a particular system lacks (an) essential component(s)
- Mineral deposits are focal points of much larger systems of energy and mass flux
- Requires identification of genetic processes and their mappable criteria at all scales of the system
- Is not restricted to a particular geological setting / deposit type / conceptual exploration model
- Can be linked to concepts of probability that allow for more meaningful and robust relative ranking
Uranium Mineral Potential Modelling

Data components (Kreuzer et al, 2010)

Block models (Fig. 3)
Brief description
Subclasses
Deposit examples
Examples X, Y, Z
Critical processes
Extraction from source
Migration to trap
Formation of trap
Deposition of metal
Outflow
Upgrading
Preservation of metal
Mappable ingredients
Tectonics
Geology
Structure
Mineralization
Geochemistry
Geophysics
Remote sensing
Economic aspects
Examples X, Y, Z
Grade
Tonnage
Mining techniques
Notes
References
Uranium Mineral Potential Modelling

Deposit models (Kreu et al 2010)

IAEA Classification Scheme

22 sub-types

14 principal U deposit types

- Published U deposit classification schemes are invaluable for communication of scientific concepts, reference and learning
- But they comprise a large number of U deposit types and sub-types, which translates into a large number of geological variables
- Working with too many variables is impractical for a continent-wide prospectivity analysis because of potential introduction of bias and reduction of efficiency
- Many geological variables are only evident at the deposit-scale, whereas at larger scales many types of U deposits illustrate fundamental similarities in terms of source, transport and depositional processes
Uranium Mineral Potential Modelling

Key Ingredients (Kreuzer et al 2010)
Uranium Mineral Potential Modelling

Datasets criteria (Kreuzer et al 2010)

Geological regions = assessment units
Uranium Mineral Potential Modelling

Permissive tracts (Kreuzer et al 2010)
Uranium Mineral Potential Modelling

Area selection based upon ranking of potential (cf small scale target generation)
Uranium Mineral Potential Modelling

Similar techniques are used in traditional smaller-scale mineral potential/prospectivity mapping. Some examples from South Australia.
### Uranium Mineral Potential Modelling

An example of IOCGU modelling of mappable criteria – SA (mag-hem distribution)

<table>
<thead>
<tr>
<th>Occurrence name</th>
<th>Residual gravity anomaly area (Sq Km)</th>
<th>Residual magnetic anomaly area (Sq Km)</th>
<th>Residual gravity anomaly maxima (mGal)</th>
<th>Residual TMI anomaly maxima (nT/Tesla)</th>
<th>Coincident anomaly Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Olympic Dam</td>
<td>53.2 (3)</td>
<td>74.2 (3)</td>
<td>5.2 (1)</td>
<td>420 (7)</td>
<td></td>
</tr>
<tr>
<td>Prominent Hill</td>
<td>51.8 (4)</td>
<td>3 (14)</td>
<td>1.9 (6)</td>
<td>2540 (3)</td>
<td></td>
</tr>
<tr>
<td>Torrens Prospect</td>
<td>3.1 (10)</td>
<td>17.5 (12)</td>
<td>2.75 (5)</td>
<td>1580 (4)</td>
<td></td>
</tr>
<tr>
<td>Acropolis Prospect</td>
<td>54.5 (2)</td>
<td>86.8 (2)</td>
<td>4.3 (2)</td>
<td>2900 (2)</td>
<td></td>
</tr>
<tr>
<td>Carrapateena Prospect</td>
<td>13.1 (12)</td>
<td>68.5 (4)</td>
<td>0.55 (12)</td>
<td>100 (13)</td>
<td></td>
</tr>
<tr>
<td>Cockay Swamp Prospect</td>
<td>15 (11)</td>
<td>10.8 (13)</td>
<td>0.6 (11)</td>
<td>230 (10)</td>
<td></td>
</tr>
<tr>
<td>Emmie North Prospect</td>
<td>11.3 (13)</td>
<td>27.5 (9)</td>
<td>1.05 (9)</td>
<td>490 (6)</td>
<td></td>
</tr>
<tr>
<td>Dromedary Dam Prospect</td>
<td>1.5 (18)</td>
<td>61.3 (5)</td>
<td>0.45 (13)</td>
<td>230 (11)</td>
<td></td>
</tr>
<tr>
<td>Punt Hill Prospect</td>
<td>3 (17)</td>
<td>45.8 (8)</td>
<td>0.8 (10)</td>
<td>120 (12)</td>
<td></td>
</tr>
<tr>
<td>Horse Well Prospect</td>
<td>45.8 (5)</td>
<td>95 (1)</td>
<td>1.15 (8)</td>
<td>350 (8)</td>
<td></td>
</tr>
<tr>
<td>Titan Prospect</td>
<td>24.3 (9)</td>
<td>23.5 (10)</td>
<td>3.35 (4)</td>
<td>4100 (1)</td>
<td></td>
</tr>
<tr>
<td>Red Lake Prospect</td>
<td>34.5 (7)</td>
<td>51.7 (9)</td>
<td>3.45 (3)</td>
<td>330 (9)</td>
<td></td>
</tr>
<tr>
<td>Winds Well Prospect</td>
<td>34.9 (6)</td>
<td>22 (11)</td>
<td>1.75 (7)</td>
<td>1270 (5)</td>
<td></td>
</tr>
</tbody>
</table>
3D Mineral Mapping of IOCGU deposits

- Hematite
- Magnetite
- Hematite – Magnetite
- Albite
- K-Feldspar
- Sericite
- Sericite – Chlorite
- Chlorite

500 m x 500 m x 10 m cell size

Alteration Voxet

10x vertical exaggeration
Uranium Mineral Potential Modelling

Calcrete hosted
Uranium potential
• An evolution of approaches…
• Mineral Potential Review
• Assessment of Key ingredients (Mineral Systems approach)
• Mappable Criteria
• **Knowledge Driven GIS**
  • Rank and combine predictor variables
  • Produce prospectivity maps
  • Visual assessment and revision

**Overlay of GIS layers producing prospectivity maps**
Combined U prospectivity (SA)

- An evolution of approaches…
- Mineral Potential Review
- Assessment of Key ingredients (Mineral Systems approach)
- Mappable Criteria
- Knowledge-driven GIS
  - Northern Flinders Ranges Case Study
  - Mineralisation Styles:
    - Hydrothermal Breccia/vein/skarn
    - Granite Sourced (elevated U)
    - Granite Sourced (High U)
    - Radiometric U
    - Combined Prospectivity
In 1996, IAEA publication of the « Guidebook » to accompany the uranium deposits map

582 deposits listed from 48 countries

≥ 500 t U, ≥ 300 ppm

14 parameters recorded

15 deposit types

Creation of the UDEPO Database (Uranium DEPOsits)
In 1995, publication by the IAEA of a geological map « World distribution of uranium deposits » with the geographical distribution of 582 deposits located in 48 countries.
Now we have new-improved UDEPO with >1500 deposits
Three-part Resource Assessments

- General locations of undiscovered deposits are delineated from a deposit type's geologic setting

- Frequency distributions of tonnages and grades of well-explored deposits serve as models of grades and tonnages of undiscovered deposits

- Number of undiscovered deposits are estimated probabilistically by type
Three-part Resource Assessments

• General locations of undiscovered deposits are delineated from a deposit type’s geologic setting

• Frequency distributions of tonnages and grades of well-explored deposits serve as models of grades and tonnages of undiscovered deposits - See talk by my colleague Subhash Jaireth in next session

• Number of undiscovered deposits are estimated probabilistically by type
Three-part Resource Assessments

Verified Grade-tonnage cumulative frequency curves are uncommon for U (but can be generated from UDEPO)

- But need to be generated for each deposit type and region - and need to be statistically valid and internally consistent

Jaireth et al, 2008, AESC
A. The 25 largest porphyry deposits, identified by magma series. A. Giant copper deposits. Data listed in Table 1. B. Giant gold deposits. Data listed in Table 2. D. R. Cooke & P. Hollings. Giant Porphyry Deposits: Characteristics, Distribution, and Tectonic Controls. Economic Geology Augustv. 100 no. 5 p. 801-818.
Uranium Resource Modelling

Exist for porphyry copper

Log ore grade and log ore tonnage quantile-quantile (Q-Q) plots by ore type. Q-Q plots compare the ranked empirical data against the standard normal quantiles and can be used as a visual test of the normality of a dataset (see Walpole et al., 1998, for more details). If the plotted data appear linear in relationship to a line drawn through the first and third quartiles, then strong evidence exists for the normal distribution. Because the data are transformed logarithmically, then the appearance of the linear relationship is evidence for the lognormal distribution. Inspection of the plots indicate that most of the datasets exhibit evidence of lognormality. Important deviations include the appearance of skewness in the VMS plots and thin tails in the Cordilleran oxide porphyry ore-grade plot. M. D. Gerst. Revisiting the Cumulative Grade-Tonnage Relationship for Major Copper Ore Types. Economic Geology May vol. 103 no. 3 615-628
Observed (solid lines) and predicted (dashed lines) cumulative distribution functions (cdf). Similar to the Q-Q plots shown in Figure 1, Figure 3 can be used as a graphic aid to assess the appropriateness of the log-normal distribution assumption. The method to create Figure 3, and its use in calculating the Lilliefors’ test statistic in Table 3, is discussed in the Appendix. The curves shown for the global VMS data are those with the outliers removed. M. D. Gerst. Revisiting the Cumulative Grade-Tonnage Relationship for Major Copper Ore Types. Economic Geology May vol. 103 no. 3 615-628.
Uranium Resource Modelling

Three-part Resource Assessments

• General locations of undiscovered deposits are delineated from a deposit type’s geologic setting

• Frequency distributions of tonnages and grades of well-explored deposits serve as models of grades and tonnages of undiscovered deposits

• Number of undiscovered deposits are estimated probabilistically by type
Three-part Resource Assessments

- General locations of undiscovered deposits are delineated from a deposit type’s geologic setting

- Frequency distributions of tonnages and grades of well-explored deposits serve as models of grades and tonnages of undiscovered deposits

- Number of undiscovered deposits are estimated probabilistically by type
Exist for porphyry copper

Histogram of porphyry copper deposit densities per 100,000 km². Singer & V. I. Berger. Porphyry Copper Deposit Density. Economic Geology May 2005 v. 100 no. 3 p. 491-514.
Uranium Resource Modelling

Exist for porphyry copper

Exist for porphyry copper

Porphyry copper control area exposed vs. number of deposits with 90 and 10 percent confidence limits for number of deposits. Singer & V. I. Berger. Porphyry Copper Deposit Density. Economic Geology May 2005 v. 100 no. 3 p. 491-514.
Uranium Mineral Potential Modelling

The end (update result)

Global Mineral Resource Assessment

Estimate of Undiscovered Copper Resources of the World, 2013

Introduction

Informed planning and decisions concerning future mineral supplies, sustainability, and trade depend on an understanding of the world’s mineral resources and their potential for future development. This database presents the results of an analysis of the world’s undiscovered copper resources based on the methodology described in United States Geological Survey (USGS) Circular 1386. The following results should be viewed as a snapshot in time, and the numbers might change as new data become available.

Table 1. Assessment results for identified and undiscovered copper worldwide

<table>
<thead>
<tr>
<th>Region</th>
<th>Deposit type</th>
<th>Identified resources (Mt)</th>
<th>Identified resources (Mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa and the Middle East</td>
<td>Porphyry</td>
<td>300</td>
<td>1,500</td>
</tr>
<tr>
<td></td>
<td>Sediment-hosted</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>3,500</td>
<td>2,100</td>
</tr>
</tbody>
</table>

The U.S. Geological Survey (USGS), the principal Federal provider of research and information on mineral and energy resources, has compiled a geology-based, cooperative international assessment of copper resources of the world. Collaborators in this assessment include national geological survey and industry and academic organizations.

This assessment indicates that in addition to identified copper resources of 2,800 million metric tons, a total of 3,500 Mt of undiscovered copper is expected in all regions spanning six continents (Table 1). Annual U.S. copper consumption (in 2 Mt) is 60%. The methodology for the assessment amounted of (i) compilation of geoscience data and characterization of identified deposits for each area considered, based mainly on published resources; (ii) definition of geographic areas (units) within which the geology and deposits for specific types of copper deposits are grouped; (iii) evaluation of amounts of metal in typical deposits by using geostatistical models; and (iv) probabilistic estimation of numbers of undiscovered deposits of specific types and tonnages using Monte Carlo simulations. Finally, results for individual areas were aggregated into regional groups, accounting for some degree of uncertainty.

Resource Summary

The USGS assessed undiscovered copper in two deposit types that account for about 90 percent of the world’s copper supply. Porphyry copper deposits account for about 60 percent of the world’s copper. In porphyry copper deposits, copper ore is disseminated in igneous rocks. Sediment-hosted stratiform copper deposits, in which copper is concentrated in layers in sedimentary rocks, account for about 30 percent of the world’s identified copper resources. Globally, metals in these two deposit types produce about 12 kt of copper per year.
The end (update result)

This is what we want for Uranium