British Geological Survey
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Gateway to the Earth

Quantitative Evaluation of Geological Risk

FINEX '18

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Outline

- Why
- Targeting
- Mineral Systems
- Prospectivity Analysis
    - Requirements
    - Methods
    - Tools
- Data Management

Conclusions

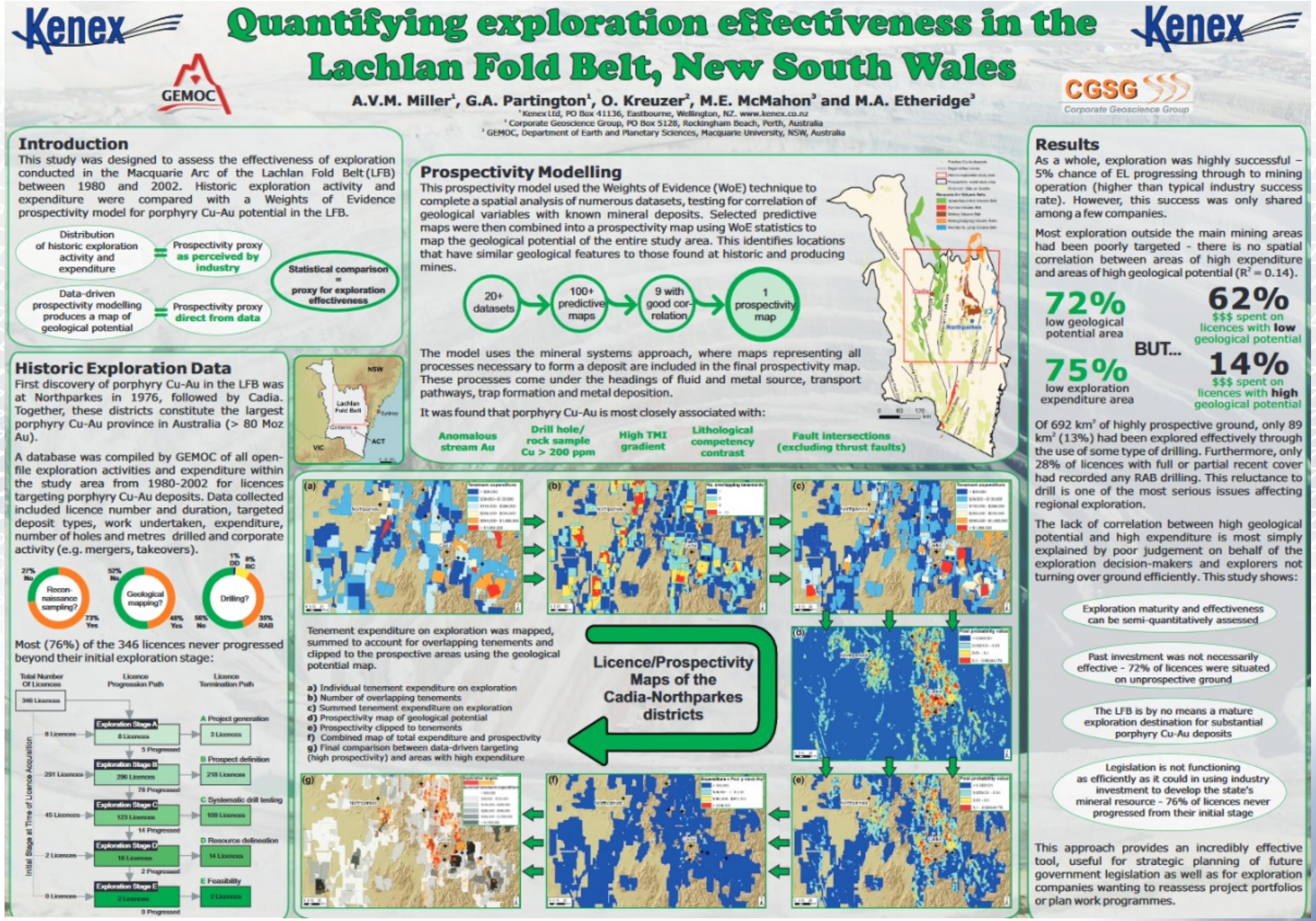
- Prospectivity Targeting
- Decreases risk
- Focuses exploration efforts
- Increase efficiency of exploration spending
- Effects on budgeting

The Reason

- Are you spending your money wisely?
  - How do you test this?

The Reason - Example

- 22 years expenditure data
- No spatial correlation between areas of high expenditure and areas of high geological potential (R= 0.14)
- 72% licences on unprospective ground

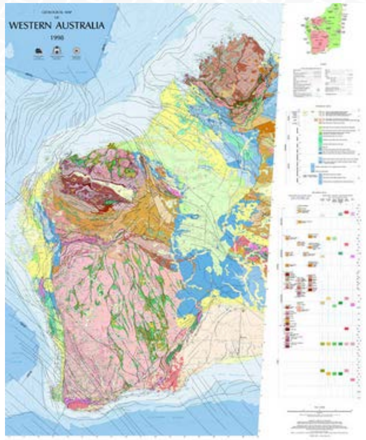


The Reason - Example

Historical discoveries - Current Methods

- Prior Knowledge
- Field Relationships
- Artisanal/Historical Workings
- Geophysical Anomalies
- Geochemical Anomalies
  - Prospectivity Analysis

Decreasing Risk?



Targeting

- Targeting - Critical first stage in the exploration business

- A good geoscientist uses the following concepts and processes in their work everyday

- Prospectivity Mapping - **What can it do for you?**

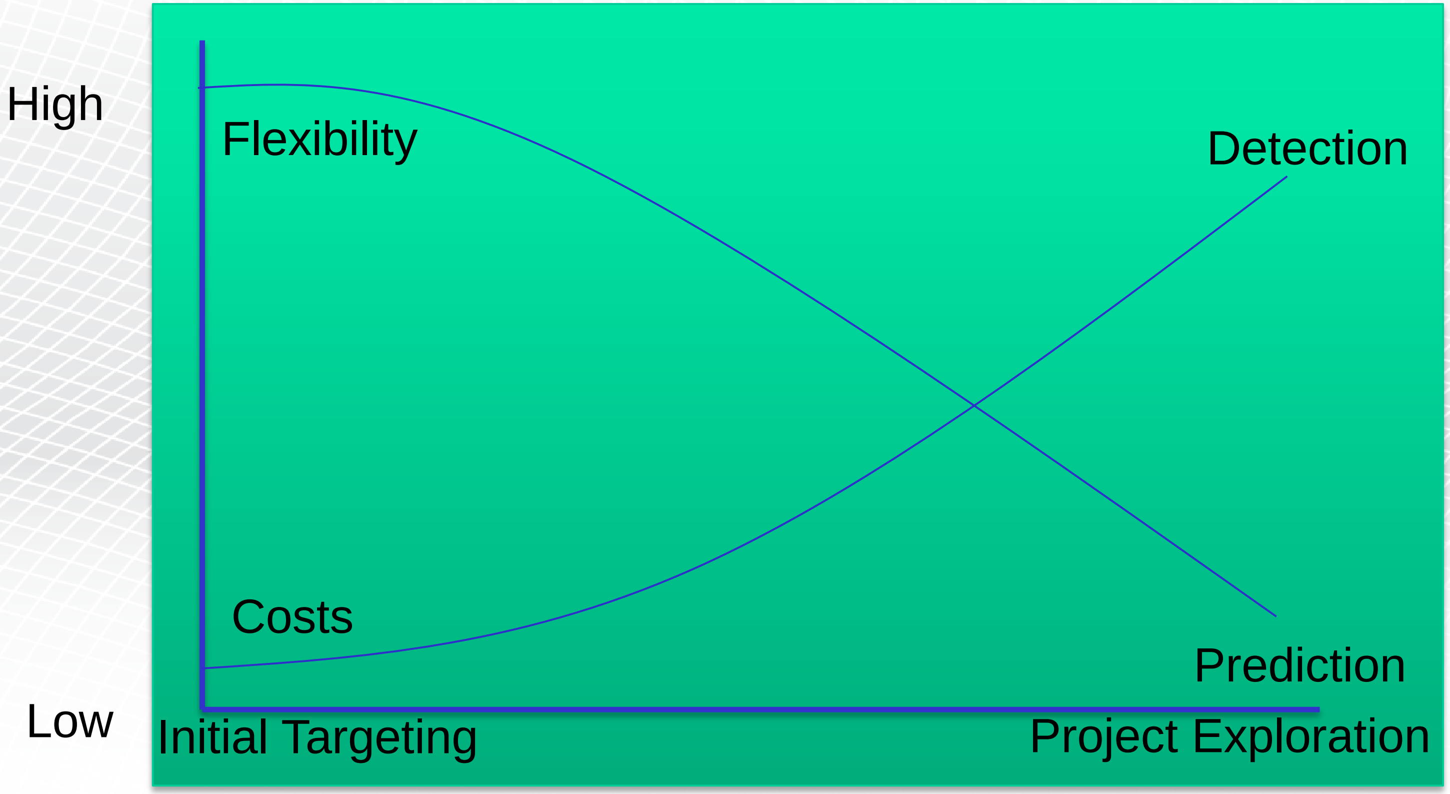
Targeting Process

Simplified

1. Business Strategy
2. Conceptual targeting model
3. Geodatabase to support targeting model
4. Generate Targets
5. Explore – direct testing of mineralised system
6. Evaluate Performance

(Hronsky & Groves, 2008)

Opportunity Cost of poor initial targeting is high



Modified from McCuaig and Hronsky (2000) and Hronsky and Groves (2008)

Targeting Science

Mineral Systems – Define key criteria of ore forming processes at different scales

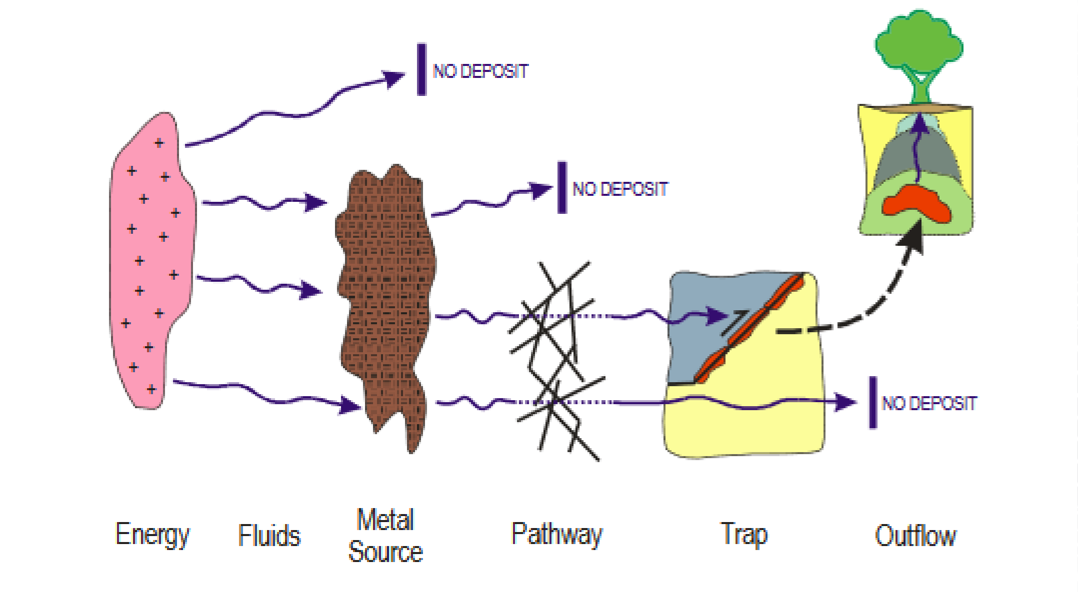
Discern physical properties which are tied to those criteria – practical proxies

Integrate scientific understanding within the economic and practical limits of the exploration industry

Mineral Systems

Focus on processes not characteristics

- Source
- Fluid flow
- Conduits
- Trap/Chemical Scrubber
- Preservation



Target geological features of those processes

Chemical Scrubber > Wallrock reactions > key alt minerals/rocks with favourable chemistry > remote sensing response/solid geology interp

After Miller, 2013

Mineral Systems

Mappable proxies often dependant on scale

Orogenic Gold System vs Komatiite hosted Ni mineral system

Similar critical processes

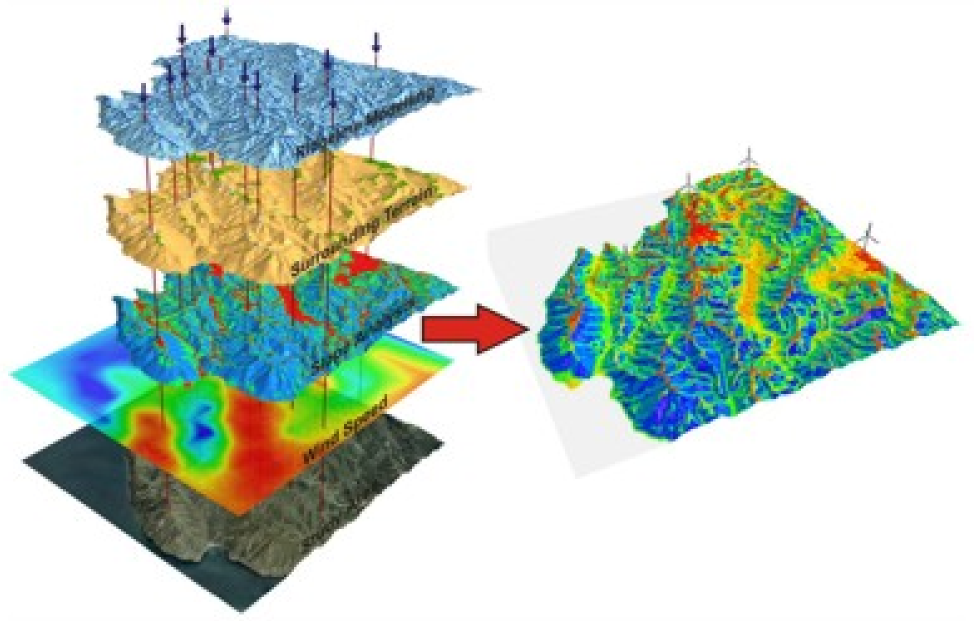
	Source	Active Pathway	Fluid Throttle (physical)	Deposition (chemical)
District	Critical • Geodynamic setting • Major metallogenic epoch	• Lithospheric architecture • Long-lived features • Paleocraton margins	Large scale damage zones	
Camp	Important • P-T windows • Magma series	•4D structure model •Crustal architecture	• Small-scale damage zones • Complexity • Broad permeability barriers	• Alteration • Metal anomalism • Chemical gradients
Prospect	Less relevant	• Large scale damage zones	• Small-scale damage zones • Competency contrasts • Kinematic framework	• Alteration • Metal anomalism • Chemical gradients

	Source	Active Pathway	S saturation (chemical)	Trap (physical)
District	Critical • High degree partial melts • Major metallogenic epoch	• Lithospheric architecture • Paleocraton margins		
Camp		•Synvolcanic crustal architecture	• Magmatic sulphides • Chalcophile enrichment	• Olivine-rich cumulate
Prospect	Less relevant			• Channels and channel size • Amygdaloidal flows • Structural complexity

After McCuaig, 2010

Prospectivity Analysis

- Integrate knowledge and spatial data
- Can be quantitative
  - Incorporate into commercial risk analysis
  - Potential to aid valuations
- Spatial analysis decreases geological bias & personal bias
- Possible in data poor and data rich areas, at all scales for all deposit types

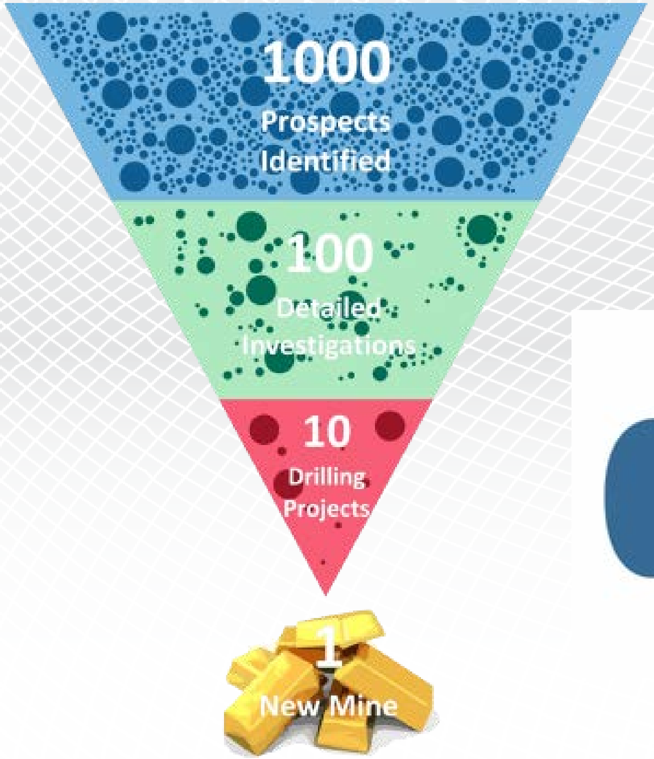


Prospectivity Approaches – End Members

- Conceptual & Empirical
- Conceptual
  - Uses all data, spatial data, reports, published & unpublished literature
  - Biased by analysts subjective interpretation, proclivity for specific models, personal experience
- Empirical
  - Mathematical models of spatial associations of targeting criteria
  - Using existing deposit locations

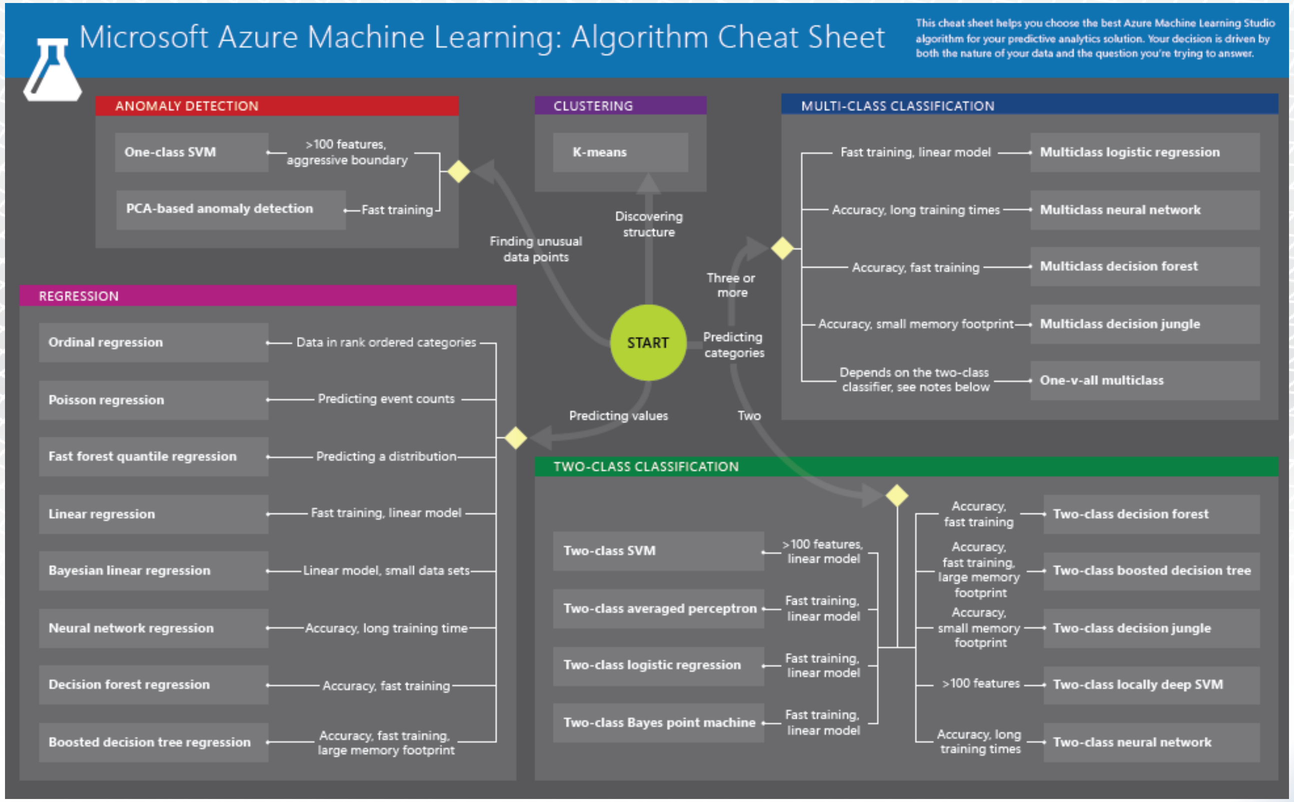
Techniques

- Manual
  - GIS
  - Semi – Quantitative
- Automated
  - Weights of Evidence
  - Neural Networks
    - Supervised
    - Unsupervised
  - Fuzzy Logic
  - Random Forests
  - Logistic Regression



New Techniques

- Cloud based platforms with machine learning tools
  - Hypercube
  - Azure platform
    - Decision forests



Techniques - Manual Analysis

- Team Geologists
- Search targeting criteria as defined in Model
- Targets Relatively ranked

$$P_{\text{mineralization}} = P_1 \times P_2 \times P_3 \times P_4$$

- Subjective believe to quantitative Probability – Sherman – Kent Scale (Jones & Hillis, 2003)

(Lord et al, 2001)

Geological Rules

- Statements that guide the process of prospectivity analysis
- Embrace evidence-based geology – conceptual approach
  - *Geological rules look for evidence of depositional processes – empirically based*

Analysis for Cu-Au porphyry deposits – *Criteria*

Regional scale – permissive areas

- Tectonic criteria (A) (Conduit)
- Magmatic criteria (B) (Source)

District scale – favourable areas/highly favourable areas

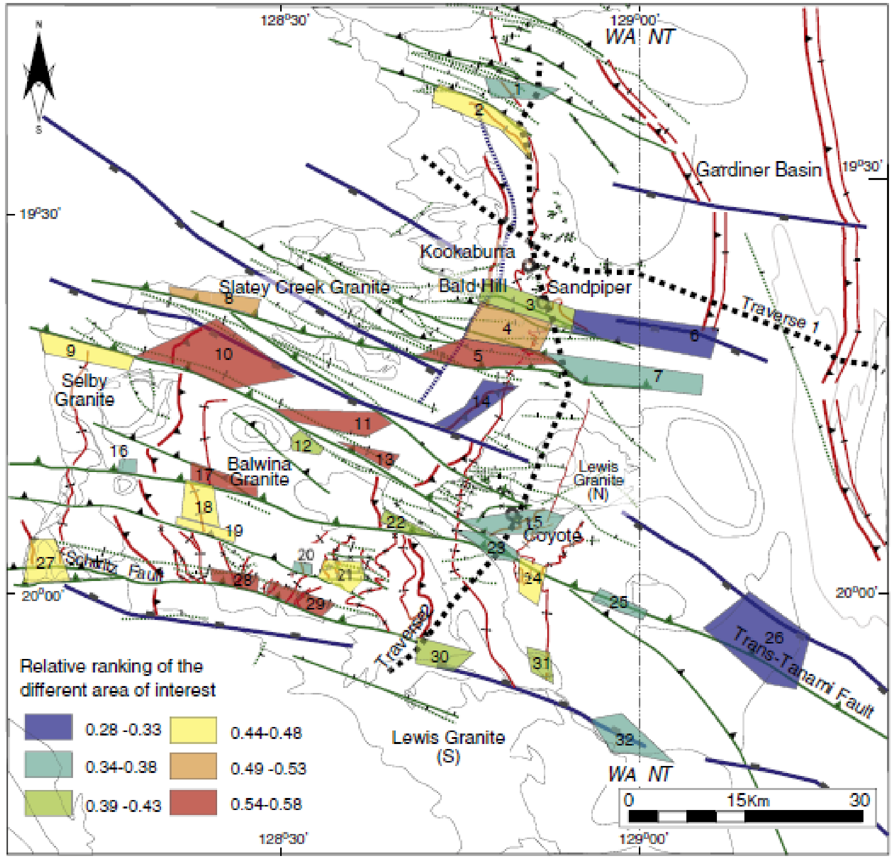
- Magmatic criteria(A) (Chemical Scrubber)
- Structural criteria(B) (Trap/Conduit)
- Alteration/mineralization criteria (C) (Chemical Scrubber)

Local scale – prospective areas

- Structural criteria(A)
- Lithological criteria (B)
- Alteration/mineralization criteria (C)

Techniques - Manual Analysis

Target	Pathway	Justification for ranking	Physical throttle	Justification for ranking	Chemical scrubber	Justification for ranking	Relative ranking
1	0.7	Minor D_{GTO2} fault	0.7	D_{GTO1} anticline	0.7	Stubbins	0.34
2	0.9	D_{GTO2} fault related to D_{GTOe} thrust fault	0.75	D_{GTO1} anticline/Footwall of D_{GTO2}-e fault	0.7	Stubbins	0.47
3	0.75	D_{GTO2} fault	0.8	NE–SW D_{GTO2} fault	0.7	Stubbins	0.42
4	0.9	D_{GTO2} fault related to D_{GTOe} thrust fault	0.8	NE–SW D_{GTO2} fault	0.7	Stubbins	0.50
5	0.9	D_{GTO2} fault related to D_{GTOe} thrust fault	0.9	D_{GTO2} anticline	0.7	Stubbins	0.57
6	0.8	D_{GTOe} fault	0.8	Hangingwall of D_{GTO2} fault	0.5	Killi Killi	0.32
7	0.9	D_{GTO2} fault related to D_{GTOe} thrust fault	0.85	End of the D_{GTO2} anticline	0.5	Killi Killi	38



(Joly et al, 2012)

- Gold in the Tanami
- Areas defined manually
- Quantitative ranking

Numerical probability value	Subjective probability estimates
0.98–1.00	Proven; definitely true
0.90–0.98	Virtually certain; convinced
0.75–0.90	Highly probable; strongly believe; highly likely
0.60–0.75	Likely; probably true; about twice as likely to be true as untrue; chances are good
0.40–0.60	Chances are slightly better than even or slightly less than even
0.50–0.50	Chances are about even; it can be true or not
0.20–0.40	Could be true but more probably not; unlikely; chances are fairly poor; two or three times more likely to be untrue than true
0.02–0.20	Possible but very doubtful; only a slight chance; very unlikely indeed; very improbable
0.00–0.02	Proven untrue; impossible

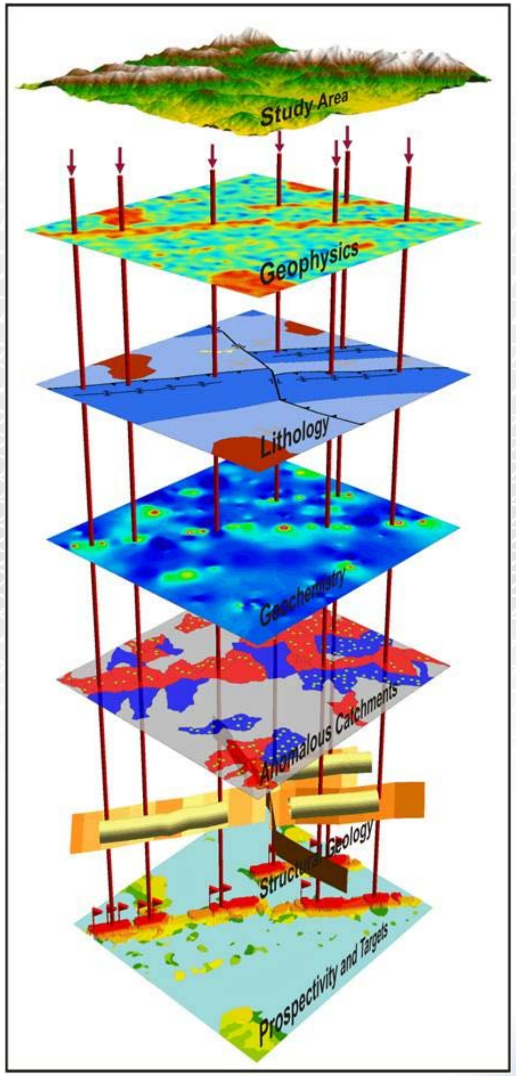
(Jones & Hillis, 2003)

Techniques – Weights of Evidence

- Developed for medical diagnosis
  - Adapted to exploration in late 80’S
  - Mineral system process = symptoms
  - Mineral deposit = disease
- Quantitative ranking – probability based

Method

- Generate binary or multiclass maps of data relevant to mineral systems process
- Use training data to establish spatial correlation (known occurrences/mines)
- Combine maps to produce probability map



Techniques – Weights of Evidence

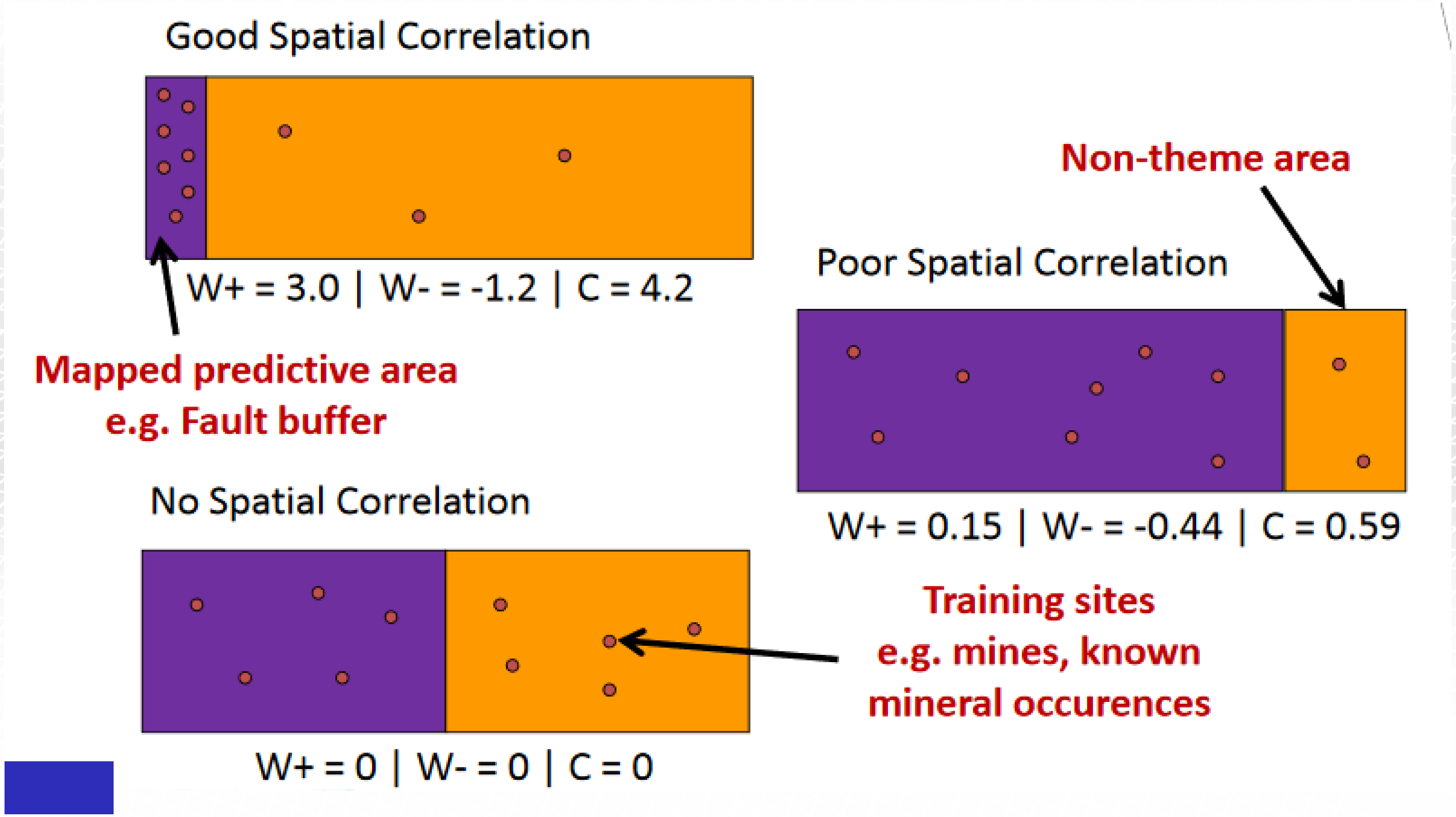
W+ = natural log = $\dfrac{\text{Proportion of deposits on theme}}{\text{Proportion of total area occupied by theme}}$

W- = natural log = $\dfrac{\text{Proportion of deposits not on theme}}{\text{Proportion of total area not occupied by theme}}$

W+ > 0 indicates positive association with theme
W- < 0 indicates negative association with non - theme

C > 3.0 Strong correlation
1.0 < C < 3.0 Moderate correlation
C < 1.0 Weak to poor correlation
Theme = Lithology/distance from structure/geochemical/geophysical response > X

Techniques – Weights of Evidence

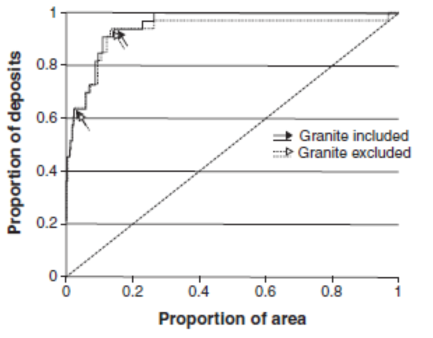


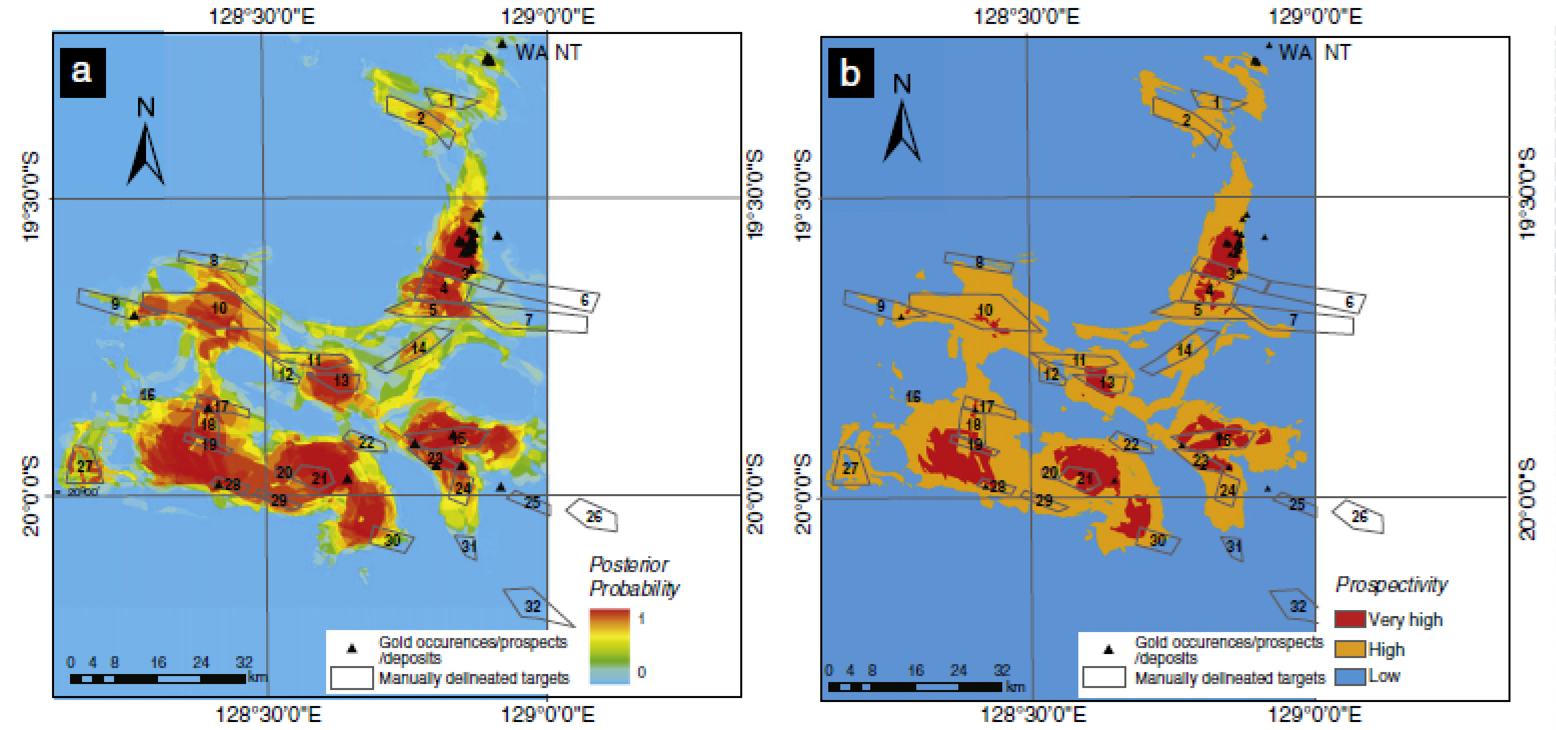
After Payne et al, 2014

Techniques – Weights of Evidence

Details of the WofE analysis of gold prospectivity analysis for the West GTO. See text for discussion.

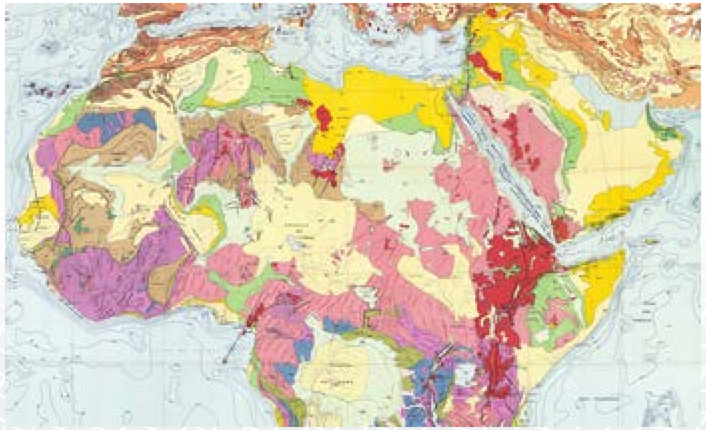
Map no.	Predictor map	Preprocessing	Id	Class	Area (Sq km)	No of training points	W+	S-W+	W−	S-W−	Contrast	Std. contrast
(A) Source												
1	Proximity to granites	The spatial association between granites and the known gold deposits is maximized within 11.7 km. This distance was used as a threshold to convert the continuous-scale distance map into a binary predictor map.	0	Granites	2957	0	0	0	0	0	0	0
			1	>11.7 km from granite	5466.8	1	−2.235	1	0.3022	0.177	−2.5373	−2.4982
			2	<11.7 km from granite	7083.3	32	0.7552	0.177	−2.888	1	3.6435	3.5874
(B) Pathway												
5	Proximity to DGTO1 Faults	This continuous-scale distance map was converted into a binary predictor map by using 7.5 km as the threshold buffer distance within which the spatial	0	No data	10,242	1	−3.084	1	1.0534	0.177	−4.1372	−4.0735
			1	>7.5 km from D_{GTO1} fault	1815.2	4	0.0349	0.501	−0.005	0.186	0.0397	0.0743
			2	<7.5 km from	3449.6	28	1.3447	0.19	−1.637	0.447	2.9819	6.137



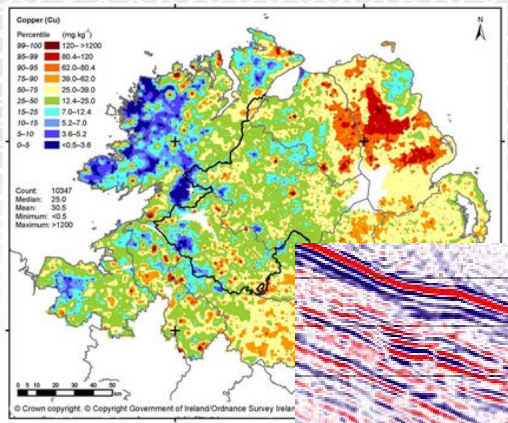


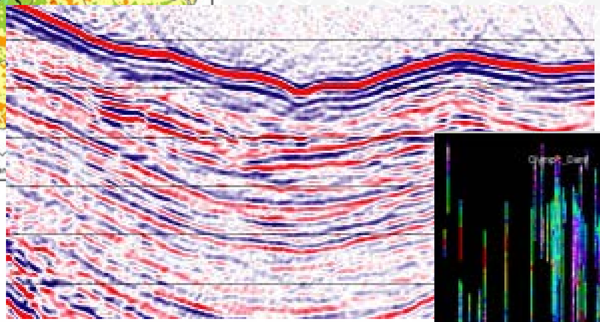
After Joly et al, 2012

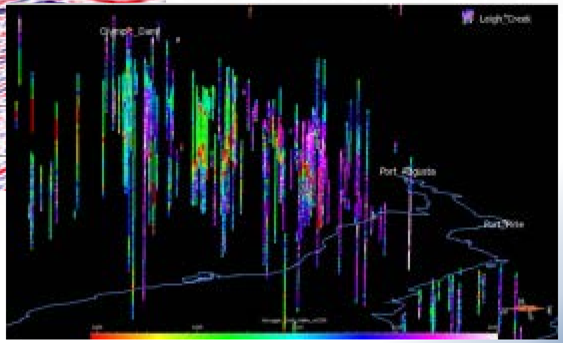
Data Required



- Minimum
  - Geological Map
- All data useful and can be integrated
  - Geochemistry
  - Geophysics (Ground/Airborne - Magnetic, Gravity, Radiometric/inversion models)
  - Geochronology
  - Land Use/Restricted Areas
  - Drillholes/Water bores
  - Seismic
  - Mines Operating/Historical
  - Remote Sensing
  - Exploration reports
  - Hyperspectral - Remote sensing/Hylogger







Data Availability

- Always a challenge
- However 45% global exploration spending is in
- Australia, Canada, US, Mexico or Europe
- All have excellent government geodata
- Often also have access to industry data

- **No excuses!**

(S&P Global Market Intelligence)

Tools available

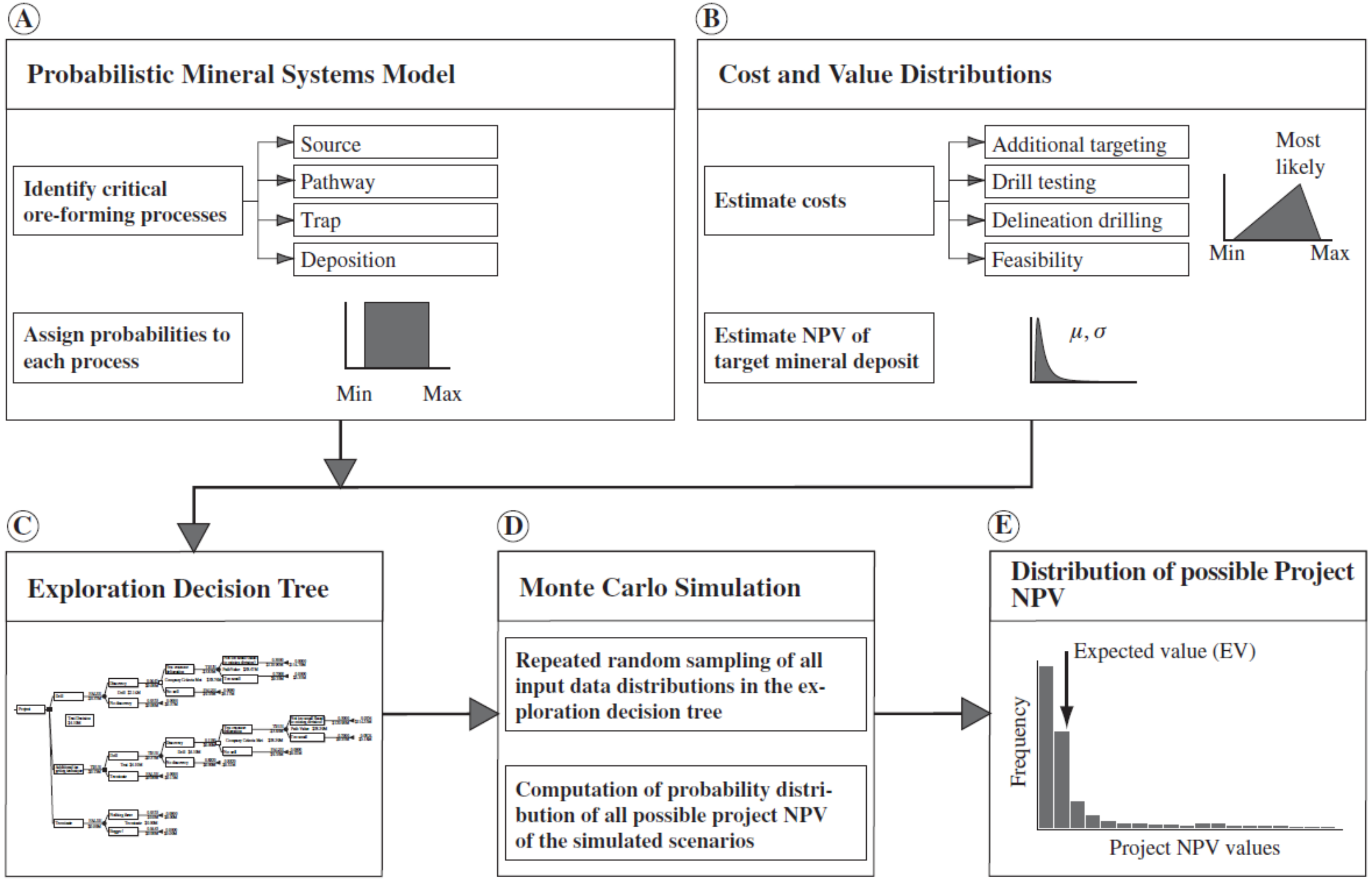
GIS – for manual semi-quantitative

Plug-ins for ArcGIS – Arc Spatial Data Modeller

Proprietary solutions – Often use same maths as above but repackaged

Libraries for R or Python

Risk Analysis



Link geologic potential – probability adjusted financial value

Consistent ranking and evaluation

Plan exploration based on EV (NPV of a drill decision)

(Lord et al 2001 & Kreuzer et al, 2008)

Other Comments – Open Standards

Software

QGIS - http://qgis.org/en/site/

Data Storage

Using proprietary data formats costs time = $$$

There are open international standards

- Geopackage/Spatialite vs ESRI Geodatabase
- Spatialite vs Shapefiles
- SDL vs ESRI lyr files
- PostGIS vs Aquire/Oracle

Any Questions?

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