Traps for the Unwary Subsurface Geoscientist

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Role of the Earth Scientist

• Selection of an appropriate method to predict the unknown value of an attribute at an unmeasured location.
  — Linear regression
  — Mapping (by hand, triangulation, kriging etc)

• Geologist
  — Maps of reservoir properties

• Geophysicist
  — Maps of structure, facies architecture and attributes

• Petrophysicist
  — Predictions of hydrocarbon pore volume and permeability
1. DETERMINISTIC MAPS
3 Types of Model - Deterministic and Stochastic

• Deterministic
  – A model from which predictions are determined directly via a functional relationship.
  – E.g. Darcy’s Law, chemical reaction rate, laws of motion

• Best Estimate
  – A model which minimises the prediction error.
  – Kriging, regression models, Wyllie’s Equation.

• Stochastic
  – A model which generates non-unique solutions.
  – A model which honours higher order statistics.
Best Estimate vs Stochastic

- These are complementary. Choice depends on the answers required
  - Best estimate for prediction/prognosis (linear problems)
  - Stochastic for volumes/connectivity/fluid flow behaviour (non-linear problems)
- The best estimate is the average of the (infinite) set of realisations.
- Different best estimate cases are NOT realisations
- In geostatistics, a spatial best estimate is called kriging - a minimum variance of error
Kriging = Mean of Realisations

\[ \frac{1}{n} \times \sum_{i=1}^{i=n} \]
2. THE DATA
Linear Regression and Cutoffs

- Equation is best predictor of permeability from porosity (under certain assumptions)
- Cutoff 1mD = 9.5% porosity
- Porosity cutoff (B+D):
  - 92.5% net
- Permeability cutoff (A+B):
  - 82.5% net
- It is only correct to do this if $r \approx 1$!
- Cutoff calculations require higher order statistics to be honoured
No cutoffs!

- Cutoffs are wrongly used for estimating
  - Porosity
  - Net:Gross
  - Net pay
  - Saturations
  - Permeability
  - Gross rock volume

- Cutoffs on best estimates = BIASED ESTIMATES

- Cutoff calculations should only be applied to realisations
  - Simulated using geostatistics
  - Actual exhaustive subsurface measurements
Is it valid to map…?

- Depth ........................................... ✓
- Time ........................................... ✓
- Velocity ....................................... ✓
- Thickness ..................................... ✓
- Permeability ................................. ✓ (If log transformed)
- Porosity ....................................... ✗
- Net:Gross ................................. ✗
- Saturation ................................. ✗
Average Net:Gross

• Well #1
  — N:G = 20%

• Well #2
  — N:G = 50%

• Therefore average N:G
  — = (50 + 20)/2
  — = 35% ✗

• THIS IS WRONG!

• Well #1
  — Gross thickness = 10 m
  — Net thickness = 2 m

• Well #2
  — Gross thickness = 40 m
  — Net thickness = 20 m

• Therefore:
  — Total net thickness = 22 m
  — Total gross thickness = 50 m

• Average N:G = 44% ✓
3. THE EXPERIMENTAL VARIOGRAM
A “Good” Variogram

Webster and Oliver (1992)

Variograms from 49 points on a 7 x 7 grid at 15 unit intervals

Variograms from 225 points on a 15 x 15 grid at 7 unit intervals
Variogram of 7 wells

![Graph of a variogram with distances on the x-axis and semivariogram values on the y-axis. The graph shows points for tail, phiH, head, phiH, and direction 1.]
4. THE VARIOGRAM MODEL
Key Components of Variogram Model

- Slope at the origin (model type)
- Nugget effect
- Range
- Sill
- Anisotropies
Comparison of Kriging Different Variogram Model Types

Exponential  Spherical  Gaussian

(Range = 38 nodes)
Comparison of Realisations Different Variogram Model Types

Exponential  Spherical  Gaussian

(Range = 38 nodes)
5. THE FASHIONABLE OBJECT
Reservoir Models Today

• Too big, too complex, too ambitious
  – Build simple, generic models
  – Sector models
  – Focus on flow units, not facies

• Finished Late, never updated, too few realisations

• Objects only, SIS only, TG only: algorithm fixation
  – Consider relevance of different methods to model the problem at hand
  – SIS and TG are the “geostatisticians choice”
  – Objects are the “geologists choice”
  – Parameterising objects is difficult from well data
Facies Models

• Indicator/Truncated Gaussian (Pixel) methods
  — Spatial model honoured independently for each facies ✓
  — Sound theory of spatial correlation ✓
  — Any facies organisation ✓
  — Do not look very “AAPG Bulletin” ❌
  — Entropy too high? ❌

• Object Models
  — Weak spatial theory. ❌
  — Trivial best estimate equivalent is average (stationary) N:G ❌
  — Parameters estimated from analogues/surmise ❌
  — Entropy ok ✓
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</table>

- **Thickness**: 2 – 4 – 10 m
- **Width**: Thickness * 25
- **Orientation**: 10 – 50 – 90
- **Amplitude**: Width
- **Wavelength**: 1000 – 3000 - 5000
- **Stop Criterion**: 26 %
- **Branch Points**: 10 – 20/1000
- **Branch Location**: 0 - default
Reservoir Model Weaknesses

- All effort is focussed on lithofacies
- Porosity is often kriged
- Coupling of porosity and permeability fields ignored
- Outcrop analogues are a poor substitute for multipoint statistics.
  - All projects use the same channel width/thickness references
  - Not enough outcrop exposure/study
  - Well statistics are censured
- More use of shallow, high resolution 3D seismic
6. BEYOND THE VARIOGRAM
Entropy

- Entropy $H(X)$ is a statistic that quantifies the intrinsic variability of some variable $X$ and can be computed from the pdf $p(X)$:

$$H(X) = -\sum_{i} p(x_i) \log[p(x_i)]$$

- Consider a categorical value $X = \{\text{shale}, \text{sand}\}$
  - If $P(X) = \{0.5, 0.5\}$ then $H = 0.693$
  - If $P(X) = \{0.9, 0.1\}$ then $H = 0.325$

- If entropy is reduced, then there is now less disorder, less uncertainty and therefore more predictability

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Muikerji et al (2001)
Entropy

• Consider a univariate variable $X = \{-2, -1, 0, 1, 2\}$

• If $P_1(X) = \{0.03, 0.44, 0.06, 0.44, 0.03\}$
  — Variance = 1.12
  — Entropy = 1.10

• If $P_2(X) = \{0.09, 0.20, 0.42, 0.20, 0.09\}$
  — Variance = 1.12
  — Entropy = 1.44

• Variance is a measure of deviation from central tendency and is not always sensitive to uncertainty. $P_1$ and $P_2$ have the same variance but $P_2$ has larger entropy and is therefore more uncertain
  — after Mukerji et al (2001)
7. THE TREND

(Getting the Drift)
Variography
Normalised Acoustic Impedance

\[ \gamma \]

Distance

Semivariogram
tail:NormAI
Re head:NormAI
Re direction 1

\[ 0.0000 \]
\[ 0.0050 \]
\[ 0.0100 \]
\[ 0.0150 \]
\[ 0.0200 \]
\[ 0.0250 \]

Distance

0.  2000.  4000.  6000.  8000.  10000.
Petroleum Case Study
07 Wells
Variogram with Trend

Seismic TWT

Easting
Northing

0 10360
0 10360

688.000 708.000 728.000 748.000
Variogram with Trend

\[ \gamma \]

Distance

Semivariogram  tail:TWT  ms head:TWT  ms  direction 1

\[ \begin{array}{cccc}
0. & 4000. & 8000. & 12000. \\
0. & 500. & 1000. & 1500. & 2000.
\end{array} \]
**Explanation of Stationarity**

Stationary Stochastic Process

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- Stationarity is a property of the *model* not of the data
- Stationarity is a *decision*
Trend or Stationary Time Series?

![Graph showing temperature anomaly over time](image)

- **Global Temperature** (meteorological stations)
- **Temperature Anomaly (°C)**
  - Annual Mean
  - 5-year Mean

Time periods: 1880 to 2000
1000 year climate

- From the Intergovernmental Panel on Climate Change report 1995 (which stated there is “a discernible human influence on global climate”)
3000 year climate

8. WORST CRIMES

(Some conclusions)
Worst Crimes

• Confusing maps with reality
  – Subsurface maps are representing the local expectation, they are a mathematical construct
  – Cartographers represent on a sheet of paper *that which they already know*
  – Geologists, geophysicists and petrophysicists *make predictions of attributes at unmeasured locations*

• Cutoff calculations should not be applied to estimates, ONLY to realisations

• There is no “Quantification of Uncertainty”!

• We can explore uncertainty with geostatistics.
Unknown uncertainty

- Unknown unknowns
- “How can we know that which we do not know?”
- “And having discovered something new, how can we be sure that that is what we did not know?”
  — Socrates