Fusion methods for strata interpretation and geochemical interpolation

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CET Members’ Day 2019
Fusion methods

   • Assistive tools for stratigraphic interpretation, incorporating multiple datasets.

2. 3D Geochemical Interpolation Supported by Geophysical Inversion Models
   • Spatially interpolates drill core properties (in 3D) while leveraging structure in collocated 3D geophysical inversion models.

Questions at the end (and during the tea break)
Machine Assisted Drillhole Interpretation for Iron Ore Resource Evaluation Drillholes in the Pilbara

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Drillhole Interpretation

- Goal to identify strand units within a drillhole
- Interpretations from multiple holes are used as the basis for block modelling
Drillhole data

- Gamma, magnetic susceptibility, density (10cm)
- Geological logging of RC chips (2m intervals)
  - Later validated against assays
- Assays (2m)
- Surface geology
- Prior models (wider spacing)
Machine Assisted Drillhole Interpretation (MADI)

Drillhole data

Gamma
Geological logging
Assays

Logged stratigraphy
Historical model & surface geology

CNN classifiers

Interactive Visualisation

Decision Support

Optimisation

Constraints include stratigraphic sequence, strand thickness, structures

Geologist
Gamma logs

- Specific gamma “signatures” can be used to identify shale bands
- Consistent across Pilbara
- Affected by hydration
- 10cm measurements
Gamma signature classifier

- Convolutional neural net classifiers output the likelihood that the gamma signal at a particular depth represents a known signature, within a strand.
- We aggregate the output in 2m intervals for consistency with other logged data.
Assays

- Fe, SiO₂, Al₂O₃, P, S, MgO, CaO, Mn, TiO₂, Total LOI
- Each element’s percentage is input to a separate NN, which provides classifier outputs for each strand.
- Similar classifier structure
Geological logging

• Intervals logged as compositions of material types encapsulating:
  • Theoretical chemistry
  • Physical properties: Hardness, lump %, density…
• Example: BIF20 GOE50 GOL20 SHL10
• Each material type’s percentage is one input to a separate NN which provides classifier outputs for each strand.
Historical model & mapping

- Holes often drilled between existing wider-spaced holes, for which prior models were created.
  - Intersect hole with prior model
  - Also incorporate surface geology as a constraint for the first interval
Logged stratigraphy

- Stratigraphy as logged at the rig, which can be added as another bias term.
Optimisation

- Maximise confidence of an interpretation, subject to stratigraphic sequence, strand thickness
  - User-editable
  - Real-time update
  - 3D context shown simultaneously
Case study

- Interval-by-interval analysis of strands
- Remember that the manual interpretations are interpretations rather than the ground truth.
  - Geologists may adjust strand boundaries to result in a smoother global model
  - Some strands covering a small number of intervals at the top or bottom of a hole may be completely omitted to simplify modelling
Case study

- We compared “prepared” results against manual interpretations for 396 holes covering 22,858m
  - “Prepared” as it is intended for review and adjustment as per existing process
- High phosphorus Brockman martite-goethite type deposit
- Mineralisation occurring in the Joffre Member (itself divided into strands J6, youngest, to J1, oldest), Whaleback Shale (strands WS2 and WS1) and Dales Gorge Member (strands DG3 to DG1), with minor mineralised detrital material flanks on the north and south margins of the deposit.
- Deposit lying on the southern limb of a major E-W striking F2 syncline, so at a local scale it exhibits a gentle dip to the north
- Contains late stage dolerite intrusions along NW-SE weaknesses caused by faulting.
Adjacent strand analysis

• We compared the manually-interpreted strand and the algorithm-interpreted strand for each interval
• Each entry is the number of intervals with that combination of prepared and manually interpreted strands
• Ideally, all entries will lie on the diagonal.
Adjacent strand analysis

- The prepared interpretation was exactly the same as the manual interpretation for 7783 intervals (68.1%).
- A large amount of errors are due to strands being misclassified as the strand immediately preceding or succeeding it in the sequence.
  - Manual interpretation involves adjusting boundaries to produce a smoother model
- We get matches for adjacent strands in 9821 (85.93%) of intervals.
Summary

- System for interpreting drillholes:
  - Independently classifies strand responses for each interval for each dataset
  - Allows user to weight individual classifier responses
  - Applies a novel algorithm for producing geological interpretations of the data best satisfying stratigraphic sequence and thickness constraints
  - Fast and objective
- Results demonstrate that the resulting drillhole interpretations are comparable with manual interpretations of the same drillholes
Acknowledgements

We thank Rio Tinto Iron Ore for funding and supporting this research.

Patent applications:
• Machine Assisted Drillhole Interpretation - “A Method And System For Sample Classification” (AU2018904128), Wedge, Hartley, McMickan, Green, Holden.
3D Geochemical Interpolation
Supported by Geophysical Inversion Models

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Introduction

1. Interpolation: existing solutions
2. Proposed solution
3. Case study results
4. Conclusions
Introduction

- **Sparse ground truth:** A “tight” 30 m grid, 10 cm diameter holes: <0.01% of the subsurface is sampled.

![Sampled space diagram](image)
Introduction

- **Sparse ground truth:** A “tight” 30 m grid, 10 cm diameter holes: <0.01% of the subsurface is sampled.

- **But it works:** Interpolation leverages local homogeneity and/or predictable spatial trends.
Existing methods

- Kriging (simple, ordinary, indicator, domain)

Spatial modelling

Sampled space (30 m spacing)
Existing methods

- Kriging (simple, ordinary, indicator, domain)
- Collocated cokriging
- Regression kriging (aka universal kriging, or kriging with external drift)

Proposed solution

- Machine learning (Li et al. 2011)
Proposed solution

- Gaussian process regression with a custom kernel

- Shares properties with kriging
  - Variogram modelling
  - Quantifies (changing) uncertainty in interpolation

- Space expands and contracts depending on auxiliary data
Kernel functions

GPR internally relies on a kernel function, which quantifies similarity between pairs of input points (related to Kriging’s covariance function)

\[
k_s(s_1, s_2) = \sigma_s^2 \exp \left( -\frac{1}{2} (s_1 - s_2) L_s (s_1 - s_2)^\top \right)
\]

\[
k_u(u_1, u_2) = \sigma_u^2 \exp \left( -\frac{1}{2} (u_1 - u_2) L_u (u_1 - u_2)^\top \right)
\]

\[s_i = (x_i, y_i, z_i) \quad u_i = (\mu_i, \chi_i, \sigma_i, \nu_i)\]

\[
k_m((s_1, u_1), (s_2, u_2)) = k_s(s_1, s_2)k_u(u_1, u_2)
\]

Warped input space
Lengthscales (1/2)

Spatial (coordinates)

- Determines ‘scale of interpolation’ and spatial anisotropy

\[ \mathbf{L_s} = \begin{pmatrix} l_{xy}^{-2} & 0 & 0 \\ 0 & l_{xy}^{-2} & 0 \\ 0 & 0 & l_z^{-2} \end{pmatrix} \]
Lengthscales (2/2)

Auxiliary (inversion model cells)
- Determines contributions to warping space
- Optimised for most accurate interpolation

\[
L_u = \begin{pmatrix}
  l^{-2}_\mu & 0 & 0 & 0 \\
  0 & l^{-2}_\chi & 0 & 0 \\
  0 & 0 & l^{-2}_\sigma & 0 \\
  0 & 0 & 0 & l^{-2}_v \\
\end{pmatrix}
\]
Case study

- Kevitsa Ni-Cu-PGE (Finland)
- Mafic-ultramafic intrusion
- 2,058 ± 4 Ma
- See Yang et al. (2013) for characterisation

Inversion models

Density ($\mu$)

Cond. ($\sigma$)

Mag. susc. ($\chi$)

Seismic ($V_p$)
Inversion models

Density ($\mu$)

Cond. ($\sigma$)

Mag. susc. ($\chi$)

Seismic ($V_p$)
Gravity inversion structure
Drillholes

- Mg concentrations from 207 collars
- 6998 drill core intervals
Evaluation

• 10-fold cross-validation without splitting holes

• Metric: log likelihood (higher is better)

\[
\log p(t|\mu^*, \sigma^*) = -\frac{1}{2} \log 2\pi - \frac{1}{2} \log \sigma^*^2 - \frac{1}{2} \frac{(t - \mu^*)^2}{\sigma^*^2}
\]
Results: spatial only ($K_s$)
Results: spatial & aux. $(K_m)$

Inversion models improve interp.
Results: spatial & aux. ($K_m$)
Inversion model lengthscales

Density ($l_\mu$)

Cond. ($l_\sigma$)

Mag. susc. ($l_\chi$)

Seis. ($l_v$)
Conclusions and further work

• Gaussian process regression can be used to spatially interpolate drill core properties while accounting for collocated rock property volumes

• Spatial part of kernel can be improved as in kriging

• Future work: quantitative comparison with regression kriging, other kernels, and investigating influence of inversion model smoothness
Acknowledgements

• This project was financially supported by First Quantum Minerals and the Robert and Maude Gledden Postgraduate Scholarship

• Case study data supplied by First Quantum Minerals Ltd.