An Evaluation of Ground Penetrating Radar for Mapping Fracture Networks in the Hawkesbury Sandstone

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Contents

• Introduction
  • Current Conflicts
  • The Southern Coalfields

• Objectives
• Survey Areas
• Field methodologies
  • Field Mapping
  • GPR
    • Basics
    • Results
    • Interpretation

• Discussion and Conclusion
• Future Research
• References
Introduction

- Subsidence due to longwall coal mining causes fracturing of the overlying rocks.

- When a longwall panel is extracted beneath or adjacent to a stream/river there can be detrimental impacts on the near surface hydrology.

- Longwall mining caused significant fracturing of the bedrock in the Waratah Rivulet. This changed the near surface flow paths, and altered the water chemistry.

- To better assess the impacts we need a good understanding of the changes to the near surface fracture network.

- It has been demonstrated that GPR can map fractures (Heikkinen and Kantia, 2011; Leucci et al., 2007).

- We opted to test the Mala Rough Terrain GPR system.
Current conflicts

- Coal is extensively mined across New South Wales
- Main extraction method is Longwall mining
- Vertical subsidence and Horizontal movements
  - Reduced water quality
  - Growth of iron oxidising bacterial mats
  - Loss of ecological habitats
  - Accelerated bank erosion
  - Extensive gullying erosion
- There are a number of environmental concerns due to continuing longwall mining activities in the Southern Coalfield
The Southern Coalfield

- Located in the Sydney Basin
- Made up primarily of Permian and Triassic sedimentary and volcanic rocks
- Intruded by dykes
- Extensive natural fracture network.
- The only Coalfield in NSW that produces hard coking coal
- Extracted from the Bulli seam at up to depths of 400 m
- Main units above the Bulli seam
  - Hawkesbury Sandstone
  - Narrabeen Group
Waratah Rivulet: Fracturing

Diverted Flow
Waratah Rivulet: Filling of Fractures
Waratah Rivulet: Increased Iron
Objectives

- To evaluate if the Mala Rough Terrain GPR system can be used to map the major and minor joint networks and bedding planes.
- Measure the alteration of fracture networks caused by longwall mining
- Test the capabilities of GPR to detect such features at an unaltered nearby site
- Frequencies tested 100 and 25 MHz
Survey areas

- Areas with extensive visible surface fracturing where chosen

- Parts of
  - The Kurnell Peninsula
  - The Royal National Park
    - Wattamolla
    - Curracurrong

- Fractures were identified from aerial photographs.

- Fractures delineated from the aerial photographs were confirmed in the field.
Geological map of Study area
Kurnell survey site
Royal National park North Survey site
Royal National park South Survey site
Fracture mapping

- Average orientation of approximately 190° and 202° at Kurnell and Royal National Park (RNP) sites respectively from aerial photographs

- NNW-SSE orthogonal fracture pattern, in sync with previous findings by Memarian Fergusson (2003) and Shepherd and Huntington (1981)

- Average spacing of fractures mapped (metres)
  - Kurnell – 6.58
  - RNP North – 2.715
  - RNP South – 7.6815

- Field mapping gave ranges of strikes
  - Kurnell – 95° -226°
  - RNP North – 230° -245°
  - RNP South – 193° -202°
Ground-Penetrating Radar (GPR) Basics

- Geophysical technique that allows high resolution imagery of the sub surface (<50m)
- Detects electrical discontinuities in the shallow subsurface
- Emits a pulse of electromagnetic energy and records the time required for the return of any reflected signal
- Reflections are produced from surfaces where there is a sharp contrast in the dielectric constant of the earth materials.
- While some energy is reflected back to the antenna, remaining energy will continue travelling through the material until it attenuates.
- Signal attenuation is dependent on the properties of the material the pulse passes through and the frequency of the GPR antenna
GPR System

- MALA Rough-Terrain Antenna (RTA)
  - 100 Mhz antenna – 2m spacing
  - 25 Mhz antenna – 6 m spacing

- Towed by a single surveyor

- Common offset survey

- Quick and Easy to use
Royal National Park (RNP) Survey Site
Photo A-A’
Photo B-B’
Digitised B-B’
Kurnell Survey Site
GPR Profiles 100 and 25 Mhz RNP North
GPR signal paths

From Neal (2004)
Fig. 7. Return-frequency spectrums, radar reflection profiles and radar-footprint size variations with depth for data collected along the same shore-parallel transect across sand-and-gravel-rich beach ridge-plain deposits, Beckfoot, outer Solway Firth, northwest England using antennae with nominal centre frequencies of (a) 50 MHz, (b) 100 MHz and (c) 200 MHz. Note expansion of the elevation axis beneath the water table (WT) due to the decrease in radar wave velocity.
Typical Dielectric Constant, Electrical Conductivity, Velocity and Attenuation Observed in Common Geologic Materials

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>K (mS/M)</th>
<th>$\sigma$ (m/ns)</th>
<th>$\nu$</th>
<th>$\alpha$ (dB/m)</th>
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</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
<td>0</td>
<td>0.30</td>
<td>0</td>
</tr>
<tr>
<td>Distilled Water</td>
<td>80</td>
<td>0.01</td>
<td>0.033</td>
<td>$2 \times 10^{-3}$</td>
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<tr>
<td>Fresh Water</td>
<td>80</td>
<td>0.5</td>
<td>0.03</td>
<td>0.1</td>
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<tr>
<td>Sea Water</td>
<td>80</td>
<td>3x10³</td>
<td>.01</td>
<td>10³</td>
</tr>
<tr>
<td>Dry Sand</td>
<td>3.5</td>
<td>0.01</td>
<td>0.15</td>
<td>0.01</td>
</tr>
<tr>
<td>Saturated Sand</td>
<td>20-30</td>
<td>0.1-1.0</td>
<td>0.06</td>
<td>0.03-0.3</td>
</tr>
<tr>
<td>Limestone</td>
<td>4.8</td>
<td>0.5-2</td>
<td>0.12</td>
<td>0.4-1</td>
</tr>
<tr>
<td>Shales</td>
<td>5-15</td>
<td>1-100</td>
<td>0.09</td>
<td>1-100</td>
</tr>
<tr>
<td>Silts</td>
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<td>1-100</td>
<td>0.07</td>
<td>1-100</td>
</tr>
<tr>
<td>Clays</td>
<td>5-40</td>
<td>2-1000</td>
<td>0.06</td>
<td>1-300</td>
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<tr>
<td>Granite</td>
<td>4-6</td>
<td>0.01-1</td>
<td>0.13</td>
<td>0.01-1</td>
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<tr>
<td>Dry Salt</td>
<td>5-6</td>
<td>0.01-1</td>
<td>0.13</td>
<td>0.01-1</td>
</tr>
<tr>
<td>Ice</td>
<td>3-4</td>
<td>0.01</td>
<td>0.16</td>
<td>0.01</td>
</tr>
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</table>
POWER REFLECTED

The amount of energy (power) reflected at a dielectric boundary depends on the dielectric contrast. It is calculated from:

\[ R = \left( \frac{\sqrt{K_1} - \sqrt{K_2}}{\sqrt{K_1} + \sqrt{K_2}} \right)^2 \]

where:

\( R \) = power reflected

\( K_1 \) = dielectric constant of the first layer

\( K_2 \) = dielectric constant of the second layer

Table 1. Power reflected from dielectric boundaries

<table>
<thead>
<tr>
<th>( K_1 )</th>
<th>( K_2 )</th>
<th>( R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0.03</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>0.15</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>0.27</td>
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<tr>
<td>1</td>
<td>25</td>
<td>0.44</td>
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<tr>
<td>1</td>
<td>50</td>
<td>0.57</td>
</tr>
</tbody>
</table>
GPR data Processing

- Processing is applied to
  - Remove horizontal banding
  - Filter out noise and enhance reflection events
  - Remove hyperbolae and return reflection events to their original dip
  - Restore the radargram to the correct spatial location

Diagram:

1. Raw Data
2. DC-Shift
3. Gain
4. Truncation
5. Background Removal
6. Bandpass Filter
7. Deconvolution
8. Migration
9. Bandpass Filter
10. Radar scan stacking
11. Hilbert Transform
12. Elevation correction
Basic Processing
Advanced processing
Surface fracture alignment

- Any air filled fractures should give no reflection in top section of the GPR profile

- Null amplitude spots in a Hilbert Transformed profile should correlate to air filled fractures (Patterson & Cook, 2001), (Porsani, 2006)
Royal National Park South Survey site with Mapped fractures and picked fractures from GPR profile
Identifying fractures in radargrams

- Termination points may cause clear diffractors
- Vertical interfaces can be seen as hyperbolae diffractors
- Fractures are not perfectly straight like modelled
- Will be jagged in situ, so will appear as multiple diffractors in profile

Figure 3. Synthetic data: (a) model, (b) raw data with air-filled fracture, (c) time domain processed data with air-filled fracture, (d) raw data with moist material-filled fracture and (e) time domain processed data with moist material-filled fracture.
Basic Processing 100 MHz
Picked discontinuous events
Hilbert Transformed 100 MHz
Picked discontinuous events
Stacked Profile 100 MHz
Advanced processed with all picked events
Fractures in MOVE
Fractures in MOVE
Conclusion

- On the Hawkesbury Sandstone it is estimated that the 100 MHz system penetrated to approximately 13 metres.
- The 25 MHz system penetrated to approximately 25 metres.
- Major surface fractures aligned with anomalies observable in the GPR profiles.
- Using GPR it was possible to identify major subsurface fractures, and major bedding planes.
- It is unlikely that GPR systems could be used to map the complete 3D fracture network.
- It is not a simple process to map the fracture in the upper 10 m using GPR.
- Further work is required on the optimal processing steps.
References


Questions?