3D Seismic for Mineral Exploration

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What’s been happening?

Last few years:

- Strong demand for expansion of mining activities:
- Emphasis on re-examining old mines or sites of mineralisation

Necessity to delineate extension of known mineralizations at greater depths

Need to define new more robust exploration targets, often beyond the reach of potential field methods

Exploration by drilling – too expensive, too slow

Application of 2D/3D surface and borehole seismic becomes an obvious choice
Whats Happening now?

- Curtin University has established a State supported COE to establish high resolution geophysical methods in 2006.

- Seismic Reflection seen as an important method. A significant investment in acquisition and processing capacity is now available in WA/Australia – 1200+ channels recording, full Promax processing largely dedicated to mineral exploration.

- Expertise to work in hard rock environments is growing:
  - More than 20 surveys conducted 2D and 3D in three years
  - 200+ line km (2D) and 30+ sq km (3D)
    - NiS (Pipes and channels), Shear hosted gold, Carlin style gold, unconformity related uranium, palaeo-channel uranium, VMS, kimberlites
    - NT, WA, Vic, USA.
  - **Curtin’s future Role**: to research and develop high resolution geophysical techniques; link with industry needs; provide for future industry needs
    - >>> Commercial spin-off: HiSeis
Elastic waves are reflected, refracted and diffracted from velocity or density boundaries (rather than lithology)

Arrival of vibrational energy is recorded against two-way travel time
Advantages of seismic reflection method

- **RESOLUTION**: Preserves resolving power with depth

- **3D IMAGING**: Can provide detailed images of lithology AND structure of subsurface

- **DEPTH OF PENETRATION**: Works well to depths of several km’s

- **EDGE DETECTION**: Good at detecting edges of structures
The issues in Mine site exploration

- Remote, inaccessible sites
- Environmental restrictions
  - Seismic line misaligned with dip of dominant structure
- Complex structure
  - Different types and elastic properties of shears, faults, dykes
- High velocity – often small change in elastic properties, long wavelength, lower resolution achieved than in soft rocks
- Massive and heterogeneous regolith
  - Scattering of energy, loss of high frequencies and excessive time delays
- Lack of sonic and density logs
  - Difficult to calibrate seismic images
Laying the geophone array out
Recording Truck – Lake Lefroy (WA) for IGO
Explosive Source and Shot Crew – Lake Lefroy (WA), IGO
Weight Drop – Otway 3D (Vic)
Weight Drop – Golden Grove 3D, WA
Seismic in the Pits – Not an easy place to work?

Vibrator Trucks
Acquiring 3d Seismic Data—

the CHDG learnings

- Lightweight system with low environmental impact
  - Recording system with 1200 channels with accessories is <2000 kg
  - Wt Drop or Explosive source is quick and cost effective
  - 3 Land Cruisers plus truck for Wt Drop/Skidsteer
- Small seismic crew for 3D - 6 people
  - Fit within existing mine camps
  - Less people for OHS/Inductions/Mngt
- Cost of survey is about $50k-140k/sq km of coverage for several sq km (including the data processing)
Processing of data: How it started.....

1999 regional seismic line - acquired to analyse deep crystalline structures

Initial processing for deep structures, 1999

Survey parameters $\Delta R=40\text{m}, \Delta S=80\text{m}$

Re-processed, 2002

Current gold mining

Difference between the two only in the application of refraction statics!

Courtesy, Placer Dome
Why success when others have failed?

Another example: Effect of computation of residual statics

Conventional approach for computing residual SC reflection statics by using a pilot “horizon” is often not useful

**Our approach:** SC LMO refraction statics (modified from Hatherly et al., 94)
Seismic Processing

Key Processing Steps

- Crooked line geometry definition - including CDP line
- Statics correction - for variable time delays in regolith
- Spectral equalisation - suppresses low f noise
- CDP sort - collects traces with common mid point
- Velocity analysis - corrects for normal moveout
- CDP stack – improves signal to noise
- Migration - moves reflectors to correct positions
- Coherency enhancement - amplifies coherent events
Seismic Processing – Statics Corrections

Statics corrections needed for elevation and regolith

Shot  R1  R2  R3  R4  R5  R6

regolith

reflector

Two Way Time

shot record

1  2  3  4  5  6

reflection

Mt Isa Seismic Workshop, June 24 2008, Mt Isa
Seismic Processing

Normal Moveout (NMO) Correction

Horizontal reflector

S ← X → R

V

Moveout relationship

\[ T^2 = T_0^2 + \frac{X^2}{V^2} \]

Uncorrected CDP gather

\[ T_0 \quad X \quad T \]

Corrected CDP gather

\[ T_0 \quad X \quad T \]
Seismic Processing

Normal Moveout Correction and Stack

Uncorrected CDP gather  Corrected CDP gather  Stacked seismic trace

Stacking improves signal to noise by $\sqrt{n}$, where $n$ is the fold

<table>
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<th>$n$</th>
<th>10</th>
<th>60</th>
<th>120</th>
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<tr>
<td>$\sqrt{n}$</td>
<td>3</td>
<td>8</td>
<td>11</td>
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Dynamic corrections – normal move-out

Old-fashioned CVS…a must!
- Event recognition (indicate out-of-plane events)
- Early interpretation stage; interpretation starts with CVS panels
Dip-move out correction / seismic imaging

DMO always useful, even when degrades the image!
- Provides an improved velocity model
- Indicates out-of-plane events
- Typically DMO+MAS provides the most reliable result (3D but also 2D)
Kambalda Ni (WA): Explored by potential field methods, but shallow penetration, low resolution...limited structural information at depth
3D seismic exploration objectives for Ni targets

- Map interface between Basalt and Kambalda Komatiite (Ultramafics)
- Map major shears, faults
- Map intrusive rocks (porphyries, felsics and intermediates) into Ultramafics; do they have seismic signature?
Seismic exploration – Lake Lefroy

- First 2D seismic – 1987 (Explosive), 2002 (Vibroseis)
- First encouraging results in 2003
- First 2D high-resolution seismic for gold in 2004

Ni exploration on the Lake
First 2D high-resolution seismic for Ni in 2005 (120 ch)
First mini 3D (1 km²) for Ni in 2006 (450 ch)
4 x 3D surveys shot on the lake by (852 ch)
First VSP planed for December
Data acquired and processed by CHD staff
IGO – Survey Plan 3D

2007 Seismic Survey
13th - 18th May

“No Unauthorised Entry” signs to be erected at start of each causeway

Contact: Jacob Pagli 0439 693 068
Luke Gibson 0427 081 150

McLeay Seismic Line
(Dec 2005)

Survey corner coordinates (MGA94)
654770N 375130E
654770N 375930E
654870N 375530E
654670N 375130E
IGO – Trial 3D Survey – Bin size 10x10 m and Calculated Fold

2007 Seismic Survey
13th - 16th May

"No Unauthorised Entry" signs to be erected at start of each causeway

Contact: Jacob Paggi | 0439 693 068
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McLeay Seismic Line
(Dec 2005)

Survey corner coordinates (MGA94)
6547770N 375130E
6547770N 375930E
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6547770N 375130E
What next? Another 8 sq km of 3D covering the Long Victor corridor
Survey Design - Kambalda Nickel, WA

Difficulties:
1. Soft part of the lake
2. Dense vegetation
3. Tailing dumps, abundant mine infrastructure
4. Unexpected rainfall
5. Survey plan: 1.5-2 months
6. (≈ 8700 shots)- actual time close to 4 months
IGO – 3D South survey (2008)
Time slices
3D Seismic Exploration in Hard Rock Environment

Tracking lava channel - depth slices
Extracting geology from 3D seismic: what is the best way?
Conventional “horizon” approach - not too useful
Attributes: instantaneous, coherency, spectral decomposition, opacity….?
Preliminary analysis of seismic cube south

Opacity x histogram

Tabular bodies - porphyries, felsics?

Shears?
Actual complexity of Ni Mine Area

Small 3D (3 Km2) – shot south of McLeay (2007) (interpreted structural elements)

depth slice at 1266m

small scale faults

depth slice at 1266m

Courtesy of CSM, designed, processed and interpreted by CHDG, co-acquired with Geoforce
Possibility for direct targeting from seismic data?

Interference “tuning” can enhance seismic response of Ni nickel bodies (black arrow) or make it less visible (orange arrows)
Ni confirmed by drill hole
possible new targets
Map showing RMS amplitude extracted in a window above (10m) and below (4m) of the basalt contact.

Real data (volumetric interpretation)

Map showing RMS amplitude extracted in a window above (10m) and below (4m) of the basalt contact.

RMS amplitudes
Targeting based on reflection attributes

Map showing RMS amplitude extracted in a window above (10m) and below (4m) of the basalt contact.
Seismic for Gold Exploration

- Reflection seismic produces higher resolution images than any other geophysical technique
- Can image shallow and deep structures
- Can resolve complex structures which are of great importance for mineral exploration

- Mineralization
  - Different settings for mineralisation
  - Halos
  - Shallow targets < 500m
  - Zones from 1 to 10’s of meters

- Fluid Conduits
  - Deeper targets > 2km
  - Mineralised zones, meters to 100’s of meters
  - Variable complexity
St Ives Gold – Explored using shallow focussed techniques
Surface Geochemistry, Magnetics… but
Gold Exploration – the St Ives Anticline

DMO corrected / Stacked

Borehole Locations
Seismic Attributes - Lambda-Mu-Rho

LRM – Softer Rocks (Orange) Harder Rocks (Blue)

>800 ppb Gold Content

>2000 ppb Gold Content

Harder Rocks

Softer Rocks
Gold Exploration - Borehole Sonic Log

- High Gold Content
- Intermediate / Volcaniclastic mix
- Condensor Dolerite

- Au (ppm)
- Density
- P-wave
- S-wave
- 0-1000 m offset synthetic
URANIUM: Exploration for Unconformity related uranium deposits with 3D seismic

Complex deposits
Intensely faulted zones provide paths for hydrothermals (chlorite)
“Rich ore pockets of limited size”
Exploration for Unconformity related Uranium Deposits with 3D Seismic

Synthetic from FWS

VSP

CVS

Mini brute stack
Processing Steps in 3D seismic

- **NO STATICS**
- **Inline brute NMO stack BY CMPT**
- **ASSUMES A HORIZONTAL MEDIUM**

**Stack DMO + FULL residual statics**
- PROPERLY ALIGN ENERGY AND CORRECTIONS

- **MIGRATIONAL, DEPTH CONVERSION**
- **Inline stack + MAS, no DMO**
Uses of Seismic

- **Brownfields Exploration** where maximum resolution and depth are important
  - A 1000m drill hole cost $250,000 to not reach a poorly defined target in 2 months.
  - For $250,000 you could image a 1 km² area to a depth of 2000m in 2 months.
    - From Seisbank 1 $250,000 hole could be designed to evaluate a well defined target, perhaps designed to avoid bad rock/drilling conditions in 1 month?
- In **Feasibility studies**, where knowledge of the geometry of 3D structures is important into understanding risk in mine development.
- In **Feasibility studies**, where the potential of the mineral system may better be appreciated/high grade or more massive portions defined to fast track payback.
- In **advanced exploration** to more effectively evaluate the depth potential of shallow smoke to be the top of the big one.
Conclusions

- Seismic reflection provides a new perspective on how to explore, especially in brownfields terrains.
- Method is tricky to make effective in weathered terrains and Hard Rock environment— but it is possible.
- 2D is good for some targets and trials; 3D is the best for imaging, but most costly to get wrong.
- Interpretation requires geophysicist and geologist to exchange information – two way process.

3D seismic is not just a tool for rich oil and gas explorers.
Acknowledgement to CHDG Sponsors

- Independence Group
- Rio Tinto Exploration
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- Anglo-Gold
- CRCLEME
- State Govt of WA
- Consolidated Minerals
- BHPB Minerals
- Goldfields
- Heathgate Resources
- Resolute Mining
- Ballarat Gold
- Oxiana
- CSIRO/GNS
- ACARP
- CO2CRC
- WaterCorp
- Dept of Water WA