Abstract

Exploration for unconventional and conventional hydrocarbons is experiencing a boom in older, onshore basins where seismic data is commonly sparse. In Australia, large onshore Proterozoic to Mesozoic basins host multiple working petroleum systems, potentially huge volumes of gas and oil, and have been affected by many igneous events. In onshore South America, the interior Paleozoic basins feature Triassic and younger igneous events that affected generation timing, reservoir quality, preservation potential and migration.

Regional 2D seismic is used to interpret the location, depth and thickness of igneous rocks that have intruded into source-reservoir systems. Seismic facies analysis is important for assessing lithofacies variations where interbedded volcanics are present. In the Jurassic-Cretaceous Otway Basin, seismic interpretation helps distinguish synrift flow-basalts from lacustrine shale source intervals.

In the greater McArthur Basin in northern Australia, dolerite sills have been intruded directly into the main marine source rock and above and beneath the main conventional reservoir. Similarly, in onshore South America (eg. Solimões, Amazonas basins) Mesozoic sills and dykes have been intruded directly into the Paleozoic petroleum systems elements and provide the critical moment for these systems.

Basalt flows and diabase sills are commonly able to be mapped on the seismic data but it is more difficult to interpret dykes on seismic data alone. Igneous units commonly exhibit high seismic reflection amplitudes compared to surrounding basin units.
Seismic interpretation of the character and type of the igneous units is important for identifying the likely location of igneous feeder systems and the possible extent of the igneous systems.

Combining seismic and potential field interpretations provides many benefits. Firstly, potential field data commonly cover a greater area than seismic grids and allow an interpretation to be expanded across an entire basin to rapidly assess prospectivity and volcanic risk. Secondly, high resolution magnetic and gravity data can help distinguish subtle igneous features such as dyke trends and igneous centres (igneous complexes, feeder systems) that may be obscured on seismic. Thirdly, the correlation of seismic and wells to potential field data is critical for mapping basement depth, and composition and interpreting deep-seated fault control on igneous bodies and the role of basement heat flow for basin modeling.

References Cited


Calibration of Igneous Systems & Basin Prospectivity using 2D seismic & Potential Field Interpretations

Andrew Krassay, Karen Connors, Lynn Pryer & Cedric Jorand
FrOG Tech Pty Ltd
Acknowledgements

Santos

MURPHY

Mitsubishi Corporation

OSAKA GAS

Cooper Energy

BEACH ENERGY
Presenter’s Notes: First case study is an old, onshore Proterozoic basin where unconventional petroleum system is the priority. This area is affected by two major thermal events with thick dolerite sills and dykes followed by flood basalt development. Second case is an offshore Mesozoic basin where conventional exploration is the priority. This area is heavily affected by Triassic-Jurassic and older intrusives and a wide range of Mesozoic extrusive and volcaniclastic igneous units. In both cases, the main seismic datasets are 2D and 3D is either unavailable or only covers small areas – The talk aims to show the importance and versatility of combining potential field geophysical analysis with traditional seismic- and well-based basin analysis.
Greater McArthur Basin

Stratigraphy

Chambers River Formation
McMinn Formation
Velkerri Formation
Bessele Creek Sandstone
Corcoran Formation
Abner Sandstone
Dolerite
Crawford Formation
Mainoru Formation
Limmen Sandstone
Dungaminnie Formation
Balbirini Dolomite
Looking Glass and Amos formations
Stretton Sandstone
Yelko Formation
Lynett Formation
Reward Dolomite
Barney Creek Formation
Teena Dolomite
Emmerugga Dolomite

Silverman & Ahlbrandt (2011)
**Regional Seismic Character**

- Cambrian
- Velkerri Fm source
- Sill 1
- Sill 2
- Roper Group
- Nathan Group
- Paleoproterozoic
- 0–5 km TWT (s)
- Cambrian
- 5 km scale

Inset map with regional geological features.
Seismic Anomalies

Sever-1

upper Velkerri Fm

Lower Velkerri Fm

Cambrian basalts

TWT (s)

1 km

1–1 km
Igneous Well intersections

Sever 1

- Kyalla Member
- Upper Velkari Formation
- Middle Velkari Formation
- Dolerite Top
- Dolerite Base
- Lower Velkari Formation
- Bassie Creek Sandstone
- Corcoran Formation
- TD
Igneous Well intersections
### Igneous Well intersections

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Stratum/Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Initial Horizon</td>
</tr>
<tr>
<td>50</td>
<td>Triassic Horizon</td>
</tr>
<tr>
<td>100</td>
<td>Kyalla Member</td>
</tr>
<tr>
<td>150</td>
<td>Upper Velkemi Formation</td>
</tr>
<tr>
<td>200</td>
<td>Middle Velkemi Formation</td>
</tr>
<tr>
<td>250</td>
<td>Dolerite Top</td>
</tr>
<tr>
<td>300</td>
<td>Dolerite Base</td>
</tr>
<tr>
<td>350</td>
<td>Lower Velkemi Formation</td>
</tr>
<tr>
<td>400</td>
<td>East Creek Sandstone</td>
</tr>
<tr>
<td>450</td>
<td>Corcoran Formation</td>
</tr>
<tr>
<td>500</td>
<td>TD</td>
</tr>
</tbody>
</table>

*Note: The diagram shows the stratigraphic column for Sever 1, with key intersections marked.*
Igneous Well intersections

Middle Velkerri Fm

- Alexander 1
- Lady Penrhyn 2
- Supply 1
- Shea 1
- BMR Urapunga 3
- BMR Urapunga 4
- Broadmere 1
- POWales 1
- Scantlebury 1
- Altree 2
- McManus 1
- Walton 2
- Sever 1
Presenter’s Notes: Two major, distinct seismic anomalies. Seismic character = v high amplitude, generally flat, parallel continuous reflections. Note the mild post intrusion deformation. Also, note the absence of apparent feeders/dykes, forced folds, saucer shapes, and lack of transgression of the seismic events – they seem to be remarkably continuous and stratiform. It appears that the dolerites have preferentially intruded the finest-grained, uniform mudstones sequences – presumably, they are exploiting competency contrasts within the stratigraphic section.
Presenter’s Notes:

- Note that the Cambrian flood basalts form an overlying igneous blanket to much of the area but had little impact on petroleum systems.
- The older igneous intrusives however have had a significant effect on petroleum systems locally and the intrusives are widely distributed.
- Note how the 1280 Ma dolerites have preferentially intruded 3 main stratigraphic intervals:
  - The Velkerri Formation (source quality risk)
  - The Bessie Creek Sandstone (reservoir quality risk)
  - The underlying Corcoran Formation (low risk as this is considered a non-source interval)
Magnetic Modelling – sills vs flood basalts

Theoretical Model
Magnetic Modelling – sills vs flood basalts

Theoretical Model

- Flat sheet-like intrusions (sills) exhibit distinct magnetic signals at edges
- Marked by a dipole effect with a negative and positive mag anomaly
- Can be distinguished from shallower flood basalts and deeper intrusives

Presenter’s Notes:
- The model profile (top right) shows the same positive and negative pair of anomalies associated with the flat “sill” body. The observed magnetic data is much noisier than the model data due to local variations in the Kalkarindji basalt. Presenter’s Notes continued on next page
• The shallow near surface bodies represent the Kalkarindji basalt disrupted by faults and/or erosion and the deeper larger bodies represent the Derim Derim sills. The depths to the top of the sills are approximate only. The depth can be varied along with the susceptibility of the bodies. The possible depth range can be tested with additional modelling.
• The theoretical model of the flat magnetic bodies (i.e. possible sills) highlights the pair of positive and negative anomalies that occur over the edges of the flat bodies. The edges of the bodies are the main features that are highlighted in the magnetic data. The colour of the model bodies (top right) indicate the relative susceptibility with red highest, yellow moderate and green lowest. The high susceptibility red bodies near surface create the dominant anomalies in the calculated magnetic response (lower left). The yellow body is less magnetic and slightly deeper and the resulting anomalies have lower amplitude and longer wavelength. Note that both of the high susceptibility red bodies show a strong anomaly along their edges, i.e. we still “see” evidence of the lower body.

Theoretical model used to better understand and interpret real data. Magnetic response generated from the theoretical model bodies. Note the positive anomaly on the northern edge and the negative anomaly along the southern edge of each sill body. The theoretical model was set up to mimic the main bodies in the Gorrie sub-basin.
Magnetic Modelling – sills vs flood basalts

Real Data
Presenter’s Notes:

Left: Observed magnetic data in the Gorrie Sub-basin northwest of the Sever 1 well and seismic line. Note the positive anomaly on the northern edge and the negative anomaly along the southern edge of the irregularly shaped sill outlined in yellow.
Integrated igneous mapping & prospectivity

Maiwok Sub-basin

Gorrie Sub-basin

Beetaloo Sub-basin

133°E 134°E

16°S 17°S

0 50 100 Kilometers
Integrated igneous mapping & prospectivity

Gorrie Sub-basin

Beetaloo Sub-basin

Maiwok Sub-basin

0 100 50 Kilometers

133°E 134°E

16°S

17°S
Integrated igneous mapping & prospectivity

Intrusive mapped on seismic

Gorrie Sub-basin

Maiwok Sub-basin

Beetaloo Sub-basin

133°E

134°E

0 50 100 Kilometers

16°S

17°S
Integrated igneous mapping & prospectivity

Intrusive mapped on seismic
Intrusive mapped or modeled on pot field data

Maiwok Sub-basin
Gorrie Sub-basin
Beetaloo Sub-basin

0 50 100 Kilometers
2nd image is an RTP_TernaryTiltMsAge filter

**Derim Derim Dolerite**

- Sills up to 100m thick and dykes
- $1324 \pm 4$ Ma age from Kimberley region (J. Claoue-Long, written pers. comm., 2005 quoted by Goldberg, 2010)
- $1280$ Ma age from this region
Browse Basin – Northwest Shelf

- Oil
- Oil & gas
- Gas & condensate
- Gas
- Gas, oil shows
- Oil & gas shows
- Gas & condensate shows
- Gas Shows
- Oil & Gas shows
- Gas, oil, & gas shows
- Gas, oil indication
- Dry hole
- Result unreported
Presenter’s Notes:
Main Igneous events are associated with:
1. Permo-Carboniferous extension
2. Early-mid Jurassic extension
There are to less voluminous and extensive peaks in igneous activity during:
1. Triassic compression and partial basin inversion
2. Minor volcanism during the Aptian (far-field effects?)
Igneous Character from Magnetics & Well Calibration
Igneous Character from Magnetics & Well Calibration

- Primary (mostly extrusives)
- Volcanic plus volcaniclastic
- Volcaniclastic
- None

Igneous Intersections

1368.8 nT

1748.4 nT

28.9 nT

14.7 nT

4.9 nT

TMI

No Kilometers
Igneous Character from Magnetics & Well Calibration

Igneous Intersections

- ★ Primary (mostly extrusives)
- ○ Volcanic + volcaniclastic
- ▲ Volcaniclastic
- ○ None

Argus-1 (178 m)
Buffon-1 (494 m)
Maginnis-1/1A (494 m)
Igneous rocks at Buffon-1

- Volcanic section 3760-4254 mRT (494 m thick)
- Clear seismic change top & base of volcanics
- 3 igneous facies: basalt flows (2-25 m thick), tuffs, coarse pyroclastics
- More lava interpreted off flanks

TD @ 4787mRT, ~ 3200 ms twt
Seismic mapping & Calibration – outer Browse
• Western Barcoo & Caswell S-b exhibit significant intra-basinal magmatism
• Massive sills and extensive Jurassic lavas. Multiple large magnetic anomalies
• Lavas reach thickness >300 ms twt (500 m+) = 483 m @ Maginnis 1/1A
Seismic mapping & Calibration – Barcoo Sub-basin

Igneous features/facies
Igneous features/facies

Chaotic, discontinuous, high amplitude, low frequency reflections at depth → early rift magmatism?
Seismic mapping & Calibration – Barcoo Sub-basin

Igneous features/facies

- Intra-Permo Carboniferous cross-cutting discontinuous & ‘climbing’ anomalies → Sills & dykes
- Chaotic, discontinuous, high amplitude, low frequency reflections at depth → early rift magmatism?
**Seismic mapping & Calibration – Barcoo Sub-basin**

Igneous features/facies

- Blue: Intra-Triassic complex terminations and geometries → extrusive and very shallow intrusive features
- Pink: Intra-Permo Carboniferous cross-cutting discontinuous & ‘climbing’ anomalies → Sills & dykes
- Gray: Chaotic, discontinuous, high amplitude, low frequency reflections at depth → early rift magmatism?
Seismic mapping & Calibration – Barcoo Sub-basin

Igneous features/facies

- Laterally continuous, conformable, high amplitude reflections with clear coherent top, rubbly internal character and a diffuse base → massive, amalgamated basalts (lava flows)
- Intra-Triassic complex terminations and geometries → extrusive and very shallow intrusive features
- Intra-Permo Carboniferous cross-cutting discontinuous & ‘climbing’ anomalies → Sills & dykes
- Chaotic, discontinuous, high amplitude, low frequency reflections at depth → early rift magmatism?
Seismic mapping & Calibration – Barcoo Sub-basin
Seismic mapping & Calibration – Barcoo Sub-basin

Zone of anomalously bright, discontinuous reflections interpreted as shallow intrusive complex. Likely comprise sills and dyke feeder system to extrusive complex.

Top basalt flow horizon – bright, coherent reflection, conformable with Callovian horizon.

Chaotic poorly imaged zone beneath thick basalt flows and upper intrusives. May represent main vertical pathways for igneous melts.

S119-11
Geophysical Modelling: testing igneous seismic scenarios
Geophysical Modelling: testing igneous seismic scenarios

Igneous Features

Scott Reef

Magnetic “highs in the Yampi Shelf

Feeder dyke

Observed
Modelled

Body Colour Susceptibility
-0.0100
-0.0078
-0.0056
-0.0033
-0.0011
-0.0003
-0.0033
-0.0033
-0.0056
-0.0078
-0.0100
Geophysical Modelling: testing igneous seismic scenarios

Igneous Features

Strongly magnetised (mafic) intrusive complexes (Triassic?)
Geophysical Modelling: testing igneous seismic scenarios

**Igneous Features**

- Strongly magnetised (mafic) intrusive complexes (Triassic?)
- Mod-strongly negative magnetised (mafic-felsic) intrusions
- Mod magnetised ?Prz basement intrusions

[Diagram showing magnetic "highs in the Yampi Shelf" and observed vs. modelled data.]
Geophysical Modelling: testing igneous seismic scenarios

**Igneous Features**

- Strongly magnetised (mafic) intrusive complexes (Triassic?)
- Mod-strongly negative magnetised (mafic-felsic) intrusions
- Mod magnetised ?Prz basement intrusions
- Scott Reef: Moderately magnetised (mafic) intrusion of ?Jur age
Geophysical Modelling: testing igneous seismic scenarios

**Igneous Features**

- Strongly magnetised (mafic) intrusive complexes (Triassic?)
- Mod-strongly negative magnetised (mafic-felsic) intrusions
- Mod magnetised ?Prz basement intrusions
- Scott Reef: Moderately magnetised (mafic) intrusion of ?Jur age
- Strongly magnetised ?Tr mafic igneous rocks

Magnetic “highs in the Yampi Shelf

Observed

Modelled

Feeder dyke

Scott Reef
Geophysical Modelling: testing igneous seismic scenarios

**Igneous Features**

- Strongly magnetised (mafic) intrusive complexes (Triassic?)
- Mod-strongly negative magnetised (mafic-felsic) intrusions
- Mod magnetised ?Prz basement intrusions
- Scott Reef: Moderately magnetised (mafic) intrusion of ?Jur age
- Strongly magnetised ?Tr mafic igneous rocks

- Negatively remanently magnetised Jurassic mafic plug/dyke
- Moderately magnetised Jurassic mafic lava flows
Integrated igneous mapping & prospectivity

Igneous Intersections

🌟 Primary (mostly extrusives)
〇 Volcanic + volcaniclastic
△ Volcaniclastic
〇 None
Integrated igneous mapping & prospectivity

Igneous Intersections

- Primary (mostly extrusives)
- Volcanic + volcaniclastic
- Volcaniclastic
- None

Deep Intrusives

Seismic calibration mapping

- deep intrusive
- igneous complex
- sill/dyke
- Triassic intrusive

Kilometers
Integrated igneous mapping & prospectivity

Igneous Intersections
- Star: Primary (mostly extrusives)
- Circle: Volcanic + volcaniclastic
- Triangle: Volcaniclastic
- Circle: None

Deep Intrusives

Seismic calibration mapping
- Black circle: deep intrusive
- Orange circle: igneous complex
- Purple circle: sill/dyke
- Pink circle: Triassic intrusive
- Blue circle: E Jurassic extrusive
- Light orange circle: M Jurassic extrusive
- Purple dot: L Jurassic extrusive

Interpreted volcanics
- Yellow: Triassic
- Light blue: Early Jurassic
- Orange: Middle Jurassic
- Light green: Late Jurassic
- Gray: Jurassic undiff
- Green: Valanginian
- Light green: Aptian
- Pink: Possible (no seismic)

[Map showing various igneous features with color coding for different epochs and types of intrusives and extrusives]
Conclusions

- Potential field data & interpretation are critical for sparse data regions and allow rapid assessment.
- Even in mature basins with good seismic coverage, magnetics & gravity data are useful:
  - Depth, extent, thickness of igneous bodies
  - Intrusives vs extrusives
  - Testing seismic facies models
- Potential field analysis can help avoid exploration pitfalls:
  - 400 m of basalt and no reservoir!
  - Map and predict areas of igneous risk to pet. sys.
- Seismic, well AND potential field interpretation are complementary and best used in an integrated approach.