The 2003 Gawler Craton Seismic Survey:

Notes from the Seismic Workshop held at Gawler Craton State of play 2004

Compiled and edited by P. Lyons & B.R. Goleby
THE 2003 GAWLER CRATON SEISMIC SURVEY:
NOTES FROM THE SEISMIC WORKSHOP HELD AT GAWLER CRATON STATE OF PLAY 2004

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Compiled and edited by
P. Lyons & B.R. Goleby
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EXECUTIVE SUMMARY

Iron oxide-copper-gold (IOCG) systems, and their related magnetite-apatite systems, are suggested to form in orogenic belts (e.g., Cloncurry, Andean magmatic arc, Urals) and extensional settings (e.g., St François Terrane, Missouri). Even so, the tectonic setting of arguably the most important of the IOCG class of the deposits, the giant world-class Olympic Dam deposit in South Australia, has been uncertain to date. It has previously been used as an example of the IOCG in an anorogenic intracontinental setting. The region has no outcrop as it is covered by Neoproterozoic sedimentary successions exceeding 5 km thick, in places. Given its economic significance and importance in defining the IOCG mineral deposit class, resolving the tectonic setting of Olympic Dam is crucially important. To address this, two orthogonal deep seismic reflection traverses, centred on the Olympic Dam deposit, were recorded to 18 s TWT.

The nearly north-south line, 193 km long, oriented as near to regional dip-direction, defined by potential-field data, as land access would allow, sounded units of the Archaean-Proterozoic Gawler Craton and a possible allochthonous Proterozoic terrane. The shorter east-west cross-line (57 km) provides control on the three dimensional geometry of the major structures and gives information about some out-of-plane structures imaged by the north-south traverse.

The seismic data show that the Olympic Dam deposit occurs in a fold- and thrust-belt, formed over a number of periods of orogeny, which was probably subject to compressional tectonics at the time of IOCG mineralisation. In the north of the study area, the upper crust, of the crystalline basement, shows south-dipping reflectors, interpreted as shear zones that cut through crust of sub-horizontal reflections. To the south, the upper crust and lower crust have reflectivity indicating thrusting to the south and, or, southwest, toward the interior of the Gawler Craton. However, the upper crustal deformation is decoupled from lower crustal deformation at a layer of sub-horizontal reflectors interpreted, by their reflection-amplitudes, to contain more mafic rocks than the regions above and below. This layer is up to 5 km thick and mostly un-deformed, except where it is duplexed. The duplexes appear to form the loci of strain partitioning in the upper crust. The lower crust of the centre of the study area contains fewer reflections, and appears anomalous but homogenised compared with the crust to the north and south.

Imaging of the cover-successions shows a previously unknown Adelaidean rift, which has been partially inverted.
PREFACE

This record contains abstracts and explanatory notes from the presentations given at the Seismic Workshop and Data Release held as part of the Gawler Craton State of Play 2004 conference, held at Adelaide in August 2004. The workshop was the first public display and discussion of data and results of the 2003 Gawler seismic survey. Interpretation of the seismic data, at the time of the workshop had only been ongoing for about two months and was still at the preliminary stage. Normally, such a quantity of seismic data takes a minimum of six to twelve months to analyse and interpret, and must be done with regard to other available datasets. The complexity of the work requires much collaboration and does not just rely on the expertise of seismic interpreters. Data processing, sequence stratigraphy, structural geology, tectonics, mineral-systems analysis, geochronology, and local and regional geology must all be taken into account.

So, at the time of compiling and editing of these notes, ideas are still emerging and hypotheses are still being formed and tested, some of which have been written into papers currently in review for formal publication. We urge readers to view the Gawler project website, www.ga.gov.au/rural/projects/gawler.jsp, for more recent papers and presentations.
EASTERN GAWLER CRATON: DEEP SEISMIC PROPOSAL

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This is a copy of the proposal to conduct a seismic survey in the eastern Gawler Craton, written in May 2002. It was not presented at the Seismic Workshop.

SUMMARY

The proposed seismic work is to be carried out within the framework of an ongoing program of seismic data acquisition across southern Australia. This extensive transect will contribute to a tectonic framework for understanding the relationships between the Gawler Craton, Curnamona Province and surrounding terranes.

The Gawler Craton, South Australia, is one of the least understood and under-explored Archaean to Mesoproterozoic terranes of Australia. It is nevertheless an emerging major mineral province, underpinned by the world-class Olympic Dam Cu-Au-U deposit, and by recent discoveries of copper and gold (e.g., Prominent Hill). Remarkably little is known of the tectonic framework and crustal evolution of the Gawler Craton, or its tectono-stratigraphic relationships to the Curnamona Craton to the east, with which it shares many features. Similarly, the relationships with the proto-Yilgarn Craton to the west have remained obscure, due in part to extensive but relatively thin cover.

This is a proposal to address a key geological and exploration problem in the Gawler Craton: What was the crustal structure of the Olympic Dam region, and what specific tectonic features controlled the localisation of early Mesoproterozoic Cu-Au mineralisation within the Olympic Cu-Au province?

A workshop, held in Adelaide in July 2000, on proposed deep crustal seismic work in the Gawler Craton, attended by approximately 40 representatives from industry, government, and academia, concluded that the highest priority for seismic work in the Gawler Craton is the Olympic Dam region. The view was that seismic data could provide a quantum increase in understanding of the crustal setting of the Olympic Dam mineral system. Hence, this dataset would provide the foundation for new exploration models for Cu-Au deposits in the Gawler Craton.

OBJECTIVES

The objectives established for the Gawler Craton seismic project were:—

- A seismic reflection transect passing near the Olympic Dam deposit to test tectonic models advanced for the Olympic Dam region. As part of its Gawler Craton Project, Geoscience Australia has developed a first-generation 3D crustal model of the Olympic Dam region, based on interpretation of potential field data integrated with drill hole geological and geochronological data (Direen et al., 2002). The proposed transect will test and constrain this 3D model, and the results will lead to subsequent 3-D models.
The profiling will test whether a large mafic/ultramafic intrusion exists beneath the Olympic Dam deposit, as implicated in some genetic models of Cu-Au-U mineralisation. Crustal underplating by mafic magmas has been proposed in the generation of the syn-mineralisation Hiltaba suite granites and Gawler Range Volcanics.

In addition to imaging crustal structure near Olympic Dam, this line will provide new insights on Neoproterozoic basin formation in the Adelaide Geosyncline to the east of the Torrens Hinge Zone.

INTRODUCTION

Deep seismic reflection investigations form a major contribution to Geoscience Australia's regional mineral systems projects. In many cases, provision of these data and interpretations have resulted in an enhanced understanding of crustal architecture and tectonic history of many significant Australian mineral provinces.

This document contains details of a deep seismic reflection survey planned for the Gawler Craton, one of Australia’s significant Archaean-Proterozoic provinces, and host to the world-class Olympic Dam Cu-U-Au deposit.

The deep seismic reflection survey will be arranged through collaboration between the South Australian Office of Minerals and Energy Resources (MER), within the Department of Primary Industry and Resources, South Australia (PIRSA) and Geoscience Australia (GA). MER and GA are joint collaborators in the Gawler Mineral Promotion Project, under the National Geoscience Accord.

This document is a summary of the views expressed by interested stakeholders at the Gawler Seismic Workshop, which was held in July 2001 in Adelaide. It also includes work from an initial internal planning document prepared by the Gawler Mineral Promotion Project (Direen, 2000).

BACKGROUND

The Gawler Mineral Promotion Project proposal was based on the following principles:

- Application of a ‘mineral systems’ approach to investigations of mineralised provinces focuses geoscientific research concerning the essential components of the mineral systems under investigation (viz, driving energy, fluid/metal source, transport pathways, depositional trap, and preservation).

- Project objectives are targeted at specific problems addressing how each mineral system operated in time and space; a broader, region- to craton-scale view of the systems will advance exploration and genetic models.

- Integration of multidisciplinary and collaborative studies allows maximum opportunity for cross-disciplinary innovation and mutual benefit among stakeholders.

- Although significant datasets of geophysics, geology and geochemistry exist for the project area, there is great potential for major advancements in geological understanding to be made via focussed acquisition of new data and their synthesis.
These principles were used in developing the three modules within the Gawler Mineral Promotion project, with each module focusing on different mineral systems. These modules represent three important regions within the Gawler Craton (Skirrow, 1999):

- Mulgathing Complex, Christie Domain - Archaean Au.
- Fowler Orogenic Belt, Fowler Domain - Palaeoproterozoic Ni.

These three regions were discussed in the July 2001 Gawler Seismic Workshop and the outcomes formed the basis for developing priorities for seismic traverses within the Gawler Craton.

The main distinguishing characteristics of each of the geological domains of the Gawler Craton (as described by Teasdale, 1997 and revised by Ferris et al., 2002; Table 1) in the three module areas of the Gawler Craton are summarised below. Inferences regarding lower crustal ages have been made using $\varepsilon$Nd model ages at 1590 Ma from Stewart and Foden (1997).

Table 1: Main distinguishing characteristics of geological domains of the Gawler Craton.

<table>
<thead>
<tr>
<th>Sub-Domain Name</th>
<th>Upper Crust composition</th>
<th>Upper Crust age</th>
<th>Middle Crust composition</th>
<th>Middle Crust age (inferred)</th>
<th>Lower Crust age (inferred)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adelaide Fold Belt</td>
<td>Sediments, Minor volcanics</td>
<td>≤ 830 Ma</td>
<td>Sediments, Granitoids, Volcanics</td>
<td>?Mesoproterozoic</td>
<td>?Neoproterozoic rift / underplate</td>
</tr>
<tr>
<td>Stuart Shelf</td>
<td>Sediments, Granitoids</td>
<td>≤ 830 Ma 1590 Ma 1750-1710 Ma 1850 Ma</td>
<td>Sediments, Granitoids, Volcanics</td>
<td>Palaeoproterozoic</td>
<td>Archaean+ Palaeoproterozoic</td>
</tr>
<tr>
<td>Moonta</td>
<td>Mafic volcs, Metaseds Granitoids</td>
<td>1760 Ma 1720 Ma 1590 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lincoln</td>
<td>Granitoids</td>
<td>1850 Ma</td>
<td></td>
<td>Archaean</td>
<td></td>
</tr>
<tr>
<td>Cleve</td>
<td>Metaseds</td>
<td>&gt;2450 Ma</td>
<td></td>
<td>Archaean+ Palaeoproterozoic</td>
<td></td>
</tr>
<tr>
<td>Launch Coulta</td>
<td>Metaseds Granitoids</td>
<td>2600 Ma</td>
<td></td>
<td>Archaean</td>
<td></td>
</tr>
<tr>
<td>GRV</td>
<td>Volcanics, Granitoids</td>
<td>1590 Ma</td>
<td>Sediments, Granitoids</td>
<td>Archaean+ Palaeoproterozoic</td>
<td>Archaean+ Palaeoproterozoic</td>
</tr>
<tr>
<td>Nuyts</td>
<td>Granitoids, Volcanics</td>
<td>1620 Ma 1630 Ma</td>
<td></td>
<td>??</td>
<td>??Palaeoproterozoic</td>
</tr>
<tr>
<td>Wilgena</td>
<td>Metaseds Metaseds Granitoids</td>
<td>&gt;2600 Ma 1690 Ma 1590 Ma</td>
<td></td>
<td>Archaean+ Palaeoproterozoic</td>
<td></td>
</tr>
<tr>
<td>Fowler</td>
<td>Mafic volcs Metaseds</td>
<td>1730 Ma 1490 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Christie</td>
<td>Granulites, Granitoids</td>
<td>&gt;2600 Ma 1670 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coober Pedy</td>
<td>Granulites, Sediments</td>
<td>1700 Ma 2500 Ma</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nawa</td>
<td>Granulites, Granitoids</td>
<td>1690 Ma ??</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
SEISMIC WORKSHOP 2001: SUMMARY OF STAKEHOLDERS' VIEWS

At the Gawler Seismic Workshop held in July 2001, interested industry, government, and university stakeholders discussed the scientific benefits of seismic reflection surveying across the three key areas within the Gawler Craton. The seismic proposal was based on the following criteria:—

- The main objective in acquiring seismic data is to improve understanding and enhance knowledge of the region's mineral systems. Therefore, the seismic traverse should cross a known (ideally major) mineral system.
- Surface and/or drill hole geological knowledge should be available to link geology with the seismic interpretation.
- There should be good coverage of potential field data (gravity and magnetics).
- The seismic traverse should be seen as a means of stimulating area selection and exploration in the area chosen.

One area was clearly identified as the highest priority for seismic investigation is the Olympic Dam region of the Olympic Cu-Au province (Figures 1, 2 and 3).

The meeting recommended that any new seismic work should cross the Olympic Cu-Au province.

Three possible traverses were identified, Traverses A, B and C, as shown on Figures 1 and 2. Traverse A was accorded highest priority by the workshop. Traverse B was identified as it addressed many of the issues that Traverse A addressed but in an area where the geology crops out and is better understood. Traverse C is a short seismic traverse running orthogonal to Traverse A, intersecting near Olympic Dam. The key scientific objectives for each traverse discussed during the workshop are given below.

Traverses A, B and C: The Olympic Cu-Au Province

The world-class Cu-U-Au deposit, Olympic Dam was discovered in 1975 by WMC, in Mesoproterozoic basement concealed by ~300 m of sedimentary rocks of the Stuart Shelf. Since that time there has been a large effort to advance the understanding of basement, mainly through potential field data acquisition and drilling (though drilling has proved very costly). However, industry representatives at the workshop stated that exploration concepts for the Olympic Dam region have stagnated. Seismic is a new way to increase the understanding of fundamental crustal controls on location of mineralisation.

The principle objectives for a seismic reflection survey in the Olympic Dam region, together with an estimate of the relative importance of the objective in understanding the region's mineral systems is shown in Table 2. Several possible traverse locations are shown in Figure 3 that meet all of these objectives. The final traverse position will be determined through liaison with ANSIR representatives.
Table 2: Principle objectives for a seismic reflection survey in Olympic Dam region.

<table>
<thead>
<tr>
<th>Scientific Objective</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Architectural setting of Olympic Dam deposit</td>
<td>High</td>
</tr>
<tr>
<td>2 Architectural setting of Acropolis, Wirdda Well and other Cu-Au occurrences</td>
<td>Medium</td>
</tr>
<tr>
<td>3 Nature of the Torrens Hinge Zone (THZ)</td>
<td>Low</td>
</tr>
<tr>
<td>4 Thickness of Stuart Shelf cover over prospective Mesoproterozoic basement</td>
<td>High</td>
</tr>
<tr>
<td>5 Lithospheric origins, linkage of fluid pathways, and role of mafic magmatism</td>
<td>High</td>
</tr>
<tr>
<td>(faults, shear zones, aquifer packages; mafic intrusions)</td>
<td></td>
</tr>
<tr>
<td>6 Proterozoic tectonic style and history of the Olympic Cu-Au province</td>
<td>High</td>
</tr>
<tr>
<td>7 Architecture of Mesoproterozoic GRV and Hiltaba intrusive systems</td>
<td>High</td>
</tr>
</tbody>
</table>

The traverse location as shown cuts several major gradients in long-wavelength gravity data (Figure 3). These major gravity gradients are interpreted to represent fundamental changes in crustal properties and architecture at depth.

The Olympic Dam deposit and Acropolis and Wirrda Well prospects are located near one of the major gravity gradients, which is sub-parallel to parts of the Neoproterozoic Torrens Hinge Zone in this region.

**Traverse A**

- A NE-SW traverse across the basement to the Stuart Shelf in the region of Olympic Dam. Major structures run NE and NW so traverse A runs roughly perpendicular and parallel to these structures.
- Commences east of the Gawler Craton margin and extends to Gawler Range Volcanics in the west, providing information along an NE–SW corridor across the Olympic Cu-Au province.
- Start in the western region of the Adelaide Fold Belt, in the vicinity of the 'Northwest Fault'.
- Crosses the Neoproterozoic Torrens Hinge Zone.
- Crosses the 'G2' lineament.
- Crosses the footprint of a major Proterozoic Cu-Au mineral system.
- Makes use of available potential field data.
- Costly to explore the basement regions under the sedimentary cover and hence seismic is crucial in imaging the basement architecture.
- Mesoproterozoic and older basement to the Stuart Shelf does not crop out in the area and hence drill hole data will be vital.

**Traverse B**

- An east-west traverse of the Palaeoproterozoic and Mesoproterozoic basement to the west of Port Augusta.
- Makes use of relatively good basement outcrop geological information along the traverse.
- Crosses several lithostratigraphic domains.
- Olympic, Spencer (previously Lincoln), Moonta and Cleve Domain boundaries are all mapped within this area and are relatively closely spaced.
- Provide some 3D information (if recorded in conjunction with Traverse A) on one or two structures as they extend northwards beneath the Gawler Range Volcanics (GRV) and Stuart Shelf sedimentary cover.
- Crosses the Neoproterozoic Torrens Hinge Zone.
**Traverse C**
- A short NW-SE traverse (orthogonal to Traverse A, Figures 1 & 2) across the basement to the Stuart Shelf in the region of the Olympic Dam deposit.
- Crosses the footprint of a major Proterozoic Cu-Au mineral system.
- Investigate NW-SE structures possibly related to the Olympic Dam Cu-U-Au deposit.
- Makes use of available potential field data.
- Costly to explore the basement regions under the sedimentary cover and hence seismic is crucial in imaging the basement architecture.
- Mesoproterozoic and older basement to the Stuart Shelf does not crop out in the area and hence drill hole data will be vital.

**Additional Experiments**

Two additional seismic activities were raised and discussed at the workshop. These activities have the advantage of bringing new researchers into the project, and would provide additional information on the crustal structure of the region:
- Teleseismic Survey / Receiver Function Survey (broadband seismometer survey) east-west across the Stuart Shelf, and well into the Adelaide Fold Belt (to the east) and across the Gawler Range Volcanics, west to the Nuyts domain (Figure 1).
- Crustal-scale seismic refraction survey (using short period seismic recorders) coincident with the deep seismic reflection survey, extending from the Adelaide Fold Belt in the east to the Gawler Range Volcanics in the west.
Figure 1: Domains of the Gawler Craton (as described by Ferris et al. 2002) in white on the aeromagnetic image of the Gawler Craton. The three deep seismic reflection traverses proposed in 2000, Traverses A, B and C are shown in black. Major mineral deposits are also shown in black.
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**FINAL POSITIONING OF SEISMIC TRAVERSES**

Final traverse positions will be determined by liaison with ANSIR (Australian National Seismic Imaging Resource) representatives. However, several aspects of traverse positioning need to be flagged in the early planning stages. These are the need to:

- Integrate the proposed seismic reflection work into work being undertaken by GA and MER Gawler research projects.
- Image key structures at near-orthogonal angles to their strike.
- Avoid areas where sideswipe and/or aliasing of subsidiary structures may reduce data quality.
- Avoid areas of Cambrian limestone outcrop/subcrop that may reduce data quality.
- Avoid sensitive land use areas e.g., National Parks, conservation/wilderness areas, heritage sites, mine leases, and seismically noisy built up areas.
- Minimise land clearance, both in order to reduce environmental impacts and cost.

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**Figure 2:** Domains of interpreted basement geology (pre-Pandurra Fm) of the Olympic Cu-Au province in the eastern Gawler Craton (from Skirrow et al., 2002). Major Cu-Au±U mineralisation occurs in the Olympic Dam, Moonta-Wallaroo and Prominent Hill (Mt Woods Inlier) areas. The three deep seismic reflection traverses proposed in 2000, Traverses A, B and C are shown as thick black lines. Open circles and black squares represent drill holes with low-temperature and high-temperature hydrothermal alteration, respectively.
Participants at the Seismic Workshop identified several logistical issues that will need to be addressed during the final planning of the traverse location. These are:

- Lake Torrens (and the Torrens Hinge Zone)
  - Two areas to the Torrens Hinge Zone
    - North end of Lake Torrens, or
    - North of Port Augusta
- Adelaide Fold Belt (rugged Flinders Ranges)
- Rugged region in Gawler Range Volcanics

**SUMMARY**

The Seismic Workshop participants recommended that the seismic traverse should cross the Stuart Shelf region within the Olympic Cu-Au province in the vicinity of Olympic Dam.

The traverse locations described above are intended to form the basis for further planning. It is likely that alternatives or modifications to these proposals will be made after consultation with the relevant stakeholders. These include ANSIR; PIRSA (including PIRSA Office of Minerals & Energy Petroleum Group); minerals industry representatives (e.g., WMC, Dominion Mining, Resolute, Gunson Resources, Minotaur Resources, etc.); petroleum industry representatives (e.g.,
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Hemley Exploration); the academic community (e.g., Adelaide University, CODES, ANU); local landowners; and local Aboriginal community groups.

REFERENCES


CHOOSING THE LINES

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INTRODUCTION

In choosing the location of a seismic line, there are four main considerations. The location of the survey must allow:—

- The scientific objectives to be met.
- Avoidance of geological problem areas.
- Logistical feasibility of recording seismic data, given the topographical constraints.
- Avoidance of sensitive areas.

In meeting these constraints, it is important to understand how the seismic method works.

The seismic reflection method requires an energy source and a series of receivers. On most seismic systems, the receivers are all connected by cable to create a seismic spread. For deep seismic surveys, this spread can be 10 km or more. The cables must connect to a recording truck that stores the data after each shot. The receivers are continuously recovered from the back of the seismic spread and redployed at the front of the spread. In this way the seismic spread moves along across the ground, along with its energy source, the recording truck, the crew, and support vehicles.

The first requirement is to have a continuous track along which to work. Ideally, it must meet the following conditions:—

- It can be driven along, or if there are obstacles, it is possible to drive around them and get back to almost the same spot.
- It can be negotiated at a reasonable safe speed. A 20 km/hr track takes too long to move from the front of the spread to the back and visa versa.
- It is wide enough to allow other vehicles to pass safely, especially the bigger trucks.
- It does not damage or delay the vehicles, through punctures, sliding, or bogging.

MEETING SCIENTIFIC OBJECTIVES

The objectives of the Gawler seismic are to:—

- Image the crustal structure of Palaeo- and Mesoproterozoic basement near the Olympic Dam Cu-Au-U deposit.
- Use the crustal structure to define tectonic controls on Cu-Au mineralisation.
- Test whether a large mafic/ultramafic intrusion exists beneath the Olympic Dam deposit, as implicated in some genetic models of Cu-Au-U mineralization.
- Determine the geometry and geodynamic significance of the Torrens Hinge Zone at the eastern margin of the Gawler Craton, with a view to ultimately understanding the relationship with the Curnamona Province.
- Provide new insights on Neoproterozoic basin formation in the Adelaide Geosyncline to the east of the Torrens Hinge Zone.

To achieve these objectives, the seismic line had to go close to the Olympic Dam deposit, cover enough distance to image the regional crustal structure, cross the Torrens Hinge Zone, and cross part of the Neoproterozoic basins (Figure 4).

Which way should the eastern Gawler Craton be crossed – north-south or east-west or somewhere in between?

In the eastern Gawler Craton, there is a significant cover of younger material. For this survey, using the available potential field images assisted in determining the regional grain to the geology and associated structures. Analysis of regional geology and regional gravity and magnetic data, ensured that the seismic lines crossed the main geophysical features and dominant strike at high angles.

**Figure 4:** Location of the 2003 Gawler Craton deep seismic reflection lines on (A) regional geological map, (B) gravity data from the National Gravity Data Set, and (C) aeromagnetic from the National Aeromagnetic Data Set. In all cases the seismic lines cross the main geophysical features interested in.
Figure 4 shows the eastern Gawler Craton seismic traverse on the interpreted basement geology, on the regional gravity coverage, and on the regional magnetic coverage. It shows that the seismic lines were recorded at high angles to the tectonic grain, and even where deviation from orthogonal approach thirty or forty degrees, the apparent dip in section was no more than about ten degrees from true.

**AVOIDING GEOLOGICAL PROBLEM AREAS**

The seismic method will always work. However, for the seismic method to produce an interpretable image of the region, then there must be a reasonable density contrast between the rock units being imaged (Jones et al., these volume).

A massive sequence of sandstones will not produce any reflections, unless there are some thin shale bands or similar or some structuring within the sandstone. Equally a homogenous granite body will produce no reflections unless there is some structuring within the granitic body.

Equally, some rock units are not conducive to the seismic method. For example, extreme variations in unconsolidated regolith, basalt sills within a sedimentary succession, cavernous limestones near or at the surface, karst units or brecciated fault zones all either absorb the seismic energy or prevent it returning to the recorders. These geological environments inhibit recording of good quality seismic data.

The optimal orientation of seismic lines, with respect to basement structures, is northeast-southwest. However, this has a major disadvantage in that such a line, passing close to the Olympic Dam minesite, would also cross large areas of near-surface limestone and along to the surface trace of one of a major fault; two serious geological problems to be avoided because of the possible degradation of data quality.

The lines shown in Figure 4 did not pose any significant geological problems that might cause data degradation. The only concern was the thickening Neoproterozoic cover-successions, at the northern end of the traverse, and the mass of Gawler Range Volcanics, to the south, but inspection of some old seismic reflection data near these areas suggested that data could be obtained beneath both the sedimentary cover and volcanics.

**TOPOGRAPHIC CONSTRAINTS**

Topographical features like mountain ranges, rivers, salt lakes and towns all can restrict the location of seismic lines (e.g., Figure 5).

Where possible, it is best to use existing roads, tracks or fence lines. However this is not always practical as the seismic line must be orientated at a high angle to regional strike and the roads do not always run that way. In such cases you must clear a track and topographical issues must be considered very carefully as clearing of new tracks significantly add to the cost of the survey. Figure 6 shows some topographical features in northeastern South Australia that would cause concern for planning a seismic line.
Figure 5: Photograph of the Gawler Ranges. This is not a trivial range to cross. If the seismic had to cross this range, considerable effort would be needed in either finding an existing route across the range or devising a new route. The later would add significantly to the cost of the seismic survey.

Figure 6: Collage of photographs of the northern region of South Australia. These show some of the topographical features you must consider when planning a seismic traverse. (These photographs have been downloaded from http://homepages.picknowl.com.au/anne_brown. Images from top left are A) extremely rough country, B) billabongs, swamps or lakes, C) fragile and boggy areas, D) creeks or water bodies, E) salt lakes, F) mountain range and G) more mountain ranges.
CULTURAL CONSTRAINTS

Cultural constraints include mines, cities or towns, main roads, national parks, exclusion areas, etc. Figure 7 shows some of these in northern South Australia.

In some ways, cultural features are often harder to negotiate than topographical features because they may provide sources of seismic or electromagnetic noise that degrades the quality of the data. Contamination of the data aside, the option of bulldozing a track through a cultural feature is not always open to us.
AVOIDING SENSITIVE AREAS

The positions of seismic lines may need to be adjusted to avoid culturally or environmentally sensitive areas, including Aboriginal heritage areas or sites of significance, early settler heritage areas.

Figure 8 shows some examples of such sensitive areas. Aboriginal heritage sites can be identified through consultation with anthropologists and archaeologists. Environmental sites can be identified through discussion with the local government environmental department.

**Figure 8:** Collage of photographs illustrating sensitive areas that may be encountered during planning a seismic survey. From top left: A) an early settlers house, B) aboriginal carvings on outcrop, C) fragile dunes with limited vegetation and D) stand of Mulga (Acacia aneura).

SUMMARY

At the end of this process of elimination, you will end up with a continuous track along which to work (or the survey will be cancelled). This track will be located to best solve the projects scientific objectives, but modified for local geological problems, topographical features, and sensitive areas. At all times, the most important aspect of locating the seismic lines is to meet the scientific objectives, which add to our understanding of the geology of the Australian continent.
GEOLOGICAL FRAMEWORK OF THE GAWLER CRATON AND THE OLYMPIC DOMAIN

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INTRODUCTION

The Gawler Craton is an Archaean to Mesoproterozoic crystalline shield that has been tectonically stable, with the exception of minor epeirogenic movements, since ~1450 Ma (Thomson, 1975; Parker, 1990, 1993).

The boundaries of the eastern Gawler Craton have been interpreted from potential-field data. Outcrop information and drill hole data are used to determine the limit of rock units known to be of Gawler Craton affinity. The eastern limit of the craton is relatively well defined by the Torrens Hinge Zone, marking Neoproterozoic rifting initiated during the development of the Adelaide Geosyncline. Later deformation, during the Delamerian Orogeny, reworked the eastern Gawler Craton.

The Olympic Domain (incorporating the Moonta Domain of Parker, 1993) is an arcuate zone of Archaean gneisses variously intruded and overlain by Palaeoproterozoic sedimentary successions and felsic igneous rocks and Mesoproterozoic granite, volcanics, quartz-rich sedimentary rocks and conglomerates.

The oldest known rocks of the Olympic Domain are of the Archaean Mulgathing Complex. It comprises aluminous metasedimentary rocks (Christie Gneiss), felsic igneous rocks (Kenella Gneiss), mafic and ultramafic extrusives, felsic intrusives and metasediments (Harris Greenstone Domain), felsic volcanics (Devil’s Playground Volcanics), and syn-tectonic felsic intrusives (Glenloth Granite) (Daly and Fanning, 1993; Daly et al., 1998; Ferris et al., 2002).

In the region of Olympic Dam, equivalents of the Hutchison Group are a schistose unit occurring as enclaves in deformed granites (Creaser, 1989). These rocks are strongly deformed, containing at least one foliation. The Hutchison Group is an extensive sequence of shallow clastic and chemical marine sediments, with minor felsic and mafic volcanics (Parker, 1993). Parker and Lemon (1982) subdivided the Hutchison Group into three main sequences; a basal quartzite sequence (Warrow Quartzite); a mixed chemical and clastic sequence (Middleback Subgroup); and an upper pelitic unit (Yadnarie Schist).

Numerous drill holes have intersected coarse-grained, deformed granite. U-Pb SHRIMP analysis of zircons from these give a crystallisation age of 1845 Ma, which is considered to be part of the Donington Suite (Creaser, 1995). The Donington Suite is defined from the southern Gawler Craton, where it crops out on the eastern coast of the Eyre Peninsula and the west coast of the Yorke Peninsula. In the Olympic Dam region, the suite varies from quartz gabbronorite to ultrafractionated granite (Parker et al., 1988), with small volumes of mafic to intermediate
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magmas, voluminous felsic, megacrystic granite and gneiss and smaller volumes of late, ultrafractionated, fine-, even-grained granite. Distinct units within the Donington Suite exhibit abundant co-magmatic relationships, suggesting evolution from a common magmatic source (Schwarz, 2003). Numerous U-Pb zircon dates from different units have all returned crystallisation ages, within error, of 1850 Ma (Fanning, 1997).

The Kalinjala Mylonite Zone separates the Donington Suite in the south from similar rock types in the Cowell-Clev region, northern Eyre Peninsula. The Kalinjala Mylonite Zone is interpreted to continue north, as a series of anastomosing mylonite zones, into the Olympic Dam region, probably passing to the west of the Burgoyne batholith.

Within the Olympic Dam region, overlying the Donington Suite, there is a sequence of intercalated, deformed felsic volcanics and schists (Creaser, 1989). This unit has not been dated, but possibly correlates with the Myola Volcanics (~1791 Ma), the Moonta Porphyry (~1760 Ma), or the Tidnamurkuna Volcanics (~1780 Ma).

Overlying the older granites of the Olympic Domain is a widespread sequence of finely laminated metasiltstone, feldspathic sandstones, calc-silicates and amphibolites. This sequence is unconformably overlain by Gawler Range Volcanics, hence Creaser (1989) correlated this unit with the Wandearah Metasilstone. Cowley et al. (2003) redefined the Wallaroo Group to include all meta-sedimentary and meta-igneous units older than the Mesoproterozoic Hiltaba Suite (Tickera and Arthurton Granites) and the Oorlano Metasomatite. The Wallaroo Group includes the Wandearah Formation, Weetulta Formation and Matta Formation. The age of the sequence has been determined from the interbedded volcanics, dated by U-Pb zircon analyses at between 1763±14 Ma and 1737±5 Ma (Cowley et al., 2003).

The last major magmatic event observed in the area is that of the Hiltaba Suite/Gawler Range Volcanic magmatic event (1595-1575 Ma). The Gawler Range Volcanics cover an area of approximately 25,000 km². They are the dominant Proterozoic unit cropping out in the Gawler Craton. They comprise a series of felsic and minor mafic volcanics. The Hiltaba Suite, which intruded its co-magmatic Gawler Range Volcanics in places, comprises mostly oxidised, K-feldspar dominant granite. The Olympic Dam Cu-U-Au ore body is hosted within the Roxby Downs Granite, a member of the Hiltaba Suite.

The Pandurra Formation unconformably overlying the basement, is a thick sequence of undeformed arenaceous redbeds that extend over a greater part of the Olympic Domain (Cowley, 1991). Fanning et al. (1983) reports that the Pandurra Formation has a minimum depositional age of 1424±51 Ma based on Rb-Sr geochronology. Unconformably overlying the Pandurra Formation in the Cultana area are subaerial basalts of the Beda Volcanics and intercalated coarse fluvial clastics of the Backy Point Formation.

REFERENCES


CAPABILITIES AND LIMITATIONS OF THE SEISMIC REFLECTION METHOD IN HARD ROCK TERRANES

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INTRODUCTION

The seismic reflection method was developed for petroleum exploration in sedimentary basins, where its accuracy, resolution, and depth penetration result in detailed pictures of structure and stratigraphy. The reflection method uses a controlled source which generates seismic waves that are reflected from interfaces between different rock units, as shown in Figure 9. An explosive or vibratory source is used. Continuous 2D coverage is achieved by moving sources and receivers along a seismic traverse.

The Earth is not homogeneous or isotropic, but a good approximation in seismology is a system of layers, individually homogeneous and isotropic, which is why the seismic method works so well in sedimentary basins. In hard rock areas too, reflections are indisputably produced. The salient questions are: What causes reflections? What can't we see? What are the pitfalls?

Some of the key features of hard rocks are steep dips associated with folds and faults, and high seismic velocities. Steeply dipping events can be difficult to image. High velocities affect resolution, but also make it easier to stack reflections since there is less move-out. In hard rock terranes, there may also be more problems correcting for delays in the weathered zone and in getting sufficient energy through it. However, a counteracting factor is that hard rock should have lower intrinsic attenuation of seismic energy, resulting in greater depth penetration of the higher frequencies.

Much of the material covered here can be found in geophysics texts. However, we have selected and developed those aspects relevant to seismic imaging in hard rock.

BASIC CONCEPTS

Seismic waves

A seismic (elastic) wave is a propagating oscillatory disturbance that travels as a series of wavefronts (equal amplitude of disturbance). Usually ray paths (path travelled by a point on a wavefront) are drawn, as in Figure 9. The distance between successive peaks (or troughs) is the wavelength (λ). The frequency of the wave (f) is the number of cycles per second, so that the velocity of the wave is \( V = \lambda f \).

Two types of seismic body waves can travel within the Earth, namely P (compressional) and S (shear). In reflection surveys, P waves predominate, being preferentially generated by the
commonly used sources. Surface waves (ground roll) can be a source of noise in reflection surveys, travelling along the surface at low velocity and arriving at the same time as reflections from depth.

![Figure 9: Schematic representation of a seismic reflection survey.](image)

Factors influencing P wave velocity in rocks include mineralogy, porosity (and cracks), pore fluid content, cementation and texture. For igneous and metamorphic rocks, the dominant factor is mineralogy, although micro-cracks in low concentrations can significantly reduce velocity. Empirical laws for such rocks show that the velocity is approximately proportional to density. In sedimentary rocks, the most important factors are porosity, pore fluid content and cementation. As a general statement, velocities are high in igneous and metamorphic rocks and lower in sedimentary rocks, particularly young sedimentary rocks.

**Generation of reflections**

When a seismic wave encounters a boundary where there is an abrupt change in elastic properties, some of the energy is reflected depending on the size of the reflection coefficient, but most is transmitted into the second medium, as shown in Figure 10. Some energy will also be critically refracted along the boundary, and forms the basis of the seismic refraction method. The reflection coefficient $RC$ is the ratio of the reflected wave amplitude $A_r$ to the incident wave amplitude $A_i$ and for near normal incidence (up to $20^\circ$) can be expressed as

$$RC = \frac{A_r}{A_i} = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1} = \frac{Z_2 - Z_1}{Z_2 + Z_1},$$
The product $\rho V (= Z)$ is the acoustic impedance, where $\rho$ is the density and $V$ is the P-wave velocity. The larger the contrast in acoustic impedance, the larger will be the reflection coefficient. An impedance decrease causes a negative reflection coefficient, i.e., the reflected wave is reversed in polarity compared with the incident wave. Typically reflection coefficients are small, generally less than 0.05, but in hard rock terranes could reach 0.075 for a felsic-mafic contact ($\rho = 2.7$ t m$^{-3}$ and $V = 6000$ m s$^{-1}$ overlying $\rho = 2.9$ t m$^{-3}$ and $V = 6500$ m s$^{-1}$).

Thus the density contrast governs whether reflections occur at boundaries between different rock types (since velocity is proportional to density for igneous, metamorphic and well-lithified rocks). It is not likely that reflections will result from a foliated fabric within a rock, unless this is strongly developed into alternating bands of material on a macroscopic scale, such as in shear zones.

As a seismic pulse (wavelet) travels down into the Earth, energy will be reflected back at each interface, with amplitude governed by the reflection coefficient, and an extra time delay corresponding to the extra time down to and back from the interface. Thus a seismic reflection trace consists of a succession of ‘echoes’ of seismic energy, as shown in the reflection seismogram in Figure 9.

Figure 9 also illustrates that the travel time for a reflection increases with increasing offset between source and receiver. It can be shown that the time ($T$), along a reflection ray path emerging at offset ($X$), from the source follows a hyperbolic relationship,

$$T^2 = T_0^2 + X^2 / V^2;$$

where $V$ is the velocity of the layer, and $T_0$ is the two way travel time for vertical incidence. The difference between $T$ and $T_0$, known as normal moveout, decreases with both increasing $T_0$ and increasing $V$. The high velocities typical of hard rock areas mean that moveout is generally small, so that uncertainties in moveout velocity are not so problematical for stacking the data. However, a corollary is that velocities for depth conversion are very poorly constrained.

For dipping reflectors, the above relationship is modified with $V$ replaced by $V/\cos \alpha$, where $\alpha$ is the angle of dip, thus increasing the stacking (moveout) velocity.
Snell’s Law \( \sin \theta / \sin \phi = V_1/V_2 \) for \( V_2 > V_1 \)

**Figure 10:** Reflection and refraction of a seismic wave at a boundary between two media with velocity \( V_1 \) and \( V_2 \) and density \( \rho_1 \) and \( \rho_2 \), respectively. The angle of incidence equals the angle of reflection. The wave is transmitted into the second medium with angle of refraction \( \phi \). For \( \phi = 90^\circ \), the refracted ray follows the boundary (critical refraction).

**SEISMIC RESOLUTION**

Seismic resolution deals with the question: How thick and how wide do features have to be to produce recognisable reflections on a seismic section?

**Vertical Resolution**

The concept of vertical resolution can be illustrated by considering waves reflected from a layer of thickness \( H \) and velocity \( V_1 \) embedded in a medium of velocity \( V_0 \), as shown in Figure 11. The reflection from the bottom will be reversed in polarity (reflection coefficient has opposite sign) and will lag behind the reflection from the top by a time \( \Delta T \), as shown in Figure 11. If the layer is

**Figure 11:** Vertical resolution (identification of an embedded layer) is determined by the superposition of reflections from the top and bottom of the layer. Because the two reflections are of opposite polarity they cancel for thin layers and reinforce for thicker layers.
thick, $\Delta T$ will be large and the two wavelets will appear as separate events. If the layer is thin, $\Delta T$ will be small and the two wavelets will almost cancel. A commonly used criterion for resolution is that interference effects are maximised when the wavelets are separated by half a cycle, which corresponds to a layer thickness of $\lambda/4$ ($\lambda$ being the dominant wavelength for the wavelet).

The seismic response of layers of different thickness is illustrated on the right hand side of Figure 11. Thickness is parameterised in terms of $\lambda$. A maximum response occurs for $\lambda/4$, but the top and bottom of the layer are not resolvable and it thus appears as a single interface. In practice, the layer can still be detected as it becomes thinner, but becomes progressively harder to see. Layers thinner than $\lambda/32$ would not be detectable. It is not until the layer thickness exceeds $\lambda/2$ that reflections from the top and bottom of the layer can just be seen as two events.

What are typical values of $\lambda$ in hard rock areas? The range of frequencies (band width) contained in a seismic pulse is narrow, normally from 5 Hz to 100 Hz. Because the amplitude loss with depth depends on frequency, the highest frequencies are rare at depth. Typically, the dominant frequency would be 40 Hz or less, corresponding to a wavelength of 150 m for a typical velocity of 6000 m s$^{-1}$. Layers would need to be greater than 75 m thick to be identified as such. However, a layer of about 37.5 m will produce a strong response, even if it cannot be differentiated from an interface. It would not be possible to detect layers less than 5 m thick (and probably not even less than 10 m). Thus the vertical resolution in hard rock is not as good as in sedimentary basins.

**Shear Zones**

Shear zones are often very strong reflectors of seismic energy, due to their layered nature on a macroscopic scale. Bands of alternating low and high velocity (density) material can explain the seismic response as shown in Figure 12. Tuning of the interference between reflections from tops and bottoms of the layers can result in a much larger seismic response than for a homogeneous layer of the same total thickness (compare Figure 12(a) and (b)). Zones in which layer thickness is variable and less than $\lambda/4$ can still produce strong reflections as illustrated in Figure 12(c) and (d). Typically shear zones exhibit a strong amplitude response, which is spatially variable. If the amplitude response is due to constructive interference of reflections from many layers, then lateral change in layer thickness could explain the variability from trace to trace.

**Horizontal resolution**

Horizontal resolution is concerned with the minimum lateral extent of features that can be detected. Consider the case of vertical incidence for a reflecting point P as shown in Figure 5. Geometrical ray theory would predict that only point P contributes to the reflection recorded vertically above on the surface at S. Wave theory shows that not only P, but surrounding points within a certain radius also contribute to the reflection amplitude.

For down-going wavefronts from source S, zones on the reflector can be constructed such that the difference in path lengths from S is $\lambda/4$ as shown in Figure 13 (a). For two-way travel, the difference in path length will be $\lambda/2$. It can be shown that the innermost zone (known as the first Fresnel zone) makes the dominant contribution to the wave amplitude observed at S.
The first Fresnel zone has a radius equal to \((\lambda d/2)^{1/2}\) where \(d\) is the depth to the reflector. Thus, the width of the zone increases (resolution decreases) as both depth (two-way time) and dominant wavelength increase. In practice, features smaller than the Fresnel zone will not be resolved, since the reflected wave amplitude depends on the average properties over the width of the Fresnel zone.

**Diffractions**

When a seismic wave encounters a feature whose dimensions are comparable to, or smaller than the wavelength, the wave is diffracted, rather than reflected or refracted. Since the seismic wavelength in hard rock is typically 150 m, there will be many instances where geological features are smaller than this. Diffractions are commonly produced from very small geological structures or where continuous reflectors suddenly stop. Examples such as tight bends on folds, ends of fault-truncated layers, and tips of dykes are illustrated in Figure 14a.

The generation of diffractions can be explained by treating the feature as a point from which secondary waves radiate after excitation by the incident wave. An incident wave spreading out from a source at P1 in Figure 14b will generate a returning wave that will travel back along the same path; similarly for point P2. On a seismic section, the returning wave is assumed to come from vertically below P1 and P2, and will lie along a hyperbolic curve as shown in Figure 14c.
In Figure 13b, two-way time (s) for the hard rock areas can be converted to depth (km) by multiplying by 3, using a typical velocity of 6000 m s\(^{-1}\). For mid-crustal depths of ~24 km (TWT = 8 s), reflecting bodies must extend over a kilometre or two to be visible. As shown in Figure 13b, horizontal resolution is poorer than it would be for a typical sedimentary basin, i.e. the Fresnel zone is larger for hard rock areas, because of the greater wavelength (~150 m). However, because of the mathematical formulation above, the Fresnel zone radius increases by a factor of only 1.4 for a doubling of the wavelength, for features at the same depth.

The crest of the diffraction locates the diffracting point (in time and space). In practice, amplitude is stronger towards the crest of the diffraction curve. The curvature of the diffraction depends on the depth to and the velocity above the diffracting point, but standard overlay curves can be produced to differentiate diffractions from structure. Migration will collapse diffractions as described later. Diffracted waves will also fill in gaps in reflectors, thus making the seismic event appear continuous when the physical interface is not (another way of visualising the concept of horizontal resolution).

**Dipping Reflectors**

In hard rock areas, rocks are commonly highly deformed, resulting in steeply dipping rock units within folds, as well as faults of varying dips. Since the seismic method was originally developed for sub-horizontal layering within sedimentary basins, a critical issue is the greatest dip that can be imaged by the method in hard rock terranes.

The maximum dip is constrained by two parameters, the length of the seismic line and the duration of the seismic record. The general picture is illustrated in Figure 15. For near coincident source and receiver at P, a reflection will return along a path that is perpendicular to the reflector. To be imaged from P, sub-horizontal reflectors must lie below P, but steeply dipping reflectors will lie off to the side by a considerable distance. Thus a seismic line must be long enough to encompass both the reflecting surface and the seismic reflection system. In addition, recording time must be long enough to record reflections from the offset reflectors.
Figure 16 shows this relationship for a typical deep crustal seismic survey in hard rock. Note that a recording time of 20 seconds would be necessary to record reflections from a distance of 60 km, assuming a velocity of 6000 m s\(^{-1}\). A semi-circular region in the Earth, centred on the observation point, is divided into equiangular segments. Each segment shows the zone within the Earth where a particular range of dips will be imaged, out to a distance of 60 km. For example, in the segments labelled 70\(^{\circ}\) to 80\(^{\circ}\), only reflectors with dips in this range towards the observation point will be imaged. In the 0\(^{\circ}\) to 10\(^{\circ}\) segments, only shallow dips will be imaged.

Consequently, shallowly dipping structures are imaged when the observation point is directly above, and continuous coverage will be obtained as the point moves along the line. Very steep dips near the surface can be imaged from the side. For lines of approximately 100 km length, it could reasonably be expected that dips as high as 50\(^{\circ}\) in the middle crust may be seen.

A further consideration concerns the survey acquisition parameters - whether these discriminate against steep dips at any frequencies of interest. In the field, geophone arrays are used to attenuate coherent noise and random noise, by summing the individual geophone responses. A source array is also used with typically three vibrators in line with moveup between sweeps. Arrays will pass vertically travelling energy, but will discriminate against horizontally travelling energy with wavelengths shorter than the effective length of the combined source and receiver array.
For a ray incident at the surface at angle $\alpha$ (to the normal) the apparent velocity across the array is $V_a = V / \sin \alpha$ with corresponding apparent wavelength $\lambda_a = \lambda / \sin \alpha$. For the ray path in Figure 15, $\alpha$ equals the dip angle. Thus, apparent wavelengths will range from infinite for reflections from horizontal reflectors to the true wavelength for reflectors with a dip of $90^\circ$. For frequencies from 40-100 Hz, the true wavelength $\lambda$ will range from 150 m to 60 m. Thus dip filtering by the array is not likely to occur for the typical combined array effective length of approximately 60 m.

A further consideration in imaging steeply dipping reflectors is that dipping reflectors require higher stacking velocities than horizontal reflectors. For example, where a horizontal reflector has a stacking velocity of 6000 m s$^{-1}$, a reflector in the same material dipping at $60^\circ$ would stack at 12000 m s$^{-1}$ ($V/cos \alpha$). The difficulty of simultaneously stacking reflectors of different dips is more pronounced at shallow depth (and TWT), since normal moveout is greater. Dip moveout

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**Figure 15:** The length of the seismic line and the recording time determine the maximum dip that is imaged. For steep dips, the observation point must be off to the side, and the recording time must be long for energy to travel out to and back from the reflector.

**Figure 16:** Each segment shows where dipping reflectors must be located, in order to be imaged from the observation point, for the dip range annotated on the segment edges.
(DMO) processing is required, but can be difficult to apply correctly for crooked lines where the fold may be low and the offset distribution irregular.

**Migration**

Migration is the process of moving reflectors to their correct positions and is essential in areas of steep dip and complicated structure. Because of the way seismic data are displayed, dipping reflectors are not correctly imaged, as shown in Figure 17. The ray paths for coincident source and receiver at points P1, P2, and P3 must be perpendicular to the reflector at the corresponding reflecting points. However, on the seismic section, these reflecting points appear to be vertically below points P1, P2, and P3. Thus the reflector segment is shifted downwards and its apparent dip, $\beta$, is less than the true dip, $\alpha$, such that $\tan \beta = \sin \alpha$. Dipping reflectors, such as faults, and the flanks of synclines and anticlines, will not appear in their correct positions. Moreover, such features will appear to have lower dip as illustrated in Figure 18. A consequence of the relationship between true dip and apparent dip is that dips will never appear to be greater than 45° on an unmigrated section.

![Figure 17](image)

**Figure 17:** On a stacked seismic section, reflecting points will appear vertically below the coincident source-receiver points on the surface. Thus dipping reflectors will appear deeper than their true position, with a lower apparent dip. The process of moving reflectors to their correct positions is known as migration.

The effect of lack of migration is shown in Figure 19a for the southern end of line 03GA-OD1. Arcuate features and dipping events can be seen throughout, crossing one another to give a ‘basket-weave’ pattern. Some of these are diffractions emanating from lithological discontinuities. Dipping features appear shifted downwards from their true position, and anticlinal features appear to be broad.

Conceptually, migration is a simple procedure. In principle, the position of the reflector shown in Figure 17 just needs to be swung back through an arc equal to the true dip angle. In actual implementation, migration is a complicated process, not only because of velocity variations, but also because of out of plane energy. Because most of the migration algorithms use the wave equation, diffractions will also collapse to a point, thus improving horizontal resolution. It is important to note that 2D migration can only be carried out in the presence of dip. Thus strike lines with apparently horizontal reflectors cannot be migrated. Migration works best for seismic data with strong lateral continuity. However, in hard rock terranes, lateral continuity of reflections is often poor, making it difficult to implement migration successfully.
The result of migration is shown in Figure 19b. Migration has collapsed the diffractions, cleaning up the image and leaving only reflections from continuous surfaces, which are shifted back to their correct position. Dipping parts of reflectors have moved up and become steeper and anticlines have thus become narrower in the process. More steeply dipping events have been migrated greater distances. For example, the steeply dipping reflectors on the left hand side of the section have been moved up to the left, off the end of the section. Note that care must be exercised in interpreting events on the ends of migrated lines. If events are dipping towards the end of the line, they will be moved up dip, but no more data exists to be migrated to fill in the gap.

Several criteria can be used to decide whether the sections are under-migrated or over-migrated. Since migration moves reflectors upwards and steepens them, the termination of reflectors against another surface can be used as a guide to the correctness of migration (see also Figure 21). On under-migrated sections, the diffractions still look like diffractions, whereas on over-migrated sections, the diffractions turn into 'smiles'. Figure 20 shows a diffraction hyperbola in the vicinity of Olympic Dam which is collapsed by migration. If this diffraction is associated with the ore body, then in this case it would be useful to interpret both the stack and migrated sections.

**EXAMPLES OF FEATURES IMAGED IN THE GAWLER CRATON**

In the Gawler Craton, the seismic reflection survey was able to image features with a range of dips, including shallow to moderately dipping lithology and moderately dipping thrusts and faults. In places, the presence of steeply dipping surfaces could be inferred from the progressive upturn of more shallowly dipping surfaces.

**Dipping features**

The migrated seismic section for line 03GA-OD1 is characterised by prominent, northerly dipping features at the southern end of the line (see Figure 19). These are among the steepest features imaged on the line, but are still of moderate dip. More steeply dipping features on the extreme edge of the line migrate off the end of the section and cannot be interpreted.
Figure 19: Seismic sections for line 03GA-OD1 from CDP 10047 to 11546 and 0-6 s TWT. $V/H \approx 1$. 100 CDP = 2 km. 1 s = 3 km. (a) Final stack. (b) Migrated section. The black line shows the position of a single dipping reflector before and after migration.
An issue still to be resolved is whether steep near-surface reflectors of limited extent can be satisfactorily imaged, in view of the vertical and horizontal resolution obtainable. Horizontal resolution would be no better than 250 m on an un-migrated section, even at the highest frequencies, for steeply-dipping shallow features. Thus small scale folding will not be seen, but enveloping surfaces may be imaged. In some cases, steep dips may be inferred from a progressive up-turning of layers before entering a reflection-free zone, as can be seen in Figure 21. Resolving these issues needs further research, using seismic modelling and pre-stack migration.

**Figure 20:** Seismic sections for line 03GA-OD1 in the vicinity of Olympic Dam from CDP 7150 to 7650 and 0–6 s TWT. V/H ~ 1. 100 CDP = 2 km. 1 s = 3 km. (a) Final stack. (b) Migrated section.
Faults and dykes

Faults can be recognised by the way they disrupt layering, with similar criteria to those used for identifying faults in sedimentary basins. These include offset of layers, abrupt change in reflection character or layer thickness, change in dip and the presence of diffractions from truncated layers. Note that vertical faults can be identified in this way, because the fault is imaged by its effects and not by reflections from it. Similarly disruption of bedding and a lack of reflectivity can indicate the possible presence of vertical dykes, as can be seen in several places in Figure 19 at approximately 0.5 s TWT.

Figure 21 illustrates a thrust surface which can be identified by the truncation of layers above and below, the change in the dip of the strata and by the occurrence of anticlinal structures in the hanging wall. Note also that after migration, the reflectors correctly truncate against the thrust surface.

SUMMARY

The seismic reflection method was originally designed for use in sedimentary basins where the sub-horizontal and continuous layers correspond to primary bedding. Reflections are generated by acoustic impedance contrasts at the boundaries between layers. In hard rock areas, too, reflections are indisputably produced at boundaries between rocks with different densities (and hence velocities). These boundaries may follow bedding, or be fault surfaces and shear zones.

Some of the key differences between hard rock terranes and soft rock are steep dips associated with folds and faults, and high velocities. High velocities affect resolution, since both vertical and horizontal resolution depends on the seismic wavelength. Compared with sedimentary basins, vertical resolution is probably only half as good, with the situation being slightly more favourable.
for horizontal resolution. The high velocities make it easier to stack reflections since there is less move-out, but more difficult to use the stacking velocity analysis to determine accurate velocities for depth conversion and migration.

Steep dips can affect the ability to image successfully. The seismic line must be long enough to encompass both steeply-dipping reflectors and the seismic acquisition system. Recording times must also be long enough for energy to travel to and from steeply dipping reflectors. Migration is essential in areas of complicated structure in order to move dipping reflectors to their correct positions and to collapse diffractions emanating from discontinuities in the layers. Unless migration is carried out, dips on the seismic section will never appear greater than 45°.

Examples from the 2003 Gawler seismic survey show that shallow to moderate dips are routinely imaged, with more steeply dipping faults inferred from discontinuities. The migrated sections provide a spectacular set of images that underpin interpretations of the geological structure of the eastern Gawler Craton.
SEISMIC ACQUISITION AND PROCESSING – 2003 GAWLER CRATON SEISMIC REFLECTION SURVEY (L163)

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INTRODUCTION

The 2003 Gawler Craton Seismic Survey (L163), consisting of 2 lines 03GA-OD1 and 03GA-OD2, was conducted in July/August 2003 for Geoscience Australia in conjunction with the Department of Primary Industries and Resources South Australia (PIRSA). The Australian National Seismic Imaging Resource (ANSIR) was responsible for seismic data acquisition, as well as for field QC and preliminary in-field processing.

The 193 km line 03GA-OD1 started approximately 120 km north of Roxby Downs and stopped just short of Woomera (Figure 22). The shorter 57 km line 03GA-OD2 ran from west to east just south of the Olympic Dam mine site.

ACQUISITION

The seismic reflection data were acquired along the edge of roads. Station coordinates were surveyed using differential GPS by Dynamic Satellite Surveys (2003). A split-spread geometry was used with the source nominally at the centre of the spread. Receiver groups were centred between station pegs, while the source array was centred on the peg.

Three IVI Hemi-60 (60,000 lb) vibrators were used in-line, with moveup between each of three varisweeps. Sweep parameters were chosen from experiments conducted at the beginning of the survey. An ARAM 24-bit 240 channel recording system was used to record and correlate the seismic data.

A summary of acquisition parameters is
given in Table 3 and in Appendix 1. Further details are provided in the Operations Report (Trace Energy Services, 2003).

Table 3: Summary of acquisition parameters for lines 03GA-OD1 and 03GA-OD2

<table>
<thead>
<tr>
<th>LINE</th>
<th>03GA-OD1</th>
<th>03GA-OD2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA</td>
<td>Roxby Downs – Olympic Dam (SA)</td>
<td>Roxby Downs – Olympic Dam (SA)</td>
</tr>
<tr>
<td>DIRECTION</td>
<td>N to S</td>
<td>W to E</td>
</tr>
<tr>
<td>LENGTH</td>
<td>193.36 km</td>
<td>57.44 km</td>
</tr>
<tr>
<td>STATIONS</td>
<td>1000 – 5834</td>
<td>1000 – 2436</td>
</tr>
<tr>
<td>CDP RANGE</td>
<td>2000 – 11546</td>
<td>2001 – 4658</td>
</tr>
<tr>
<td>GROUP INTERVAL</td>
<td>40 m</td>
<td>40 m</td>
</tr>
<tr>
<td>GROUP PATTERN</td>
<td>12 in-line @ 3.33 m</td>
<td>12 in-line @ 3.33 m</td>
</tr>
<tr>
<td># VIBRATION POINTS</td>
<td>2446</td>
<td>718</td>
</tr>
<tr>
<td>VP INTERVAL</td>
<td>80 m</td>
<td>80 m</td>
</tr>
<tr>
<td>SOURCE TYPE</td>
<td>3 x IVI Hemi-60</td>
<td>3 x IVI Hemi-60</td>
</tr>
<tr>
<td>SWEEP TYPE</td>
<td>3 x 12 s: 7-56, 12-80, &amp; 8-72 Hz</td>
<td>3 x 12 s: 7-56, 12-80, &amp; 8-72 Hz</td>
</tr>
<tr>
<td>SOURCE PAD-PAD</td>
<td>15 m</td>
<td>15 m</td>
</tr>
<tr>
<td>SOURCE MOVE-UP</td>
<td>15 m</td>
<td>15 m</td>
</tr>
<tr>
<td># CHANNELS</td>
<td>240 (&lt;240 on roll off)</td>
<td>240 (351 on roll off)</td>
</tr>
<tr>
<td>FOLD (NOMINAL)</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>RECORD LENGTH</td>
<td>18 s @ 2 ms</td>
<td>18 s @ 2 ms</td>
</tr>
</tbody>
</table>

PROCESSING

Production processing utilised the Disco software package, while the interactive version Focus was used for parameter tests, first break picking and QC. Table 4 shows the final processing flow, including migration, for the 6 s data for line 03GA-OD1. For adequate resolution, only 4 ms sampling was required. The 18 s processing stream was similar, except that dip moveout correction (DMO) was not applied pre-stack and a run mix equivalent to combining two CDP gathers was used pre-migration.

The processing flow was designed with the aim of enhancing reflections, while avoiding processes that could potentially degrade data, particularly in the shallow section. Parameter testing was done on shot records, CDP gathers or stack panels for the processing modules that were used. The key processing steps are discussed in the following sections, with particular emphasis on those that resulted in the most improvement in data quality.

Crooked line definition and CMP/CDP sort

The geometry for each line (i.e., receiver and shot locations) was entered into an internal seismic database prior to actual seismic data processing. Since the receiver groups were centred between the surveyed stations, the receiver station coordinates for processing were defined to be half-way between surveyed stations (i.e. station 1000 for processing is located at 1000.5 as surveyed).

CDP (common-depth-point) locations were also defined. Ideally, for a horizontal reflector, the midpoint between a source and receiver pair lies vertically above the depth point (or reflecting point) for that pair, so that the CDP location is the same as the common midpoint (CMP) location. For dipping reflectors, this correspondence no longer holds, but the CDP terminology is so entrenched in seismic processing that it is used in place of the more correct term “common midpoint”. Note that the midpoint spacing along a straight line is half the receiver group interval.
Table 4: Final processing flow for 6 s data for line 03GA-OD1

[1] line geometry and crooked line definition (fixed CDP interval)
[2] field segy to ‘disco’ data format; resample to 8 s at 4 ms
[3] quality control displays and trace edits
[4] spectral equalization (with 1000 ms gate AGC)
[5] common mid point sort (bin wide open)
[6] gain recovery (spherical divergence option)
[7] application of refraction statics, datum 0 m (AHD)
[8] application of automatic residual statics
[9] bandpass filter
[10] stacking velocity analysis using velex, 1st pass after refraction statics, 2nd pass after automatic residual statics, 3rd pass after DMO correction
[12] stretch mute used as front end mute
[13] dip moveout correction (DMO)
[14] common mid-point stack
[15] trace amplitude balance
[16] f-x migration with migration velocities
[17] signal enhancement (digistack 0.8)
[18] run mix, trace amplitude scaling and resample to 6 s for display

Crooked line processing was used for both 03GA-OD1 and 03GA-OD2, and was essential for the latter due to bends in the existing roads. In the crooked line case, the midpoints do not always lie along the line defined by the surveyed stations. The CDP line is defined as a smoother representation that follows the highest density of midpoints, while keeping as close as possible to the original line (Figure 23). Note that the CDP bins extend perpendicular to the CDP line as shown in Figure 23. For both lines, the CDP line was defined with a constant CDP interval of 20 m. Since the CDP line is shorter than the line of stations, the CDP number will be less than twice the station number.

Figure 23: Crooked line geometry, with X and Y coordinates in m. A series of triangles indicates the surveyed station line, with the smoother CDP line in black. Shaded area shows midpoints. Unshaded strip perpendicular to the CDP line is a diagrammatic representation of a CDP bin, showing location of midpoints assigned to a particular CDP. (Actual bins 20 m wide).