The Capricorn seismic survey: experimental design, acquisition, and processing

by

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Introduction

Following the establishment of the AuScope infrastructure initiative in 2007, a call for proposals was made for transect components, particularly seismic reflection profiling. Ian Tyler (Geological Survey of Western Australia) and Peter Cawood (University of Western Australia, now University of St Andrews) had already developed a comprehensive plan for reflection transects across Western Australia, and they selected a line crossing the Capricorn Orogen for submission to the AuScope call. The proposal received excellent reviews and was selected for AuScope support. Detailed planning was therefore undertaken to establish a practical line of survey.

The objective was to start in the Pilbara Craton, cross the Fortescue, Hamersley, Turee Creek, Ashburton, Edmund and Collier Basins, and the Gascoyne Province, and finish in the northern part of the Yilgarn Craton. This was rather more than could be supported by AuScope alone; fortunately, the Western Australian Goverment's 'Exploration Incentive Scheme' enabled the Geological Survey of Western Australia (GSWA) to join as an equal partner in the reflection survey. AuScope also provided additional support for a detailed magnetotelluric survey to be run along the line of the reflection profiles.

The nature of the terrain and availability of access meant that it would not be possible to have a single continuous survey line. However, by exploiting roads and minor tracks, it was possible to identify three segments that were logistically feasible, and which allowed along-strike connection of geological structures (see Frontispiece 1; Plate 1). The length of reflection profiling over the three segments was 581 km; although some sharp bends were required by the nature of the available access, these were confined to a small part of the total survey.

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Background to the transect

The following summary of the Capricorn Orogen's geological history is modified from Cawood and Tyler (2004), Sheppard et al. (2010), and Johnson et al. (2010, 2011). The Capricorn Orogen records the operation of one or more Paleoproterozoic Wilson cycles. These cycles involved the late Archean and early Paleoproterozoic rifting and break-up of two late Archean continents to form continental margin assemblages on what are now the southern margin of the Pilbara Craton and the northern margin of the Yilgarn Craton. These margins were juxtaposed, overlain by foreland basin sequences, and deformed — together with accreted exotic continental and ?oceanic fragments, and arc sequences — during the subsequent subduction and closure of an intervening ocean or oceans. The cycles culminated in mid to late Paleoproterozoic collision and suturing to form the amalgamated West Australian Craton. The Capricorn Orogen is more 'complete' than any other within the Australian Precambrian, and is unique in having distinctly different, opposing, continental fragments exposed along both the northern and southern orogen margins, together with the exposure of upper- to mid-crustal rock units within the orogen itself. As such, this orogen provides an important insight into Paleoproterozoic collisional processes.

The Capricorn Orogen consists of the Paleoproterozoic plutonic igneous rocks and medium- to high-grade metamorphic rocks of the 2550–1620 Ma Gascoyne Province; a series of Paleoproterozoic volcano-sedimentary and sedimentary basins, including the 2200–1805 Ma Ashburton Basin, the c. 1805 Ma Blair Basin, the 2150–1840 Ma Yerrida Basin, the 2020–1900 Ma Bryah and Padbury Basins, and the 1840–1800 Ma Earaheedy Basin; and the deformed margins of the Pilbara and Yilgarn Cratons. The Narryer Terrane, located along the northwestern margin of the Yilgarn Craton, includes early Archean granitic gneisses (3650–3300 Ma) that contain older lenses and fragments of c. 3730 Ma anorthosite, and mafic to ultramafic rocks; metasedimentary rocks from this region contain detrital zircons as old as c. 4400 Ma. The Pilbara Craton and overlying Hamersley Basin contain some of the earliest records of life on Earth, and are a source of major hematite iron ore deposits.

The orogen underwent major tectonothermal events during the 2215–2145 Ma Ophthalmian Orogeny, the 2005–1950 Ma Glenburgh Orogeny, the 1820–1770 Ma Capricorn Orogeny, and the 1680–1620 Ma Mangaroon Orogeny. The Mesoproterozoic Edmund and Collier Basins are exposed across significant areas of the central part of the orogen, and reactivation within the orogen has produced extensive deformation of these basins during the Mesoproterozoic Mutherbukin Tectonic Event (1385–1200 Ma), and the Neoproterozoic Edmundian Orogeny (1030–955 Ma) and c. 570 Ma Mulka Tectonic Event.

The Errabiddy Shear Zone separates early to late Archean rocks of the Narryer Terrane (northwestern Yilgarn Craton) from the latest Archean to Paleoproterozoic rocks of the Glenburgh Terrane (Gascoyne Province). The Narryer Terrane underwent reworking in part during the Glenburgh and Capricorn Orogenies, and the southern margin of the Capricorn Orogen is defined by the southern limit of this reworking. The northern margin of the Capricorn Orogen comprises the Paleoproterozoic Ashburton, Blair, Mount Minnie, and Bresnahan Basins. Deformation of this region during the Ophthalmian and Capricorn orogenic events formed a number of fold belts; the northern limit of the Ophthalmia Fold Belt marks the northern limit of the orogen.

Thus, the present transect across the Capricorn Orogen and bounding margins of the Yilgarn and Pilbara Cratons passes through a world-class example of Precambrian continental assembly and reworking.

The major objectives of the transect were to:

1. image the crust and upper mantle structure along the survey lines, passing through the Fortescue, Hamersley, and Turee Creek Basins of the Pilbara Craton, the Gascoyne Province, and the northern margin of the Yilgarn Craton
2. establish the subsurface extent of Archean crust beneath the Capricorn Orogen, and identify whether the Pilbara and Yilgarn Cratons are in direct contact, or whether they are separated by one of more Proterozoic crustal elements
3. determine the nature and character of basement to the Proterozoic basins flanking the Yilgarn and Pilbara Cratons (e.g. the Ashburton, Yerrida, and Earaheedy Basins)
4. link surface units and structures (e.g. the Errabiddy Shear Zone) — including their age, geochemical signature, and, in the case of structures, their movement history — with their deep geophysical character, in order to better understand the geological evolution of the orogen
5. understand the processes driving the Proterozoic assembly of the West Australian Craton, and the subsequent processes of repeated crustal reworking within a long-lived orogen
6. identify structures cutting through the crust to the mantle, which may have acted as pathways for fluid flow to mineral systems, including the world-class hematite iron ore deposits of the Hamersley Basin, copper–lead mineralization at Abra, and orogenic lode-gold mineralization at Mount Olympus on the Pilbara Craton margin.

Acquisition of the seismic reflection data

AuScope and GSWA collaborated with Geoscience Australia in the acquisition and processing of the reflection survey, with Terrex Seismic contracted to collect the data in the field. Due to wet conditions in central Australia at the time, the seismic crew became available somewhat earlier than anticipated, and the survey was carried out in April and May 2010.

Acquisition of the reflection seismic survey commenced on 11 April 2010, at the north end of the 10GA–CP1 line. The first base camp was on Rocklea Station; the survey headed initially in a southwesterly direction, and afterwards in a more southerly direction. Conditions at the southern end of the line were found to be too difficult for seismic acquisition, and the line was terminated about 4 km short of the original target.

Following the completion of 10GA–CP1, there was a significant remobilization to start at the northern end of the 10GA–CP2 line. The first base camp on 10GA–CP2 was located on the Wanna Station access road, approximately 19 km north of the Cobra – Mount Augustus Road. The northern part of this line exploited station tracks that allowed access into the rugged Minnierra Range. The reflection profiling then continued south along the Cobra – Dairy Creek Road.

The 10GA–CP3 line started at the junction of the Dalgety Downs – Landor Road and the Erong Road, following the Erong Road south to end at the junction with the Beringarra–Byro Road. The crew then shifted from the end of the 10GA–CP3 line to the east, to the start of the 10GA–YU1 line of the Youanmi Survey, approximately 8 km west of Beringarra Homestead. The survey was completed on 20 May 2010.

Seismic processing was carried out at Geoscience Australia, with preliminary migrated sections made available for interpretation workshops held in Perth, in March and June 2011.

The location of the line segments, superimposed on a gravity image of the area, is displayed in Frontispieces 2 and 3. The seismic acquisition parameters for the survey are shown in Table 1.

The seismic data were collected using 300 live channels spread over 12 km, with the source array located at the centre of the spread. The maximum offset receiver groups were 6 km from the source. The seismic data were recorded using a Sercel 428XL recording system in SEG-D de-multiplexed format. The recording system cross-correlated each of the three recorded sweeps for each vibration point (VP) with its respective reference sweep, and then stacked the cross-correlated sweeps, creating a single, 20 s record for each VP that was then written to a LTO2V tape. The average survey production rate was of 182 VPs, or 14.9 km, per day.

Table 1. Acquisition parameters used for the Capricorn seismic survey

Source type	3 IVI Hemi-60 vibrators
Source array	15 m pad-to-pad, 15 m moveup
Sweep length	3 x 12 s
Sweep frequency	6–64 Hz, 12–96 Hz, 8–72 Hz
Vibration Point (VP) interval	80 m
Received group	12 geophones @ 3.3 m spacing
Group interval	40 m
Number of recorded channels	300
Fold (nominal)	75
Record length	20 x @ 2 ms

Processing of the seismic reflection data

The reflection seismic data from the Capricorn seismic survey were processed by the Seismic Acquisition and Processing team of the Onshore Energy and Minerals Division at Geoscience Australia, using Disco/Focus processing software on a Red Hat Enterprise Linux Sun Fire X4600 M2 server.

The following sequence was used to process seismic reflection data for lines 10GA–CP1, 10GA–CP2, and 10GA–CP3:

- SEG-D to Disco format conversion, resample to 4 ms
- Quality control displays
- Crooked line geometry definition (CDP interval 20 m)
- Inner trace edits
- Common midpoint sort
- Gain recovery (spherical divergence)
- Spectral equalization (1000 ms AGC gate)
- Application of floating datum residual refraction statics
- Application of automatic residual statics
- Velocity analysis
- Normal moveout
- Band pass filter
- Offset regularization and dip moveout (DMO) correction
- Velocity analysis
- Common midpoint stack
- Migration
- Signal coherency enhancement (digistack and fkpower)
- Application of mean datum statics, datum 200 m (AHD), replacement velocity 5900 m/s
- Trace amplitude scaling for display

A reduced processing stream was used in the field to produce field stacks to control and monitor data quality whilst the survey was in progress. As the transect was linear, with some changes of geometry, it was processed using algorithms based on an assumption of 2D geometry. This 2D assumption has implications for the processing and interpretation of the resulting processed data; these implications are explained in the description of the key processing steps.

Crooked line geometry definition

As the seismic line followed the available access routes, none of the three segments were straight. 10GA–CP1 had strong changes in direction, and the northern end of 10GA–CP2 also had sharp bends around topographic ridges. Therefore, the processing was based around the definition of a section line (Common Depth Point, or CDP, line) that smooths out variations in the line.

The data was binned into common midpoint gathers based on a calculated CDP line, and then processed using the CDP method. The CDP line is a curve of best fit through the midpoints between sources and receivers, which optimizes the fold of the data and minimizes the subsurface area of reflections contributing to each nominal CDP. Each trace (source–receiver pair) is allocated to the CDP bin nearest to its midpoint. The CDP bins were defined to be 20 m along the line. The effects of bin size, and of midpoint scatter within the bin, are most critical at shallow depths. Where the line has sharp bends, there is likely to be smearing and poor resolution of shallow data. The effect of bends on deeper data can also be significant, depending on the relative directions of the seismic line, and the dip of the structures to be imaged.

The CDP line was processed as if it was straight, ignoring the effects of changing azimuth along the line. This simplification of the processing to 2D geometry, applied at the start of the processing sequence, is reasonable for large sections of the line that are relatively straight, although it later becomes impossible to correctly migrate reflections, and therefore to correctly image reflectors at significant bends in the line.

Refraction statics

Variations in surface elevation, weathering layer depth, and weathering layer velocity can produce significant time delays in land seismic data. Variations over distances shorter than the spread length can degrade the stack, with the reflections no longer aligning across the traces to be stacked. Variations over distances longer than a spread length will not significantly affect the stack quality, but can introduce spurious long wavelength structures in the stacked reflections; static corrections are applied in the processing stream to remove these effects. For the Capricorn reflection seismic processing, static corrections were calculated by picking first-break refracted arrivals from shot records, and then creating a near-surface refractor model of the weathering layer. The refraction static corrections were applied in two stages using a floating datum. An intermediate step of automatic residual static corrections produced fine tuning of the corrections.

The final static corrections were calculated relative to a datum of 200 m (AHD), using a replacement velocity of 5900 m/s.

The process of picking first breaks for each shot is time consuming. Although automatic methods of picking are used, each set of first breaks needs to be checked and these frequently require editing. Also, the quality of the first-break waveforms depends on the nature of the geology, both at the source and at the receiver arrays. In some parts of the line, a significant proportion of the first break picks were discarded due to poor signal-to-noise ratios. The number of picks for each shot in the model can vary along the lines, and as a result, the number of layers to be modelled must be specifically selected. Once the first breaks for the line have been picked and edited and the number of layers to be modelled is selected, the refractor model can be calculated. A one or two layer model can usually provide a suitable solution to the effects of weathering. For the Capricorn line, a single layer model was selected to best represent weathering over the entire transect.

Spectral equalization

Spectral equalization is a process used to sharpen the reflection wavelet and to suppress low-frequency energy, primarily ground-roll energy, which is surface wave energy generated by the vibrators. The frequency spectrum of the data is flattened over a specified frequency range and within a specified time gate, thereby reducing the high energy, low frequency surface-wave noise relative to the higher frequency energy of the reflections. Therefore, the resulting data has better resolution, particularly in the shallow part of the section (0–2 s two-way travel time (TWT)). The selection of an appropriate frequency range and time gate is based on selective testing and on spectral analysis of the data.

Normal moveout correction

The normal moveout (NMO) correction removes time variations across CDP gathers, by adjusting for time delays caused by progressively increasing offset between source and receivers. The NMO correction is applied as a stacking velocity that best aligns the reflections in the CDP gather. Two different techniques were used to calculate the stacking velocities: velocity scans and constant velocity stacks. Both techniques result in a velocity field varying in time and space (along the line), which maximizes the stack response of the data. Velocity analysis requires interactive selection of optimal stack responses, and is one of the most time consuming processes in the processing sequence. Velocity analysis is usually made on spectral equalized CDP gathers after automatic residual statics, and also after dip moveout corrections are applied. Analyses can also be iterated where required, and areas of complex geology or poor stacking quality may require more closely spaced velocity analyses. The velocity boxes annotated onto the seismic sections are the final velocities picked from the dip moveout gathers, with all corrections applied except for the mean refraction statics; that is, the velocities are applied prior to moving the data to its final datum.

Dip moveout correction

The dip moveout (DMO) correction, also known as partial pre-stack migration, adjusts the NMO correction based on the increase in stacking velocity encountered as the structural dip increases, and has the effect of correcting the NMO to account for different dips occurring along the line. The process effectively moves reflection energy between traces within and between CDP gathers based on the apparent dip of the reflectors, creating a new set of DMO-corrected CDP gathers. After DMO, intersecting dipping and flat reflections will correctly stack with the same stacking velocity. DMO is a computationally intensive processing step.

Common midpoint stack

The common midpoint stack is simply the summing of traces in a CDP gather to produce a single trace at the CDP location. The traces in the gather are aligned by the NMO and DMO processes, with the aim of an optimal sum. In principle, stacking the data can improve the signal-to-noise ratio of the data by $\sqrt{n}$, where n is the number of traces summed (the fold). A nominal fold of 75 resulted from the acquisition geometry for the Capricorn seismic survey.

Post-stack time migration

Migration is the final processing step, and involves moving dipping reflections to their most likely lateral positions based on an assumed velocity distribution. Reflections that appear to be dipping on the stack section will be moved up-dip and shortened after migration. Diffraction hyperbolas resulting from discontinuities, such as the termination of reflectors at faults, and which are visible on the stack section, should collapse into a small region after migration. Note that areas with poor signal-to-noise ratios, and those with sharp bends in the line, can produce artefacts in the data that will not migrate successfully. The main parameters to be selected when performing migration are the velocity field, and the dip ranges to process. The velocity field used usually consists of a percentage of the stacking velocity. Tests are run with different percentages and the optimum migration velocity selected. If migrated correctly, the final time section should have dipping reflections in the correct spatial location. A migration velocity function of 70–85% of the stacking velocities was applied to the Capricorn seismic data. The Omega-X (frequency–space) migration algorithm is a finite difference approximation to the monochromatic wave equation (Yilmaz, 2001), used to migrate data for lines 10GA–CP1 and 10GA–CP2. The time–space Kirchhoff migration algorithm (Stolt and Benson, 1986) was used to migrate data for the 10GA–CP3 line. The effect of migration on the stacked data is illustrated in Figure 1, which shows stacked and migrated images for part of the Capricorn Orogen. Coherency filters were applied to the data to enhance reflections for the final display images.

Conclusions

Reflection profiling has provided very clear images along the Capricorn Orogen seismic lines, identifying many

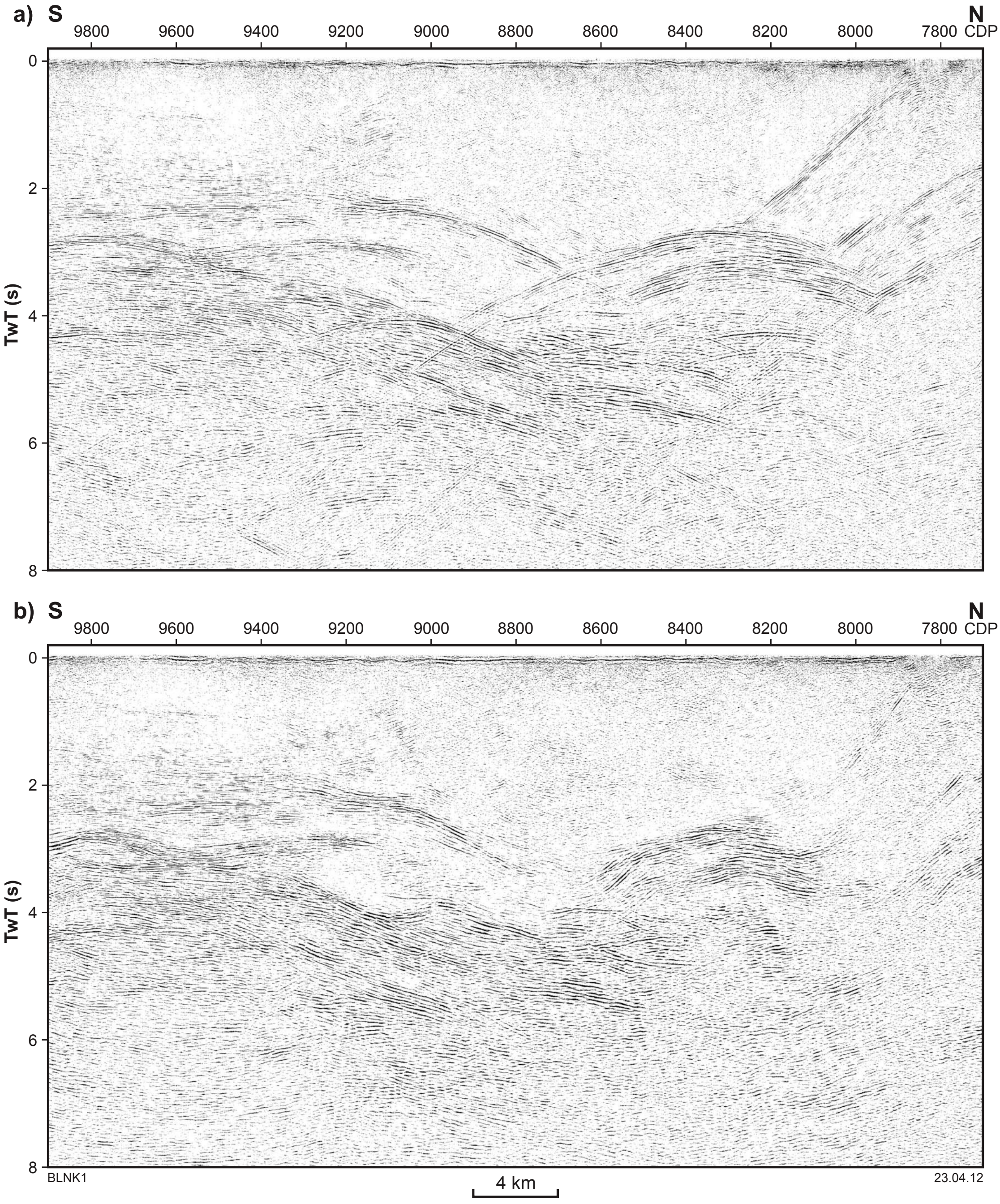

Figure 1. a) fragment of the final stack section for seismic transect 10GA–CP1 of the Capricorn seismic survey; b) final migrated section for the same part of the line, showing how the migration process collapses diffraction energy and moves dipping reflections to the correct location. CDP equal 20 m; V:H=1 for a crustal velocity of 6000 m/s.

dramatic structures that extend right through the crust. As most of the geological targets can be recognized and tracked to depth, the transect provides valuable information to help elucidate the evolution of the orogen.

Unfortunately, in the Hamersley region, the transect geometry imposed by the available access meant that the resolution of near-surface structures was diminished at the edges of some major geological contrasts. The base of the crust varies significantly, changing from a shallow but variable Mohorovičić ('Moho') character visible beneath the Pilbara Craton, to a deep, indistinct crust–mantle boundary beneath the southern part of the Capricorn Orogen, and passing into a shallower Moho once the northern edge of the Yilgarn Craton is reached (at the southern end of line 10GA–CP3).

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