EXPLORATION OPPORTUNITY

ARROWIE BASIN

AREA G

DATA PACKAGE BROCHURE

DEPARTMENT OF
MINES AND ENERGY
SOUTH AUSTRALIA

APRIL, 1989
ARROWIE BASIN

EXPLORATION OPPORTUNITY - AREA G

DATA PACKAGE BROCHURE
ENVELOPE 8085
SR 27/2/96

Prepared by

OIL, GAS & COAL DIVISION

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

APRIL 1989
EXPLORATION OPPORTUNITY - AREA C
DATA PACKAGE BROCHURE

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1. STATEMENT OF INTENT

Applications are invited by 31st September, 1989 for a Petroleum Exploration Licence (PEL) in the eastern Arrowie Basin over AREA G, or part thereof, shown on Figures 1 and 2. It is not necessary to apply for the whole area. Area G covers approximately 15,900 km² of the eastern Arrowie Basin.

A data package has been prepared which contains a selection of regional gravity and magnetic data, seismic survey interpretation reports and sections, well completion reports from petroleum, mineral and stratigraphic wells, source rock analyses and relevant geological maps. This selection forms the basis for assessment of the area and is not intended to be totally comprehensive. References to all relevant petroleum exploration work carried out to date in Area G are listed in the bibliography.

A brief up to date review of the geology and hydrocarbon potential of Area G, is set out below. This contains new interpretations which are not available in the existing literature. An order form is provided at the back of this brochure. Please note that the orders received prior to May 31st 1989 will receive preference. Packages will be supplied promptly after that date.

Applications for petroleum exploration licences covering this area will close on 30th September 1989. Any enquiries should be directed to:
2. GEOLOGICAL SUMMARY

2.1 Introduction

A portion of the Frome Embayment east of the Flinders Ranges is available for petroleum exploration licence application. The area, of approximately 15900 km² designated Area G, includes prospective Early to Middle Cambrian sediments of the eastern Arrowie Basin. The Moomba-Adelaide gas pipeline and the liquids pipeline to Port Bonython cross the area and a portion of the Gammon Ranges National Park occupies the northwestern sector (Fig. 3). No access for petroleum exploration is permitted in this Park, although access may be possible for scientific purposes.

The Arrowie Basin fill of carbonates and siliciclastics was deposited unconformably over Precambrian sediments of the Adelaide Geosyncline (Wopfner, 1970, 1972; Fig. 4). The western margin of the Arrowie Basin is a north-south fault complex (Torrens Hinge Zone) which separates thin Adelaidean and Cambrian platform cover on the Stuart Shelf from thicker and more complete sequences in the fold belt, now exposed as the Flinders Ranges. The Adelaidean Barrier Ranges in western NSW form the
Figure 1

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

AREAS AVAILABLE FOR APPLICATION

NORTHERN TERRITORY
QUEENSLAND
SOUTH AUSTRALIA
NEW SOUTH WALES

SCALE IN KILOMETRES

100  50  0  100  200

COMPiled
R. FRears
C.D.O.
DRAWN
E. CAlabro
DATE
Jan. '89
PLAN NUMBER
CHECKED
Figure 3

SCALE IN KILOMETERS

National Park

Conservation Park

Area covered in this report

DEPARTMENT OF MINES AND ENERGY
SOUTH AUSTRALIA

NORTHEASTERN SOUTH AUSTRALIA
PARKS and RESERVES
Fig. 5 Arrewo Basin. Comparison of formations drilled in the eastern Arrewo Basin with the complete succession outcropping in the Flinders Ranges.
eastern boundary, while to the southeast Cambrian sediments thin onto crystalline basement of the Willyama Inlier.

During the carbonate-dominated depositional phase (Hawker Group, Dalgarno, 1964, Fig. 5) there probably was continuity of sedimentation with the Warburton Basin to the north and Stansbury Basin to the south. However, connections were restricted or severed as uplift of the Willyama Inlier and north-northeast trending basement blocks exposed Early Cambrian and older rocks to erosion prior to widespread regression. This episode of tectonism—the Kangarooian Movements (Daily and Forbes, 1969)—led to locally severe downcutting and channel fill with coarse siliciclastics before regressive carbonates at the top of the Hawker Group were deposited. These channels, recognized in seismic sections (Adams, 1987), present a new play, not yet explored for petroleum.

Redbeds of the Billy Creek Formation, and the shallow marine Wirrealpa Limestone were deposited as tectonic activity waned at the end of the Early Cambrian prior to outpouring of siliciclastics of the Lake Frome Group (Daily, 1956). These arkosic to quartzose sediments were deposited in shallow marine to deltaic environments, perhaps fluvial in the uppermost Grindstone Range Sandstone. Paleocurrent data indicate sources from the Gawler Craton to the southwest, with some input from the Willyama Inlier to the southeast. These exposed basement regions also supplied siliciclastics to the
Figure 6. Palaeogeographic sketch of Eastern South Australia during Early Cambrian.
Kanmantoo Trough which was rapidly subsiding at that time. There is no record of sedimentation above the Grindstone Range Sandstone in the Arrobie Basin, but deposition continued in the Warburton Basin into the Late Cambrian and possibly Ordovician (Gatehouse, 1986).

2.2 Geological setting

The Arrobie Basin as presently defined is not in fact a basin with a pronounced depocentre and encircling marginal facies. As stated above there was probably continuity with the Warburton Basin during the Early Cambrian, and the regional depocentre was somewhere beneath the southern Cooper Basin. An arcuate hingeline in the northern Arrobie Basin (Fig. 6) separated platform margin carbonates and associated slope sediments from truly distal basin sediments to the north in the Warburton Gulf (as yet undrilled). The platform margin consisted of an evolving reef complex with reef-front talus and slope megabreccias, while basinal sediments encroached locally in structural depressions (Clarke, 1986; James & Gravestock, in press). To the south, east and west, open marine shelf facies prevailed with deeper water carbonates and shales in intrashelf depressions and wide embayments. Area C situated on the substable Curnamona Cratonic Nucleus occupied part of such an embayment during the carbonate-dominated phase of the Early Cambrian.
Structure

Area G is situated southeast of the ancient platform margin, between the Flinders Ranges and the subsurface Proterozoic Benagerie Ridge (Figures 7, 8). Both the east and west margins are fault bounded. Total Cambrian is thought to be up to 2300 m thick in this embayment known as the Moorowie Syncline. The shallower Yalkalpo Syncline east of the Benagerie Ridge is suggested here to have once been connected, but this connection was severed by uplift of the Benagerie Ridge during the Kangarooian Movements.
Figure 7. Eastern Arrowie Basin structural elements.
Figure 8. Moorowie Syncline location summary, Area G.
Table 1. Seismic surveys

<table>
<thead>
<tr>
<th>Year</th>
<th>Survey Name</th>
<th>Energy Source</th>
<th>km</th>
<th>Envelope</th>
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<tr>
<td>1960</td>
<td>Geosci-Arrowie</td>
<td>Explosive</td>
<td>63</td>
<td>68</td>
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<tr>
<td>1962</td>
<td>SADME Surveys</td>
<td>&quot;</td>
<td>RB 61/116</td>
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<tr>
<td>1966</td>
<td>Blinman-Wirrealpa area</td>
<td>&quot;</td>
<td>RB 63/26</td>
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<tr>
<td>1966</td>
<td>Eromanga-Frome</td>
<td>&quot;</td>
<td>175</td>
<td>719</td>
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<tr>
<td>1970</td>
<td>Frome Downs</td>
<td>&quot;</td>
<td>543</td>
<td>1 275</td>
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<tr>
<td>1975</td>
<td>Billy Creek</td>
<td>&quot;</td>
<td>40</td>
<td>2 639</td>
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<tr>
<td>1976</td>
<td>Frome Downs</td>
<td>&quot;</td>
<td>10</td>
<td>1 566</td>
</tr>
<tr>
<td>1981</td>
<td>Wertaolona-Arr</td>
<td>&quot;</td>
<td>184</td>
<td>4 808</td>
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<tr>
<td>1982</td>
<td>Christmas Creek-Arr</td>
<td>&quot;</td>
<td>200</td>
<td>5 064</td>
</tr>
<tr>
<td>1984</td>
<td>Hogarth Arr</td>
<td>&quot;</td>
<td>633</td>
<td>5 561</td>
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<tr>
<td>1985</td>
<td>Morphett Arr</td>
<td>&quot;</td>
<td>223</td>
<td>5 995</td>
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<tr>
<td>1986</td>
<td>Fletcher Arr</td>
<td>Vibroseis</td>
<td>156</td>
<td>6 483</td>
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<td>1987</td>
<td>Mitchell Arr</td>
<td>&quot;</td>
<td>193</td>
<td>6 826</td>
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<td></td>
<td></td>
<td></td>
<td>2 738</td>
<td>Total</td>
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Table 2. Petroleum, mineral and stratigraphic bores

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<th>Completion Date</th>
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<th>Operator</th>
<th>Total Depth (m)</th>
<th>SADME Ref.</th>
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<td>Lake Frome 1</td>
<td>Delhi/Santos</td>
<td>781.8</td>
<td>Env. 966</td>
</tr>
<tr>
<td>7/8/68</td>
<td>Lake Frome 2</td>
<td>Delhi/Santos</td>
<td>771.8</td>
<td>Env. 966</td>
</tr>
<tr>
<td>13/7/68</td>
<td>Lake Frome 3</td>
<td>Delhi/Santos</td>
<td>780.9</td>
<td>Env. 968</td>
</tr>
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<td>16/3/76</td>
<td>Yalkelpo 2</td>
<td>SADME</td>
<td>799.0</td>
<td>Rept. Bk. 77/66</td>
</tr>
<tr>
<td>18/12/80</td>
<td>MU 2</td>
<td>Oilmin/Marathon</td>
<td>614.7</td>
<td>Env. 4011</td>
</tr>
<tr>
<td>25/4/81</td>
<td>BWM1A 1</td>
<td>Minad</td>
<td>600.0</td>
<td>Env. 6131</td>
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<tr>
<td>1/9/83</td>
<td>Moorowie 1</td>
<td>Delhi</td>
<td>3 249.2</td>
<td>Env. 5616</td>
</tr>
</tbody>
</table>

B00086
Seismic surveys since 1960 have recorded 2738 km of line (Table 1). Seismic evidence shows that the eastern and northern regions of the Moorowie Syncline are structurally complex. A major double fault system, the north-south trending Poontana Fracture Zone occurs beneath Lake Frome sub-parallel to the Benagerie Ridge (Figures 7, 8). Adams (1987) recognized predominantly east-west compressional forces with a minor north-south component, and documented episodes of Cambrian and Adelaidean reactivation, with a major reversal of movement during the Adelaidean. This was later recognized by Santos (1988) as a wrench fault zone with uplift and erosion of Adelaidean sediments during the mid-Cambrian. This interpretation is thought to be essentially correct, with the further observation that reactivation occurred during the Kangarooian Movements (late Early Cambrian), which also affected uplift of the Benagerie Ridge. Evidence for this is found in core from Yalkalpo 2 (see below). With few exceptions, fault displacements are small (<10msec).

Analogous fault systems of the same age are known from the Stansbury Basin west of Adelaide (Fig. 6) (Pine Point Fault: N-S antithetic; Cygnet Fault: E-W P-fracture) attesting to onset of a major compressional strike-slip regime at this time.

Reprocessed 1970 vintage seismic lines suggest that the Benagerie Ridge Complex may be structurally linked to the Mount Painter Inlier, this structural high terminating the Moorowie Syncline to the north (Adams, 1987). Again, this may be related to intra-
Cambrian tectonic activity. The Wirrealpa Limestone and thick redbeds of the Lake Frome Group appear not to have been deposited east of the Benagerie Ridge. Alternatively they may have been eroded during the Late Cambrian prior to onset of the Delamerian Orogeny. The entire Curnamona Cratonic Nucleus appears to have escaped deformation during this orogeny. Cambrian strata remaining flat lying to gently folded on seismic records. However, steeply dipping fault blocks are anticipated at least locally in wrench-affected zones.

Cambrian redbeds of the Lake Frome Group are overlain unconformably by Late Jurassic to Early Cretaceous sediments of the southern Eromanga Basin. Although local channelling is evident on seismic sections, both the Mesozoic and overlying Tertiary are essentially flat lying. Principal structural traps identified on seismic recorded to date (Fig. 11) are rollovers associated with the Wirrealpa Limestone and with thick Hawker Group channels. Pinchouts at the base of the Billy Creek Formation and en echelon anticlines in the Poontana-Benagerie Ridge complexes should also be considered but further seismic work is required for their delineation.

Sedimentary facies and stratigraphy

The few deep petroleum, mineral and stratigraphic bores that have been drilled in the eastern Arrowie Basin are shown in Table 2. Of these, 4 penetrated the Hawker Group (Yalkalpo 2, MU2, BWM1A 1, Moorowie
1). Moorowie 1, the most recently drilled petroleum exploration well, intersected 1500m of Lake Frome Group redbeds, 117 m of Wirrealpa Limestone, 332 m of Billy Creek Formation and only 41.8 m of Hawker Group before entering Adelaidian sediments at a depth of 2228 m. The well reached total depth in Adelaidian sediments. Thicknesses of the Lake Frome Group, Wirrealpa Limestone and Billy Creek Formation in Moorowie 1 are comparable with those measured in outcrop in the Flinders Ranges. In contrast, the 42 m Hawker Group is extremely thin compared with outcrop (note max. recorded thicknesses in Fig. 5) and consists mainly of dolostone and limestone with quartz sand interbeds capped by anhydrite (Elliott, 1984). Significantly the only porosity developed in the well (4-8%) was in these carbonates and the anhydrite forms an effective caprock.

A composite stratigraphy of the Cambrian in the Flinders Ranges is shown in Figure 5 from which it is evident that a regional unconformity exists at the base of the Cambrian, and a widespread disconformity separates the lower Wilkawillina Limestone from the upper Wilkawillina Limestone and its complexly intertonguing equivalents. On structurally positive regions of the Early Cambrian shelf the discontormity is expressed as a subaerial exposure surface with associated mild to locally intense karst development. However in persistently subsiding intrashelf depressions and open marine embayments where sedimentary facies indicate deeper water, there is no evidence of a break in deposition. The exposure surface and its
correlative deeper water conformity form the top of the older of two stratigraphic sequences in the Hawker Group—here designated Sequence 1 (Figs 5 and 9).

The Yalkalpo Syncline is thought to have been an open marine embayment since in Yalkalpo 2, east of the Benagerie Ridge (Figs 4, 7), the Parara Limestone conformably overlies lower Wilkawillina Limestone. There is no evidence that the Benagerie Ridge existed at this time and there presumably was a connection with the Moorowie Syncline, but no wells have penetrated the older sequence there.

The younger Sequence 2 consists of the upper part of the Wilkawillina Limestone and correlative units, as well as the Billy Creek Formation (Figs 5 and 9). Sequence 2 is characterised by marked differentiation of platform and slope carbonates and basinal shales. Carbonates in shallow marine platform settings became more restricted, shallowing up to evaporitic facies near the top of Sequence 2.

Moorowie 1 is considered herein to have intersected the uppermost Moorowie Formation (Fig. 5) either because the well was drilled on a Precambrian structural high, or more likely because the Moorowie Structure was elevated during the Kangarooian Movements. A slightly older section was fully cored in Minad BWMLA-1 adjacent to the west flank of the Benagerie Ridge (Figs 4, 7). In this well the upper Wilkawillina Limestone is overlain by Oraparinna Shale and Narina Greywacke, the whole Cambrian
sequence representing moderately deep to shallow water facies. The uppermost section below the Billy Creek Formation may have been deposited but presumably was eroded prior to or during the Mesozoic. The Hawker Group is expected to be more complete in deeper parts of the Moorowie Syncline. This is important because the thin tongues of Orsoparia Shale found in BWM1A-1 and Yalkalpo 2 represent the best source rocks sampled to date in the region (see below).

A synopsis of the styles of sedimentation and contemporaneous structural events is shown for the Arrowie Basin in Figure 9. This series of cartoons depicts 6 scenes in the two major depositional sequences represented by the Hawker Group. Yalkalpo 2 intersected the oldest Cambrian yet drilled in the eastern Arrowie (unnamed sandstone, lower Wilkawillina, lower Parara). This is equivalent to scene 3 but because the Yalkalpo/Moorowie Syncline region was an open embayment it remained submerged, and there is no evidence of subaerial exposure. However, MU 2 well drilled 64 km to the southeast (Fig. 7) intersected thin lower Wilkawillina Limestone disconformably above the Late Precambrian Brachina Formation. The contact exhibits karsting associated with the subaerial exposure phase depicted in scene 3. Reef rimmed platform and bypass margins are sketched in scenes 4 and 5, but the platform is located to the west and northwest of the Moorowie Syncline. BWM1A-1 in the southeast flank of the syncline intersected shallow ooid/peloid grainstone in the upper Wilkawillina,
ARROWIE BASIN
SYNOPSIS OF HAWKER GROUP DEPOSITION

After James B Gravestock (in press)

EVENT

Apparent tectonic quiescence but volcanic activity (extrusion?)
Shoaling upward sequence to eventual exposure landward of platform margin.

Compression "Kongolago" Movement
Uplift of basement blocks; Siliciclastic input to basin via channels breaching margin; Sandy turbidites, submarine fan sands.

Extension.
Differentiation of platform margin, mega-breccias, persistent karst on structural highs, first tabulate corals.

Extension.
Shallow exposure meteoric overprint, neptunian dykes, structural lows remain submerged, first trilobites.

ARROWIE BASIN FORMATION not shown
Paratidal exposed highstand, high redbeds - complex, Sequence 2
Stromatolites, platy algal-dominated, evaporites e.g. top upper Wilkawilina, Ajka, Moarowie,
Edecus Limestone Calcimicrobe-dominated biherms.
Exposed basement e.g. Menangerie Ridge, Mt. Poitier Inlet, Glory Inlet. Volcanic sources not yet located - possibly Mt. Wright (NSW), Gidgegal, Twra.

Erosional channels filled with backswamps' sands and sandy limestone breccia in upper Ajka Limestone (Mt. Scott Range), upper Wilkawilina Limestone (Mount Wilkawilina Mine, Ten Mile Creek) and upper Maorowie Formation (Moorowie Mine). Narrow grey carbonate may be downslope equivalent. Shell sands (Bunkers Sandstone) may be local variant.

Platform margin reef complexes of archaeocyaths and calcimicrobes (Renacis, Epypyton, Girvanella) in lower Wilkawilina Limestone,
Moarowie Formation: Slope megabreccias, slumps, turbidites in Moarowie Formation, Paroria Limestone.
Coral, stromatoporoids (Crappergenia) in intra-shelf basins and possibly seaward of platform margin. Karst on exposed shelf carbonates e.g. North of Brachina Gorge, Ten Mile Creek.

Lower Wilkawilina Limestone, high energy skeletal sands subaerially exposed. Red laminated crusts, microstromatolites, collapse breccias. Fractures and fissures in active fault zones filled with marine cements and dolosite debris. Renacis and archaeocyath biherms in persistent subaerially exposed areas.

Renacis and Epypyton - archaeocyath biherms in x-beded skeletal sands on shelf. Archaeocyaths + sponges + stromatolites in deeper water mounds in intrashelf depressions. Limited matted limestones,stromatolites. Pebbles shed from locally exposed edges e.g. Wilkawilina.

whereas in Yalkalpo 2, deeper water mottled lime mudstone of the upper Parara is overlain disconformably by silty sands and thin granule sands. These are either possible equivalents of the shelfal Bunkers Sandstone, or a distal expression of margin bypass sands shown in scene 5. The overlying upper Wilkawillina is a shallow water oncinite packstone. From the mid Parara to the base of the Billy Creek Formation, the sequence is riddled with very thin (2-5cm) tuff beds attesting to repeated volcanic activity. Although a volcano is shown only in scene 6 of Figure 9, tuffs have been recorded from scene 4 onward in the Arrowie and Stranbury Basins, Kanmantoo Trough and from the Mt Wright area in western NSW.

The thin (up to 0.4 m) quartzo-feldspathic granule sands found in Yalkalpo 2 also contain abundant red volcanic porphyry clasts indicating uplift of the Benagerie Ridge in response to the Kangarooian Movements (Fig. 9, scene 5). The Poontana Fracture Zone is suggested here to have been active at this time. This tectonic event triggered the release of coarse, well rounded sands that had been residing in high energy beaches shoreward of the platform and which had been transported intermittently into the carbonate setting. These sands crossed the platform, heading generally northward and incising channels in reefs and bioherm complexes before being redeposited in local structural depressions or in deeper water beyond the platform margin (equivalent to Narina Greywacke). The channel sands mapped in the Hogarth Seismic Survey (Adams, 1987) were part
of this event. Wopfner (1970) mapped high sand:carbonate ratios in the eastern Flinders Ranges, originating from uplift of the Willyama Inlier. This interpretation was confirmed by the drilling of Yalkalpo 2 (Youngs, 1977a), but it is only very recently that the extent and significance of these sandy units has been recognized. Away from the channels in deeper water the Opararinna Shale and Narina Greywacke were deposited.

Uplift of the Benagerie Ridge appears to have isolated the Moorowie Syncline from the Yalkalpo Syncline prior to the final phase of Hawker Group deposition (Fig. 9, scene 6). From the Stuart Shelf west of the Arrowie Basin, eastward across the Flinders Ranges, the uppermost 50 m or so of the Hawker Group were deposited in a shoaling upward, increasingly restricted marine setting characterised by thrombolitic calc-algal bioherms, ooid grainstones, dolomitised stromatolitic and fenestral limestones and evaporites. The dolostone/anhydrite sequence intersected in Moorowie 1 forms part of this facies suite. Redbeds of the Billy Creek Formation completed this regressive phase in a tectonically quiescent setting.

A return to shallow marine conditions is recorded by the thin (85-120 m) but extensive Wirrealpa Limestone (Youngs, 1977b; Youngs & Moorcroft, 1982). However, seismic and drillhole evidence shows no Wirrealpa Limestone or overlying Lake Frome Group east of the Benagerie Ridge. Whether these were originally deposited and have been subsequently
eroded is not known but the latter is more likely. Almost 3000 m (twice the thickness drilled in Moorowie 1) of Lake Frome Group redbeds crop out in the Flinders Ranges. Descriptions of the constituent formations, shown in Figure 5, are provided by Daily (1976) and Youngs & Moorcroft (1982). Collectively the Lake Frome Group comprises feldspathic siliciclastics with minor carbonates in the upper Moodlatana and Balcoracana Formations. These consist chiefly of laminated and stromatolitic limestones and ooid grainstone, which with occasional trace fossils and bioturbated units, indicate episodic shallow marine conditions. The bulk of the detritus appears to have been transported into the basin by fluvio-deltaic systems from the Gawler Craton. However, at this time, carbonates, mixed carbonate/siliciclastic units and volcanogenic sediments were accumulating in the Warburton Basin to the north. Thus it is likely that finer grained sediments and a greater proportion of carbonate will have been deposited in the northern Arrowie Basin.

2.3 Hydrocarbon Potential

The first Cambrian oil shows in Australia were discovered in 1956-57 by Santos Ltd in a number of shallow wells at Wilkatana in the southwest Arrowie Basin. The shows consisted of 26°API paraffinic crude oil and semi-consolidated wax in vuggy dolomitised limestone unconformably overlain by Tertiary sediments. Fossil evidence (arachaeocyaths) indicates that the reservoir is in the upper part of
the lower Wilkawillina Limestone (Fig. 9, scene 3). Whether or not the vuggy porosity was due to exposure and karst development during the Early Cambrian is unknown but seems likely. Other shows encountered in drillholes include oil staining in the Andamooka Limestone (Wilkawillina equivalent) on the Stuart Shelf, staining of the lower Wilkawillina Limestone at Brachina Gorge, and traces of free oil in a thin limestone in the upper Moodlatana Formation at 1622m depth in Moorowie 1. It is clear that oil has been generated in the Cambrian sequence. Source and reservoir rocks are discussed below.

Source Rocks

A comprehensive account of the source rock and petroleum geochemistry of the Arrowie Basin has been given by McKirdy (1986). In summary, his findings can be subdivided into 3 categories: source richness, source quality and maturity.

Source richness

1. Most samples from the Wilkawillina Limestone and shallow shelfal equivalents, the Wirrealpa Limestone and Moodlatana Formation, have uniformly low organic carbon content (TOC < 0.1%). Even allowing for the effects of deep weathering, these carbonates would not have had sufficient organic carbon necessary to generate producible hydrocarbons.
2. Argillaceous limestones of the Parara Limestone have TOC values ranging from 0.13 to 0.34% and constitute the most organically rich carbonates. These are still nevertheless lean, and the TOC variations reflect alternating oxic-anoxic conditions during deposition and early diagenesis. This is confirmed from core studies.

3. Somewhat reducing conditions were characteristic for the Oraparinna Shale (leached in outcrop). Two samples yielded TOC values of 0.19 and 0.35%.

4. The Wirrealpa Limestone is lean in outcrop and in some subsurface wells e.g. Lake Frome 1 and 2 (TOC = 0.02 - 0.07%). However richer values were found in Moorowie 1 (TOC = 0.10 - 0.73%) which may reflect facies variations.

5. Samples from formations of the Lake Frome Group occasionally have fair TOC values (0.48%) but have poor source richness (SI + S2 = 0.8 kg hydrocarbons/tonne).

Source quality and kerogen type

Rock extracts have pristane/phytane and kerogen δ¹³C values that indicate algal/cyanobacterial origins. Elemental analysis of kerogens and Rock Eval pyrolysis data, together with the low TOC contents of most samples, indicate the preservation of poor quality gas-prone Type III or essentially non-
generative Type IV kerogen. However, the Moodlatana Formation and Wirrealpa Limestone in Moorowie 1 have micrinitised bituminite as a major component of their organic matter, implying the prior existence of oil-prone Type II kerogen. Unfortunately this type of DOM is volumetrically insignificant.

Maturity

McKirdy's (1986) preliminary assessment of source rock maturity from limited kerogen elemental, organic petrological and Rock Eval data suggest that many parts of the Arrowie Basin are within the oil window. In Moorowie 1 the oil window (equivalent V.R. = 0.5 - 1.35%) is in the depth range 1330 to 2050 metres (lower Pantapinna Sst. - lower Billy Creek Fm). Current seismic data indicate that the top Hawker Group (27 Time Structure Map; Adams, 1987) is in this depth range east of longitude 139°30'E (Poontana Fracture Zone) and north of latitude 30°45'S.

McKirdy (1986) concluded that the more argillaceous facies of the Parara Limestone, and to a lesser degree the Oraparinna Shale, are the most attractive source rocks. However, fresh, unweathered samples had not been analysed.

It is imperative to note that two more recently analyses samples of Oraparinna Shale (89.5, 135.5 m depth) in BWM1A-1 yielded TOC values of 0.18 and 1.15 per cent. In addition, argillaceous (?Parara) limestone from drillcore in the Flinders Ranges
(drillhole BRD-2) yielded 0.79 to 1.43% TOC (Watson, 1987). Evidently there are source rocks in the shalier units that yield promising TOC levels. The Orarapinna Shale in BWMLA-1 is leached owing to proximity to groundwater. Calculated VR from methylphenanthrene index measurements ranged from 0.91 to 1.66% (av. = 1.16%) for the samples yielding the highest TOC values, indicating that the aromatic fraction of the sample extracts was in the oil window when hydrocarbon generation occurred. The amount of fresh, unweathered material available for source rock analysis is extremely limited. Despite this, high quality source rocks have been found in the Parara Limestone and Orarapinna Shale. Most samples from the Wilkawillina Limestone which is a shallow carbonate platform sequence are better regarded as potential reservoirs than source rocks.

**Reservoir Rocks**

**Hawker Group**

No systematic study of potential Hawker Group reservoirs has been carried out, chiefly due to the unsuitability of weathered outcrops and the lack of sufficient representative deep drillcore. It had been hoped that Moorowie 1 would intersect thick Hawker Group which would provide the basis for core analysis, but the prognosed thick Early Cambrian sequence turned out to be Adelaidian when drilled. Descriptions of porosity in the Wilkawillina Limestone are thus largely qualitative, these include:
1) Vuggy and fracture porosity in Wilkatana wells, and in Coho Yarrah 1 drilled in the same vicinity to test the Wilkawillina Limestone (Lane, 1982).

2) Vuggy porosity (visual est. 15%) and a water flow of 300 gallons per hour from the Wilkawillina Limestone at Moage Old Motpena 1 (Vakil, 1983). This well is located on the eastern shore of Lake Torrens.

3) Low (4-8%) porosity in sandy dolostone of the upper Moorowie Formation beneath the anhydrite cap in Moorowie 1 (GLOBAL Interp., in Elliott, 1984) (Fig. 10).

4) Moldic porosity (visual est. 20%) in thin (0.5 - 0.8 m) ooid grainstones in Yalkalpo 2 at 550m depth. This facies, and comparable ooid/peloid grainstones in BWMLA-1, are interbedded with Orparinna Shale, potentially the richest source rock in the basin.

Wirrealpa Limestone

Porosity/permeability measurements of Wirrealpa Limestone specimens from outcrop (Youngs, 1977b) and Moorowie 1 core (Elliott, 1984) yielded very low values (outcrop: porosity 1.4 - 3.0%, permeability <0.5 - 3.8 md; Moorowie 1: porosity 0.01 - 0.5%, permeability < 0.01 - 0.09 md; vuggy zone porosity 3.0 - 11.1%, permeability < 0.01 -
Figure 10. Delhi Moorowie 1, selected downhole logs and GLOBAL litho-interpretation.

SADME S20675
1.8 md). From mapping of ooid shoal facies in Wirrealpa Limestone outcrops, Youngs (1977b) suggested their subsurface extension into the Moorowie Syncline. She pointed out the high reservoir potential of leached ooids, and judging by the moderately high visual porosity in Valkalpo 2 ooids (4 above), the Wirrealpa Limestone should not be disregarded as both possible source and reservoir.

Lake Frome Group

Youngs & Moorcroft (1982) summarised porosity/permeability data of formations in the Lake Frome Group. Values range from 9.5% and 0.1 md in the Moodlatana Formation to 13.7% and 35 md in Balcoracana Formation. These authors noted a trend of increasing secondary porosity with depth in the Balcoracana Formation from Lake Frome-2, from thin section examination. They also pointed out that the sandier Pantapinna Formation and Grindstone Range Sandstone extend over much of the Moorowie Syncline and constitute potential reservoirs. However, the Lake Frome Group lacks a cap seal, and intraformational seals are few and unpredictable.

Near top Hawker Group Channels

Seismically mapped channels in the Moorowie Syncline represent a new play (Adams, 1987). A widespread episode of channel incision and/or coarse arkosic sandstone deposition in the upper parts of the upper Wilkawillina Limestone and its correlatives has
recently been recognised in the Flinders Ranges. Localities include:

1) Upper Ajax Limestone, Mount Scott Range (channels)

2) Upper Wilkawillina Limestone, Old Wirrealpa Mine (?channels)

3) Upper Wilkawillina Limestone, 10 Mile Creek (X bedded sands)

4) Upper Wilkawillina Limestone/basal? Billy Creek Formation (Coats Hill Member of Moore, 1980) at Reaphook Hill (X bedded and ? channel sands)

5) ?Bunkers Sandstone equivalent comprising 36 m of fine sands, silts and occasional grit bands in Yalkalpo 2.

6) Moorowie Formation, Moorowie Mine (coarse grits incising reef-rocks on the platform margin).

These occurrences are all evidence of a widespread event which transported sand across the platform and over the platform margin in response to tectonic activity (Kangarooian Movements, Fig. 9, conc. 5). The presence of finer sands and silts, with occasional grits in Yalkalpo 2, suggests that some clastic material was also transported into deeper embayments from the rising Olary Inlier and
Benagerie Ridge. General transport direction was northward, as are the axes of the channels mapped seismically in the Moorowie Syncline.

In outcrop these sands are quartzo-feldspathic and very well rounded, but tight with a calcite matrix. Occasionally they contain carbonate breccia clasts. The channels are stratigraphically above, or cut into, potential source rocks (Oraparinna Shale, Parara Limestone), and are below the widespread regressive carbonate-evaporite sequence that comprises the uppermost Hawker Group (Fig. 9, scene 6) which, judging by its thickness in Moorowie 1 (Fig. 10), is likely to provide an excellent cap seal. Primary porosity may have been preserved where the sands are not deeply buried. However, since Youngs & Moorcroft (1982) have found that secondary porosity is common in the overlying Lake Frome Group red beds, dissolution of the carbonate matrix will be required for the channel sands to constitute good reservoirs. Alternatively, there may be areas where carbonate matrix was lacking. Trapping mechanisms are likely to have a high stratigraphic component while the location and orientation of channels will have been structurally controlled.

Conclusions

1) Potentially rich source rocks occur in deeper water argillaceous facies of the Parara Limestone, the Oraparinna Shale, and in certain facies of the Wirrealpa Limestone.
2) The oil window in the Moorowie Syncline appears to be between 1330 and 2050 metres, and seismic data suggest that the Hawker Group should be at these depths in the northern and eastern parts of the Moorowie Syncline.

3) Syndepositional tectonic activity has resulted in complex compressional wrench-related fault zones (Poontana Fracture Zone, Benagerie Ridge).

4) The same fault movements caused widespread deposition of near top Hawker Group channel sands.

5) A regional seal to the Hawker Group is provided by both the Billy Creek Formation and a carbonate-evaporite regressive section at the end of Hawker Group time.

6) Reservoir potential is demonstrated in thin leached ooid grainstones within Oraparinha Shale equivalents, while ooid shoals in the Wirrealpa Limestone and channel sands in the Hawker Group could constitute excellent reservoirs if similarly leached. Sandstones in the Lake Frome Group have some reservoir potential but lack a regional seal. Low porosity dolostones beneath an anhydrite cap in Moorowie 1 (upper Moorowie Formation) may improve as reservoirs elsewhere in the subsurface. Vuggy porosity due to subaerial exposure of the lower Wilkawillina Limestone
has not been demonstrated in the Moorowie Syncline. However, a thin karst surface is present in the southern Yalkalpo Syncline at this stratigraphic level (Oilmin/Marathon MU-2 well), suggesting that, locally, karst-associated leached porosity is feasible.

(7) Porosity in archaeocyathan/cyanobacterial reef complexes has been largely occluded by early diagenetic marine and burial cements. However, extensive areas dolomitised in outcrop display fracture and intercrystalline porosity. Such pervasively dolomitised reefs may provide reservoirs if they are present in the subsurface.

3. DATA PACKAGE CONTENTS

If you wish to purchase the data package for Area G (Arrowie Basin) please complete the order form at the rear of the brochure. Orders received before May 31st will receive priority. The contents of the data package are listed below. Additional unpublished reports listed in the bibliography can be ordered, and will be included in the package at extra cost. The cost of the package is $Aust 2572 including freight charges.

Copies are to be supplied as microfiche where possible. Seismic sections and shotpoint location maps will be supplied as sepia copies.
The SADME contact persons for enquiries relating to the data package are:

PRODUCTION/SALES  GEOLOGICAL INTERPRETATIONS
Mr V Hilditch    Dr D. Gravestock
Information Services  Oil Gas & Coal
Branch  Division
   (08) 274 7523  (08) 274 7633

3.1 GEOLOGICAL DATA

(i) Geological reports


(ii) Published geological maps

1: 250 000 Geological series
COPELEY and explanatory notes
FROME and explanatory notes
PARACHILNA and explanatory notes
CURNAMONA
1: 500 000 Special series

200086
Figure 11. Seismic line locations, Area G
Figure 12. Seismic data included in data package, Area G
Adelaide Geosyncline and Stuart Shelf (2nd edition).

(iii) Well completion reports

Note: digital (LIS format) tapes of limited log data are available from the Department of an additional cost of $35/tape plus $30/well for all wells listed. Complete data tapes for petroleum wells can also be purchased from Wiltshire Geological services and Ian Northcott and Associates Pty Ltd.

<table>
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<th>Designation</th>
<th>Completion date</th>
<th>SADME Ref.</th>
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<td>Lake Frome 1</td>
<td>petroleum/strat</td>
<td>22/8/68</td>
<td>Env. 968</td>
</tr>
<tr>
<td>Lake Frome 2</td>
<td>petroleum/strat</td>
<td>7/8/68</td>
<td>Env. 968</td>
</tr>
<tr>
<td>Lake Frome 3</td>
<td>petroleum/strat</td>
<td>13/7/68</td>
<td>Env. 968</td>
</tr>
<tr>
<td>Yalkalpo 2</td>
<td>stratigraphic</td>
<td>16/3/76</td>
<td>Rept Bk 77/66</td>
</tr>
<tr>
<td>BWM1A 1</td>
<td>mineral expl.</td>
<td>25/4/81</td>
<td>Env. 6131</td>
</tr>
<tr>
<td>Moorowie 1</td>
<td>petroleum expl.</td>
<td>1/9/83</td>
<td>Env. 5616</td>
</tr>
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</table>

3.2 Geophysical Data

(i) Seismic Data

. Computer generated seismic line location map 1:100 000 scale (SEPIA copy)

. Seismic shot point location map 1:50 000 scale (SEPIA copy)

. Seismic sections listed below and shown on Figure 12 are chiefly unmigrated full-scale final stacks. Pre 1970 lines are not included.
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<th>Survey</th>
<th>Line</th>
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<td>70-CFA</td>
</tr>
<tr>
<td></td>
<td>70-CFB</td>
</tr>
<tr>
<td></td>
<td>(re-shot in 1981, see 70-CFF below)</td>
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<tr>
<td></td>
<td>70-CFQ</td>
</tr>
<tr>
<td></td>
<td>70-CFR</td>
</tr>
<tr>
<td>1981 Wertaloona Arr</td>
<td>81-CFF</td>
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<tr>
<td></td>
<td>81-QLD</td>
</tr>
<tr>
<td></td>
<td>81-QLE</td>
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<tr>
<td>1984 Hogarth Arr</td>
<td>84-SPG</td>
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<td>84-SPY</td>
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<td>1985 Morphett Arr</td>
<td>85-ZDD</td>
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<td>85-ZDM</td>
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<td>86-AHT</td>
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<td>1987 Mitchell Arr</td>
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<tr>
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<td>87-BBZ</td>
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<td>87-BCB</td>
</tr>
</tbody>
</table>
(ii) Gravity maps

Bouguer gravity contours 1: 250 000
FROME, CURNAMONA

(iii) Magnetic maps

Total magnetic intensity contours 1: 250 000
COPLEY, FROME, PARACHILNA, CURNAMONA

4. BIBLIOGRAPHY

4.1 References


4.2 SAMREF

Comprehensive information is available in the Department’s SAMREF bibliographic database. SAMREF is available for public access either at this Department, or through ARID (Australian Resources Industry Database), forming part of GEOPAC on INFO-ONE International. Prior to November 1, 1988, INFO-ONE International was known as CLIRS Information Services. With this change of name, there is now a lower price schedule applying to membership and annual fees and connect times rates. New access menus have also been provided to facilitate use by casual and inexperienced users. INFO-ONE International is available Australia-wide and overseas and can be accessed online by computer.

The South Australian Department of Mines and Energy is progressively adding abstracts to the SAMREF database on INFO-ONE International, including:

- company reports released since 1983
Departmental reports and publications released since 1981 and

some pre-1961 revised company and Departmental reports.

Other references are only available at the Department in Adelaide.

5. LICENCE APPLICATION PROCEDURES

Petroleum exploration and development in South Australia are administered under the Petroleum Act, 1940 (onshore) and the Petroleum Submerged Lands) Acts, 1967 of the Commonwealth and 1982 of the State (offshore). Vacant onshore areas are continuously available for licence applications, whereas offshore permits are open to application only after release of areas by the Commonwealth and State Governments.

There is no set form for making an application other than by a written request addressed to the Director General, Department of Mines and Energy. Application guidelines, licence conditions, obligations, etc for onshore petroleum exploration are summarised in Table 3. For any enquiries relating to licence applications contact:

Mr Bob Laws
Director, Oil, Gas and Coal Division
Phone (08) 274 7612
### Table 3: Onshore petroleum exploration guidelines

**PETROLEUM ACT, 1940**

Note: The area to which this Act applies covers all of onshore South Australia exclusive of Commonwealth Lands; it extends south to the State Territorial Sea Baseline and includes the waters of Spencer and St Vincent Gulfs.

<table>
<thead>
<tr>
<th>ONSHORE PETROLEUM EXPLORATION</th>
<th>Petroleum Act Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Title of Tenement</strong></td>
<td>Petroleum Exploration Licence (P.E.L.)</td>
</tr>
<tr>
<td><strong>Who Can Apply</strong></td>
<td>An individual, a body corporate (i.e. a company) or an unincorporated association of persons and bodies corporate (i.e. a joint venture involving several persons and/or companies. Where application is made on behalf of a company, the application must be made under the company seal.</td>
</tr>
<tr>
<td><strong>When Application Can be Made</strong></td>
<td>Initial Licence - At any time over any area not already under licence. Renewal of Licence - not less than 3 months before existing licence is due to expire</td>
</tr>
<tr>
<td><strong>Maximum Area</strong></td>
<td>26 000 sq km.</td>
</tr>
<tr>
<td><strong>Application Fee</strong></td>
<td>For initial application - $400 For each renewal - $400</td>
</tr>
<tr>
<td><strong>Bond (to ensure compliance with licence conditions)</strong></td>
<td>$4 000 minimum. Amount required is specified in letter of offer. Bond may be in the form of cash, cheque or bank guarantee.</td>
</tr>
<tr>
<td><strong>Term of Licence</strong></td>
<td>Initial Term - 5 years Each Renewal (to a maximum of 3) - 5 years</td>
</tr>
<tr>
<td><strong>Annual Rental Payable</strong></td>
<td>Initial 5 Year licence term - 16 c/sq km First Renewal (2nd 5 Year licence term) - 24 c/sq km Second Renewal (3rd 5 Year licence term) - 32 c/sq km Third &amp; Final Renewal (4th 5 Year licence term) - 40 c/sq km.</td>
</tr>
<tr>
<td><strong>Minimum Work Commitments</strong></td>
<td>As negotiated with applicant after application (which must contain a proposed 5 year work program) has been received.</td>
</tr>
<tr>
<td><strong>Minimum Expenditure Commitments</strong></td>
<td>Initial 5 Year licence term - first two years - $16 per sq km per year - last three years - $24 per sq km per year First Renewal (2nd 5 Year licence term) - $62 per sq km per year Second Renewal (3rd 5 Year licence term) - $80 per sq km per year Third &amp; Final Renewal (4th 5 Year licence term) - $94 per sq km per year</td>
</tr>
</tbody>
</table>

B00086
Area to be Relinquished on each Renewal 25% of original licence area. This is in addition to any areas voluntarily surrendered during each 5 Year licence term. 18(2)

Fee for Minister’s Consent to Dealings in Licence $400 per transaction (document) 42(3)

Fee for Inspection of Register $2 Reg.7(1)

Fee for Copy or Extract from Register 50c per page Reg.7(2)

Method of Application Letter of application addressed to the Director-General, Department of Mines and Energy (there is no prescribed form).
Attached to the application should be:
(1) full names and addresses of the party/parties making the application, including (where applicable) the percentage interests of the various parties.
(2) two copies of a map and description of the area being applied for.
(3) a table showing the work intended to be carried out, and the estimated cost of that work, during each year of the five year licence term.
(Expenditure estimates should satisfy the minimum expenditure commitments set out in Sections 17 and 18)
(4) particulars of the technical qualifications and expertise available to the applicant party/parties (e.g. qualifications and experience of employees, consultants retained etc.)
(5) particulars of the financial resources available to the applicant party/parties to carry out the proposed terms and conditions of the licence.
(In the case of a company application, this is generally supplied in the form of a copy of the company’s most recent Annual Report).
(6) the $400 application fee.
Where the application is made on behalf of a company, the application must be made under the company seal. 7(2)

Penalty for Non-Payment of Annual Rental Fees All fees are payable in advance. If fees are not paid by the due date, a fine of 10% is imposed and in addition, interest accrues at the rate of 6% per annum. If any fee is in arrears for 3 months or more, the licence may be cancelled. 83(1) &8(c)

Licence Variations Only on application by the licensee, the Minister may at any time during the term of the licence, vary or revoke a condition of the licence or attach new conditions to the licence. 17(3)

Environmental Conditions These will be outlined in the letter of offer attached to the licence.
Surrenders
(Partial or Whole of Licence)
The Act requires the licensee to:
(1) apply to the Minister for permission to surrender,
(2) give three months notice in writing,
(3) pay all outstanding fees,
(4) pay all outstanding monies and wages to workmen and employees.
Surrenders are only permitted if the licensee has fulfilled all the terms and conditions of the licence up to and including the year in which the application to surrender is lodged.
Licensees are required to lodge all outstanding data on their licences and carry out the cleanup and rehabilitation of their licence areas (where necessary) as a condition of surrender.
Surrenders are effective from the end of the appropriate year of the term of the licence (unless specified otherwise).
38(1)
38(1)(a)
38(1)(b)
38(1)(c)
38(2a)
38(2b)

Required Notice for Approval to Undertake Work in Licence Area
Three months notice is required to arrange necessary clearances with other Government Agencies. This is carried out by DME on the licensee's behalf.
51(1)

Required Notice of Entry to Latchholders
No risk of damage to land or improvements thereon - 14 days.
Risk of damage to land or improvements thereon - 28 days.
51(1)

Gazettals
Gazettals occur on:
(1) Grant of Licence
(2) Surrender of Licence
(3) Cancellation of Licence
6(2)
71(1)

Suspension and Cancellation
The Act provides for suspension and/or cancellation for failure to comply with licence conditions.
87a(1)

N.B. All fees under the onshore legislation are subject to review.
SR 27/2/76

To the Director-General
South Australian Department of Mines and Energy
PO Box 151
EASTWOOD   SA    5063

ATTENTION: OIL, GAS AND COAL DIVISION

Dear Sir/Madam,

Re: Area G Data Package

Please provide the Area G data package as specified in Section 3.

Company .................................................................

Address ........................................... Postcode ..............

Contact .................................................................

Telephone ....................... Telex .........................

Facsimile .........................

Please find enclosed a cheque for $Aust. 2572, made out to Dept. Mines and Energy, account # 86G25 144/076.

Date ....................... Signed .......................